D2.2

Technical Solutions Portfolio

Date 30.09.2024
Doc. Version 04

Work Package Title	WP2 – Market Technical and Financial Assessment
Deliverable number	D2.2
Description	A report describing the main elements of District Heating (DH) and strategies/technologies to adapt/integrate low-grade energy sources to high-temperature DH distribution networks.
Lead Beneficiary	UNIPARTHENOPE
Lead Authors	Federico Scarpa (UNIGE), Luca Tagliafico (UNIGE), Vincenzo Bianco (UNIPARTHENOPE)
Contributors	Annalisa Marchitto (UNIGE), Mattia De Rosa (UNIGE)
Submitted by	CREARA
Doc. Version (Revision number)	1
Sensitivity (Security):	Public
Date:	12/09/2024

Document Approver(s) and Reviewer(s):

NOTE: All Approvers are required. Records of each approver must be maintained. All Reviewers in the list are considered required unless explicitly listed as Optional.

Name	Role	Action	Date
Gabriel Garcia Hernandez	Project Board Member	*Review*	23/09/2024
Galina Ivanova	Project Board Member	*Review*	23/09/2024
David Pérez	Project Board Member	*Approve*	27/09/2024

Document history:

The Document Author is authorized to make the following types of changes to the document without requiring that the document be re-approved:

- Editorial, formatting, and spelling
- Clarification

To request a change to this document, contact the Document Author or Owner.

Changes to this document are summarized in the following table in reverse chronological order (latest version first).

Revision	Date	Created by	Short Description of Changes
01	01.06.2024	UNIGE – Federico Scarpa	1st draft created
02	20/07/2024	UNIGE – Luca Tagliafico	2nd draft released
03	06/09/2024	UNIGE – Luca Tagliafico	3rd draft released
04	16/09/2024	UNIPARTHENOPE – Vincenzo Bianco	4th draft released
05	23/09/2024	CREARA – Gabriel García	Review
06	23/09/2024	EUROPROJECT – Galina Ivanova	Review
07	27/09/2024	CREARA – David Pérez	Review and approval

Configuration Management: Document Location

The latest version of this controlled document is stored in Deliverables

Nature of the deliverable		
R	Report	x
DEC	Websites, patents, filing, etc.	
DEM	Demonstrator	
O	Other	

Dissemination level		
PU	Public	x
CO	Confidential, only for members of the consortium (including the Commission Services)	

ACKNOWLEDGMENT

Copyright

Disclaimer

TABLE OF CONTENTS

Executive Summary

This report, *Technical Solutions Portfolio (D2.2)*, provides a comprehensive evaluation of Low-Grade Energy Resources (LGERES) and their potential integration into District Heating (DH) networks. The focus of the study is on developing technologies and strategies to upgrade low-temperature energy sources, such as solar thermal, geothermal, biomass, and industrial waste heat, to the higher temperature requirements of DH systems. The report pays special attention to the situation in countries like Lithuania, Poland, and Slovakia, where DH systems are historically relevant for the energy system, particularly High-Temperature District Heating (HT-DH) networks.

District Heating systems are pivotal in efficiently supplying heat to urban areas, especially in colder climates. However, many of these systems, particularly in Eastern Europe, were built during a time when fossil fuels such as coal and natural gas were abundant and inexpensive. As the energy landscape shifts towards sustainability, these older systems require significant technological upgrades to incorporate renewable energy sources. This report outlines 24 innovative technological solutions designed to facilitate the integration of LGERES into DH networks, with the aim of reducing dependency on fossil fuels and lowering greenhouse gas emissions.

Key technologies explored in the report include:

- **Heat Pumps (HPs):** These devices are essential for upgrading low-temperature renewable sources to the higher temperatures required by DH networks. They can be used to integrate renewable heat from solar, geothermal, or waste heat sources.
- **Mechanical Vapour Recompression (MVR):** MVR systems boost low-pressure steam into high-energy steam, allowing waste heat to be recycled and reused efficiently in DH networks.
- **Thermal Energy Storage (TES):** TES systems store excess heat during low-demand periods, making it available during peak heating needs, thereby improving the overall efficiency and reliability of DH systems.

The report emphasizes the need for a staged transition, starting with hybrid systems that combine fossil fuels and renewable energy sources, before moving to fully renewable-based DH systems. This gradual approach allows for the integration of LGERES into existing networks without disrupting heat supply, while also making use of existing infrastructure.

A significant focus of the report is the financial and operational viability of the proposed solutions. The Levelized Cost of Heat (LCOH) is used as a primary metric to evaluate the generic cost-effectiveness of various technological strategies. While some solutions, like waste heat recovery, offer lower LCOH and immediate economic benefits, others, such as retrofitting existing systems with geothermal or solar technologies, may require higher initial investments but result in long-term environmental and financial gains. The report concludes that despite potential increases in short-term costs, the LCOH for renewable solutions remains competitive within the European energy market, particularly when factoring in the long-term reduction in carbon emissions and fossil fuel dependency. In addition, the impact of the externalities cost reduction should be also considered.

The report's detailed analysis of 10 specific case studies provides a more in-depth examination of how these solutions could be applied in real-world scenarios. Each case study explores both the generic energy

and financial performance of a particular technological integration, offering insights into the practical challenges and benefits associated with transitioning DH systems towards renewable energy. The 10 case studies include:

1. **High-Temperature Solar Integration in CHP Systems** (Tech. Sol. No. 05): This case study explores the integration of solar thermal energy into a Combined Heat and Power (CHP) system. By using solar concentrators, high-temperature heat can be injected into the DH system, reducing reliance on fossil fuels. The analysis shows that this solution offers a significant reduction in carbon emissions but comes with moderate increases in capital expenditure (CAPEX).

2. **Flat Plate Solar Panels and Steam Heat Pump Integration** (Tech. Sol. No. 11): This solution integrates flat plate solar panels with a steam vapor compression heat pump, which upgrades low-temperature heat to higher temperatures suitable for DH networks. This system is particularly effective in regions with high solar irradiance, offering good LCOH results when paired with waste heat recovery.

3. **Parabolic Trough Solar Integration** (Tech. Sol. No. 13): This case focuses on the use of parabolic trough solar collectors to preheat water for DH systems. It demonstrates how solar thermal technology can be used to complement existing fossil fuel-based systems, reducing fuel consumption and emissions without major infrastructure changes.

4. **Industrial Waste Heat Recovery with Absorption Heat Pump** (Tech. Sol. No. 18): This case evaluates the potential of using waste heat from industrial processes, upgraded with an absorption heat pump, to supply heat to a DH network. The study highlights that this is one of the most cost-effective solutions, with a low LCOH and a fast payback period.

5. **Waste Heat and Low-Temperature Heat Pump Combination** (Tech. Sol. No. 19): This case study looks at integrating low-temperature waste heat from industrial sources with steam compression heat pumps. The solution offers significant reductions in energy costs and emissions, making it ideal for retrofitting older DH systems with minimal disruption.

6. **Geothermal Heat Pump Integration** (Tech. Sol. No. 22): Geothermal energy is used in this solution to replace traditional fossil fuel boilers. The analysis shows that while the LCOH for geothermal systems is higher than other options, the environmental benefits and long-term sustainability make this a promising solution for DH systems in areas with abundant geothermal resources.

7. **Sewage Waste Heat and Steam Compression Heat Pump** (Tech. Sol. No. 24): This case focuses on recovering heat from municipal sewage systems using a vapor compression heat pump. The study shows that this solution can offer considerable savings, especially in urban areas where sewage heat is readily available, and it performs well in terms of energy efficiency.

8. **CHP Retrofit with Solar Concentrators** (Tech. Sol. No. 05 – Detailed Model 1): A detailed analysis of how high-temperature solar concentrators can be integrated into existing CHP systems. This case study presents a strong environmental benefit but highlights the need for high CAPEX, requiring government subsidies or incentives to be economically viable.

9. **Boiler Substitution with Biomass** (Tech. Sol. No. 23): This case study focuses on replacing traditional boilers with biomass-powered alternatives. The results indicate a significant reduction in carbon emissions, though the financial viability depends heavily on the local availability of biomass.

10. **Boiler Substitution with Waste Heat and MVR Systems** (Tech. Sol. No. 24): The final case explores the use of Mechanical Vapour Recompression (MVR) combined with waste heat recovery to

substitute existing fossil fuel boilers. The analysis shows that this solution can provide both high efficiency and cost savings, particularly in industrial areas with a surplus of waste heat.

Overall, these case studies provide a roadmap for transitioning DH systems from fossil fuel-based to renewable energy-based, offering quantitative data on both energy performance and financial feasibility.

In conclusion, the report highlights the vast potential of LGERES in DH networks and presents a clear path towards reducing carbon emissions and fossil fuel dependency. While there are significant financial and technical challenges, particularly in the retrofitting of older systems, the long-term benefits in terms of sustainability and energy security make these investments critical. By adopting a phased and region-specific approach, European countries can achieve a smooth transition towards a sustainable, low-carbon energy future for their DH systems.

List of Figures

List of Tables

Low2HighDH

List of Acronyms and Abbreviations

Abbreviation	Definition
ABS-HP	Absorption Heat Pump (heat transformer)
CAPEX	CAPital EXpenditure
CHP	Combined Heat and Power
CI	Carbon Intensity
COP	Coefficient Of Performance
CSP	Concentrated Solar Power
DC	District Cooling
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
AHP	Absorption Heat Pumps (heat transformers)
EHP	Electrical Heat Pumps
El_RES/El_NRES	Electric energy input (from res/nres)
EU	European Union
FFS	Fossil Fuel Savings
FWH	Feed Water Heater
GHG	Greenhouse Gas
HP	Heat Pump
HT	Heat Transformer
HT-DH	High Temperature District Heating
LCOH	Levelized Cost Of Heat
LT	Low Temperature
LGERES	Low-Grade energy RESources
MSV	Municipal Solid Waste
MVR	Mechanical Vapour Recompression
NRES	Non-Renewable Energy Sources
OPEX	OPerational EXpenditure
RES	Renewable Energy Sources
RSH	Renewable energy SHare
SDH	Solar District Heating
TES	Thermal Energy Storage
TRL	Technology Readiness Level
VC-HP	Vapour Compression Heat Pumps

Introduction

District Heating (DH) has evolved over in a sustainable solution for providing heat to urban communities. An important feature of this system is its capacity to centralise heat production, providing thermal energy to a large network of commercial, industrial, and residential structures. Currently, it focuses on the idea of effectively distributing heat coming from renewable resources and is a fundamental component in the shift to a low-carbon economy. Its foundations include minimising environmental effects, maximising energy efficiency, and utilising economies of scale to lower overall costs. This approach not only promotes environmental sustainability but also provides greater control over heat production and distribution, thereby encouraging smart and responsible energy management. District heating has a crucial role in constructing more efficient and eco-friendly communities.

There are significant differences in how District Heating and Cooling (DHC) systems are implemented within the European Union's member states. For instance, whereas less than 5% of people in the Netherlands and Switzerland had access to district heating (DH) in 2015, over 60% of people in Denmark and Estonia had. Differences exist in the DC (District Cooling) capacity as well. The vast range of DH production sources further affects the greenhouse gas emissions from DHC systems.

Future needs for DHC systems and technologies are significantly impacted by these differences in DHC infrastructure, market dynamics, and national constraints. Hence, it's crucial to consider the current and projected scenarios when devising new concepts and technologies.

An overview of the distribution of district heating and cooling throughout Europe may be found on the map below as per the EU project W.E.DISTRICT (Ramboll, 2020).
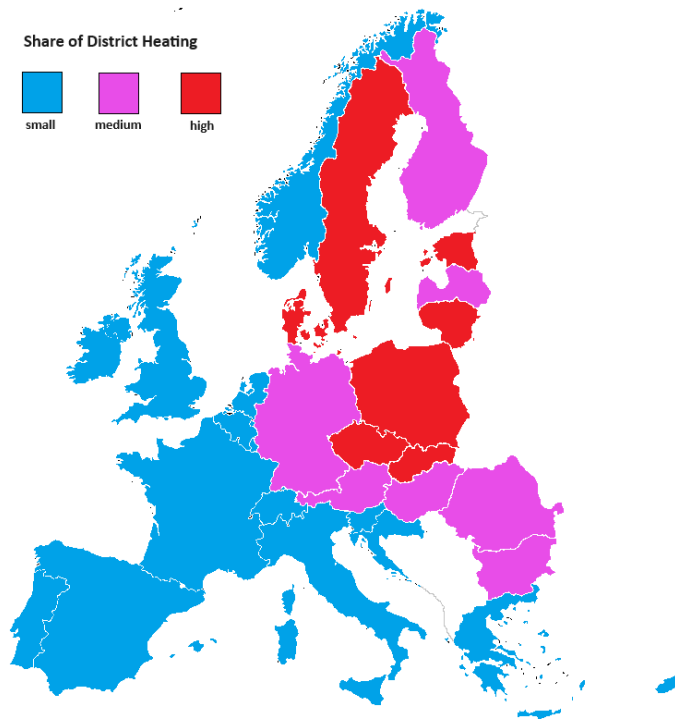
Figure 1. Distribution of district heating and cooling throughout European Countries (Adapted from EU project W.E.DISTRICT).

	Denmark	Lithuania	Slovakia	Estonia	Sweden	Polonia	Czech Republic	Finland	Latvia
DH Share (%)	65	56	53	52	50	42	40	38	30
RES Share (%)	77 (*)	33	0	42	18	7	7	16	n.a.

Table 1 Share of DH and percentage of use of renewable energy in DH. Top Countries. (*) (Rasmussen, 2024)

Historically, Eastern European Countries, have developed great and articulated DH networks well before the rest of Europe. However, the implemented technologies were those of early applications, in which attention to sustainability problems where low. So, there is the challenge and the opportunity to upgrade those systems in such a way as to integrate them with modern and more "green" energy sources.

Like all evolving technologies, district heating has advantages and disadvantages compared to independent condominium or individual apartment heating systems. Among the advantages are energy efficiency, a better predisposition to use renewable sources, economies of scale, and the reduction of emissions.

The higher energy efficiency typically observed in DH systems compared to traditional ones also stems from the scale of production, whether it is centralized or involves a network articulated across multiple sources. Besides the increased flexibility in using renewable sources, the size of the facilities and centralized management enable heat production characterized by higher energy efficiency.

In both centralized and distributed production systems, DH exhibits great flexibility concerning the possible energy sources (Figure 2). When considering renewable sources, these range from solar thermal installations to deep geothermal systems and the use of biomass. The use of appropriate technologies in the transfer from source to end-user, an aspect that will be further explored in this chapter, allows even greater flexibility to elevate low-grade or waste heat to high-temperature levels without resorting to the use of fossil fuels.

Speaking of DH from renewable sources, another advantage is the overall reduction in environmental impact. It is indeed possible to both select and optimize energy sources and develop targeted monitoring and maintenance systems. Lastly, DH systems undoubtedly benefit from economies of scale, leading to a reduction in overall heat production and consumption costs compared to many small autonomous units.
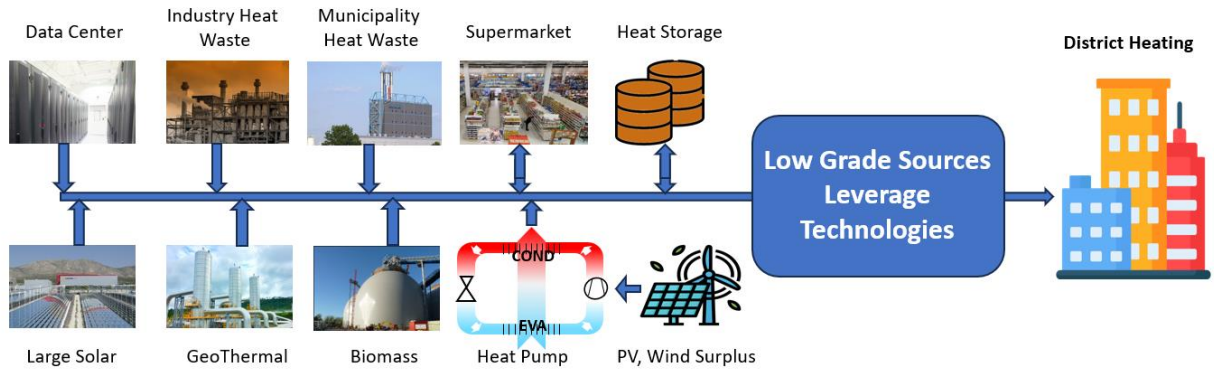
Figure 2. Multiple Energy Sources District Heating Technology (Unige)

However, District Heating is not exempt from drawbacks, implementation challenges, and general disadvantages. The initial installation of a DH system may require significant investments in infrastructure, such as distribution networks and substations. In the absence of incentives, this obstacle can sometimes be insurmountable for a local administration. In the case of dependence on a single centralized heat source, there may be risks in the event of failures or technical problems, risks that are mitigated, if not eliminated, in the case of a distributed and modular architecture of energy sources.

From an efficiency standpoint, long distribution networks could lead to heat losses during transport, especially if not well-insulated, thereby compromising efficiency. Users, in the end, may have less control over local comfort adjustment and may not be able to adopt personalized solutions.

It is quite clear how, in the implementation of a DH system, the current trend is leaning towards distributed generation, based on multiple renewable energy sources, essentially gaining advantages in terms of environmental impact and risk management, perhaps foregoing some benefits associated with centralized facilities.

District heating (DH) systems have undergone four distinct generations, as outlined by (Zeh, et al., 2021), each marked by varying technologies and approaches to heat generation and distribution (Figure 3). From the 3rd generation onwards (1980-2020), extensive solar energy systems have been integrated as a resource. This phase of DH systems is marked by the growing adoption of renewable energy sources like geothermal, solar, and biomass, alongside the incorporation of smart grid technologies aimed at enhancing system efficiency and adaptability.

When dealing with a multitude of sources, varied both in terms of power and temperature, there arises the need to adopt multiple technologies that can adapt to the different temperature levels required by users. The following will provide an overview of the renewable sources used and their energy characteristics. In particular, we will discuss solar energy and its derivatives, photovoltaic and wind energy, deep geothermal energy, and biomass. Appropriate technologies will be explored to ensure that these sources are efficiently utilized within the context of District Heating from renewable sources. To this end, depending on the temperature gap between the source and the temperature required by users, reference will typically be made to Heat Pumps, Mechanical Vapor Recompression boosters (MVR), and Heat Transformers (absorption heat pumps), whose main technical characteristics will be analysed.
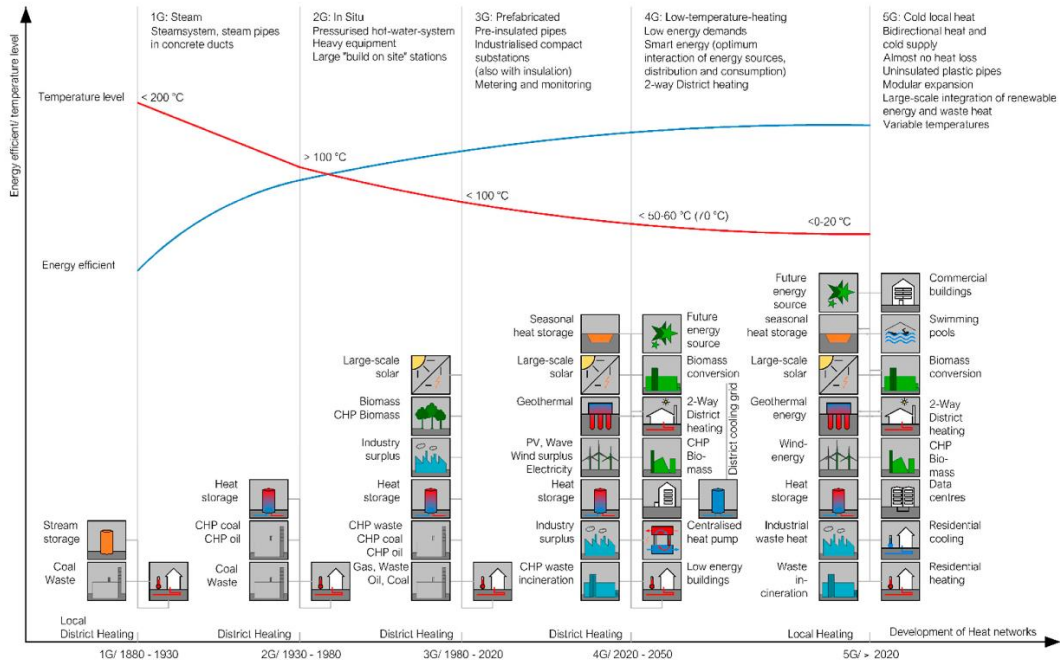
Figure 3. District heating network generations over the last 150 years (credit: MDPI Open Access, Zeh et Al., 2021, 10.3390/su13116035)

MAIN CONCEPTS OF LOW-GRADE ENERGY RESOURCES INTEGRATION INTO HT-DH

The concept of Low-Grade energy RESources (LGERES) does not have a clear definition in literature, even if it could be easily associated to "low temperature heat sources". However, a more general access should also involve the concept, which clearly distinguish between renewables (RES) and traditional (fossil) fuel energy resources, linked to the surface-intensive exploitation of energy sources. These last can be accounted for by means of proper Key Performance Indexes (KPI).

A possible definition of Low-Grade Renewables, which will be used in this report, can be stated as follows:

Low-grade energy resources refer to renewable or cascade energy sources that produce energy at relatively low temperatures or in forms that require additional processing to be converted into usable heat or power.

These sources are often characterized by their lower energy intensity, in comparison to high-grade renewables like solar photovoltaic or wind power. Low-grade renewables are typically used for applications such as space heating, water heating, or industrial processes that operate at moderate to low temperatures. Examples include solar thermal energy, geothermal energy, biomass, waste heat recovery, etc. In this respect their exploitation also implies a great amount of land surface, since they are always distributed over a large extension of the territory.

The upgrade LGERES at temperatures useful for High Temperature District Heating (HT-DH) applications some specific technology must be employed, such as Electrical Heat Pumps (EHP), absorption Heat Pumps (AHP, also known as heat transformers) and in some cases Mechanical Vapour Recompression systems (MVR). In other cases, such as solid biomass, a not obvious collection and pre-treatment operation are needed. The application and usage of Thermal Energy Storages (TES) is always needed.

The intervention can also be achieved by inserting the RES source as an integration to fossil systems currently in use (CHP and Boiler, for example solar, geo, and waste preheating). Although this intervention does not completely replace the fossil source, it allows for a decrease in its use and represents the least expensive and quickest modification. A possible scheme of technological solutions could be at the beginning classified as follows:

- Interventions aimed at integrating LGERES directly into heat generation systems (the entire HT-DH system is retained, from generation to the network, with modifications and technical changes only on the existing heat generation system).
- Interventions aimed at the partial replacement of the source with subsequent application (or not) of upgrading techniques (the HT distribution network is retained but an upgrading technology needs to be interposed between LGERES and the users, be it in the central plant, or locally on district heating points, or even in single buildings).

The possibility to apply one or more of the available technologies depends on the actual status of the DH network.

The use of Heat storage is always included because it is proven that the use of TES (at any level, be it in the central heat generation plant or in single separate buildings) increases the DH efficiency of about 5 to 20%, improving also regulation performance and flexibility.

In this report a brief review of all the so far mentioned issues will be addressed, including:
- Main LGERES
- the mentioned upgrading technologies
- actual main HT-DH technology, with particular reference to possible points (temperature levels) of intervention
- a portfolio of possible combination of the above able to effectively integrate LGERES into HT-DH
- some criteria to evaluate the performance of such integration, with reasonable KPI (such as coefficient of performance, cost analysis, and so on)
- a list of 10 detailed models of LGERES/HT-DH integration with preliminary performance assessment

Low Grade Renewable Energy Sources

INTRODUCTION

Low-grade renewable energy sources include a broad range of resources, such as ground, water, and ambient air, which may not have temperatures high enough to be directly utilised for heating purposes. However, these low temperature sources can be upgraded to fulfil HT district heating networks' heating demands by utilising cutting-edge technology such as waste heat recovery systems, heat pumps, and heat transformers. Numerous advantages stem from this integration, such as improved resilience to variations in the energy supply, decreased environmental impact, and increased energy efficiency.

SOLAR THERMAL

Solar energy is the primary energy source for our planet, with over 175,000 terawatts of solar radiation reaching Earth, approximately 10,000 times greater than the world's total energy consumption. Utilizing this abundant and infinite energy source for our needs seems like an obvious choice. A plethora of plant typologies and embodiments characterizes the exploitation of thermal solar energy. Depending on the reached temperature this energy can be converted in an electrical one or used to directly supply heat.

Typically, these solar plants are situated in vast open areas, often in desert regions. Similar to PV panels, these large-scale facilities are constructed outside urban areas, often in the outskirts. Figure 4 shows a concentrated solar power (CSP) system utilizing mid-temperature technology in the form of parabolic arrays, while Figure 5 shows a low temperature source out of a field of planar thermal solar collector in Marstal, Denmark.

Regarding Solar District Heating (SDH) systems, the initial solar thermal (ST) plants for SDH originated in Sweden during the late 1970s. Subsequently, additional installations have been established mainly in Denmark, Germany, Austria, and Sweden. Comprehensive guidelines and a dedicated website have been created as part of EU initiatives like SDHtakeoff, SDHplus, and SDHp2m since 2009. Europe boasts numerous instances of successful solar district heating systems in urban areas, including:

Figure 4. Medium Temperature parabolic trough arrays (credit: ArséniureDeGallium, Public domain, via Wikimedia Commons)

In Denmark, the city of Silkeborg boasts one of the world's largest solar district heating systems. Completed on schedule in December 2016, the 156,694 m^2 (110 MW$_{th}$) SDH plant was constructed in approximately seven months. The municipal utility, Silkeborg, intends to utilize the captured solar energy to meet 20% of the annual heating demands for 21,000 users connected to the plant.

In Germany, the city of Freiburg in the Black Forest region is home to a vast solar district heating network satisfying over 9,000 buildings. With a population of 230,000, Freiburg identifies itself as Germany's environmental capital.

Figure 5. District heating using a solar thermal collector field of 18300 m2. Denmark, Marstal (credit: Erik Christensen, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons)

From a technical perspective, incorporating solar sources into district heating systems proves viable in regions with ample sunlight and appropriate space for solar panel installation. Ground-mounted solar collectors are the preferred choice in most cases. Furthermore, solar district heating systems require minimal maintenance and boast a long lifespan, rendering them a dependable heat source for communities.

GEOTHERMAL

Geothermal energy represents a significant and sustainable resource for District Heating, offering opportunities both at the surface and in depth. Shallow geothermal energy exploits the thermal capacity of the soil and the relatively constant temperature found in the top meters of the ground. It cannot be properly considered an energy source since the soil is, on average, at exergy zero. As a result, this approach generally involves the use of geothermal heat pumps operating at relatively shallow depths to extract heat from the surrounding ground. Utilizing shallow geothermal energy has the capacity to effectively enhance the long-term enhancement of energy supply systems. This involves slowing down the rise in energy consumption, modifying the mix of energy sources, and reshaping community energy infrastructure. We will discuss this further in relation to heat pumps.

Geothermal energy from the deeper soil layers, or "deep geothermal," instead harnesses high-exergy content heat from aquifers located in deeper layers of the Earth's crust, typically at depths exceeding 500 meters. This represents a medium to high-temperature source and enables the development of technology suitable for large-scale DH and industrial applications. Deep geothermal resources offer continuous heat

production, making them suitable for meeting the constant demand of large-scale district heating systems. They contribute significantly to environmental sustainability by providing a low-carbon heat source and reducing dependence on fossil fuels.
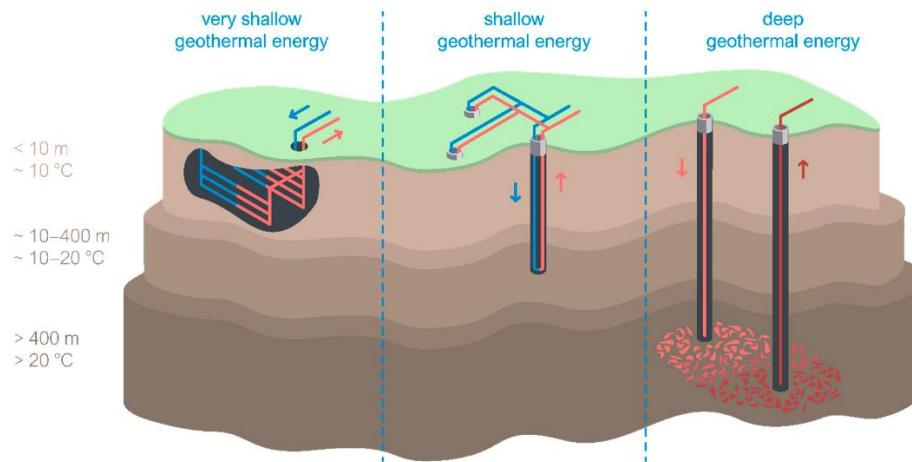
Figure 6. Very shallow, shallow, and deep geothermal potential classification. (credit: MDPI Open Access, (Zeh, et al., 2021))

Nevertheless, this type of source must face several challenges to maximize its potential, especially in the context of District Heating (DH). The implementation of deep geothermal wells involves significant initial costs. Investments in specialized equipment and drilling technologies can serve as a barrier to access, particularly for large-scale projects. Specialized expertise and advanced engineering are required as complex geological conditions must be addressed, adding complexity that may increase the likelihood of delays and additional costs during the development phase. Deep drilling may also entail geological risks, such as the presence of unstable rocks or the possibility of seismic events, the management of which is crucial to ensure operational safety.

Not all regions have convenient deep geothermal resources. Some areas may have lower temperatures or thermal flows, reducing the efficiency of the process. Accurate mapping of geothermal resources is therefore essential to identify suitable zones.

Ultimately, how the community views geothermal activities, particularly those involving deep drilling, can influence the approval and execution of projects. Therefore, it is crucial to involve the local community and offer clear information. Addressing these challenges necessitates a blend of technological advancements, supportive policies, focused investments, and collaboration between the public and private sectors. High energy thermal basins that are now only found in a few restricted areas, like Iceland, Central Italy, and Turkey, are already economically viable for producing power. When lowering the temperature, the performance of the available technology must be taken into consideration when determining how economically affordable the conversion systems are for producing power. Thermal basins with high and medium temperatures, on the other hand, are better suited for DH use and have a far wider diffusion, encompassing nearly all of the Member states. Roughly 25% of Europeans reside in regions where geothermal DH is possible, according to EGEC [25].

This geothermal potential is recognised by some EU Member States in their National Renewable Energy Action Plans. Geothermal DH can be developed and installed everywhere, also with existing DH systems during extension or renovation, advantageously replacing fossil fuels; new Geothermal DH systems can be

built in many regions of Europe at competitive costs. According to Eurostat, about one third of the EU's total crude oil (34.5%) and natural gas (31.5%) imports in 2010 originated from Russia. Of this, 75% of the gas is used for heating (2/3 in households and 1/3 in the industry). Geothermal DH technology has the potential to replace a significant part of that fuel.

In Aarhus, Denmark, drilling has begun for the initial wells of the European Union's most extensive geothermal district heating system. Project Aarhus will involve the establishment of 17 wells across seven locations, boasting a total capacity of 110 MW. The system aims to supply 20% of the city's district heating by the year 2030.

BIOMASS

Biomass, the predominant renewable energy source in the European Union (EU), can generate electricity, and heat, and can be used as transport fuels. Wood, among various sources, is the most prevalent form of biomass. EU regulations classify biomass as carbon neutral, positing that the carbon emitted during the combustion of solid biomass will be roughly offset by subsequent absorption during plants growth. This cycle makes biomass a sustainable and renewable energy source. Existing EU policies offer encouragement for the utilization of biomass in power and heat generation. Despite the absence of obligatory sustainability standards for biomass at the EU level, certain criteria are in place at the national and industry levels.

Biomass also refers to organic materials, such as agricultural residues, and organic waste, that can be used as a source of energy also in the context of district heating, where biomass can play a crucial role in providing sustainable and environmentally friendly heat.

Several uses for biomass exist, including the production of heat and power (Figure 7), biogas, transportation-related biofuels, and plastics through green chemistry. The term "bioenergy uses" refers to the first three uses of biomass.
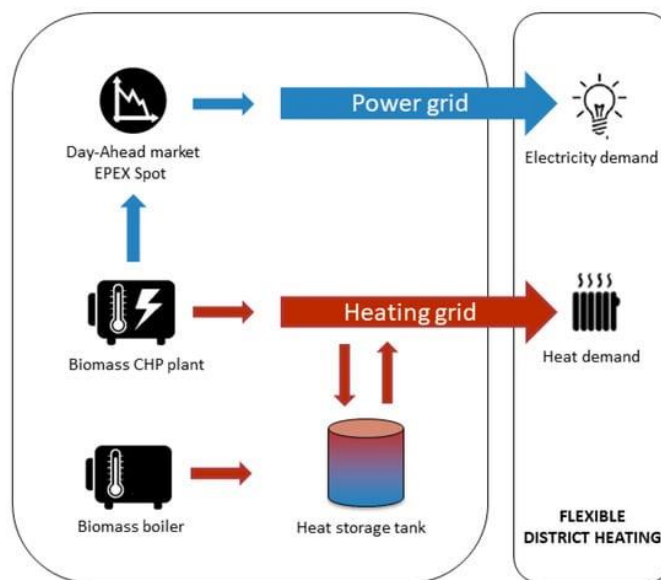
Figure 7. Concept of the decarbonized district heating system (credit: : MDPI Open Access, (Koch, et al., 2020), https://doi.org/10.3390/en13164134)

Beyond the heat obtainable from biomass combustion, it should be remembered that the full degradation of biomass through aerobic processes, where oxygen is present, yields an equivalent amount of energy to what was initially stored in the biomass cells through photosynthesis or ingestion. This heat is usually disposable at temperatures of about 60 °C (Sokolovs, et al., 2015).

As to (EU_Parliament, 2018) Directive on the promotion of energies from renewable sources, only a portion of the biomass that is accessible for energy use can be utilised sustainably. Specifically, when putting the RES Directive into practice at the national level, two sustainability criteria ought to be applied: 1) The use of biomass derived from primary forests, high carbon stock areas, and very biodiverse areas is prohibited; 2) The minimum amount of greenhouse gas emissions must be reduced using a standard calculation technique. One of the aims is to prevent adverse incentives associated with unsustainable bioenergy paths, as highlighted in the 2021 report from the Commission's Joint Research Centre titled 'The use of woody biomass for energy production in the EU' (Camia, et al., 2020).

A large amount of Municipal organic solid waste can be used in some processes to create compost for use in agriculture, energy, and biofuels. Utilizing organic waste and byproducts for energy and heat production, biofuels offer a significant waste management solution. However, several challenges persist, including feedstock availability, land usage, and ensuring the adoption of sustainable production practices (Sipra, et al., 2018).

Figure 8. Biodigester CSTR (Continuous-flow Stirred Tank Reactor) for biogas production (credit: geraldK (pixabay.com))

WASTE HEAT RECOVERY (INDUSTRIAL/MUNICIPAL)

District heating from waste heat recovery is an energy-efficient and sustainable method of utilizing excess heat generated during industrial or municipal processes. To heat residential, commercial, or industrial buildings within a certain region, waste heat must be captured and used. This not only helps in reducing overall energy consumption but also minimizes environmental impact by utilizing otherwise wasted energy.

Industrial waste heat primarily originates from diverse manufacturing and power generation processes, with large temperature range. Municipal waste heat, on the other hand, is derived from sources like sewage treatment plants and data centres, generally presenting lower temperatures. Examples include

cooling water, exhaust gases, and heat from manufacturing for industrial waste, while municipal waste heat encompasses heat extracted from wastewater, air conditioning, and ventilation systems.

According to the ECOHEATCOOL WP4, the EU27 would gain 1106 PJ annually if all Member States recovered from industrial excess heat with the same efficiency as Sweden, which is the best Member State practice (Werner, 2006). Several studies have determined which industrial sectors are typically the primary producers of waste heat. They are the metal industry, especially iron and steel production, the chemical and petrochemical industry, food and beverage sector, pulp, paper, and printing, and non-metal minerals like cement, ceramic, and glass.

Speaking about Municipal waste, one of the EU's largest issues is managing waste, which is produced in enormous quantities in modern society due to the increased consumption of products and services. The following treatment alternatives must be prioritised under the guidelines provided in the Waste Framework Directive (EU_Parliament, 2009) the treatment options must be given the following priority order: reusing, recycling, composting, incineration (with energy retrieval or not) and, as a final option, landfilling are all methods for waste treatment. However, landfilling persisted as the predominant waste treatment approach in the EU between 1995 and 2012, with a linear decrease from 40% to 34%, notably declining from 2008 to 2013 (Persson & Münster, 2016). Anyway, incineration offers a large unemployed energy potential also for the most virtuous countries (Sweden, Denmark, Germany, Netherlands, Austria, and Belgium) that still make large use of landfilling, thus ignoring the indications of the mentioned European Directive. Given the absence of evidence thus far indicating an impending decoupling between human well-being and waste production in the EU, the majority of energy scenarios for future European energy systems anticipate a linear increase in municipal solid waste production until at least 2030.

OTHER LOW TEMPERATURE HEAT SOURCES FOR DH

In addition to the heat sources already described, there is also the possibility of heat sources with temperatures between 10°C and 50°C. Because of the temperature difference between the source and the sink, these sources are unable to directly deliver heat in High Temperature DH networks. Using massive central heat pumps, alone or aided by HP boosters or in conjunction to other technologies like Heat Transformers, is one approach that might be taken. (Lund & Persson, 2016) investigated the potential of seven different low-grade heat sources in Denmark: low temperature industrial surplus heat (at <100°C), drinking and usage water, supermarkets, wastewater, groundwater, data centres, rivers, lakes, and sea water. Groundwater exhibited the most significant potential in terms of both geographic accessibility and potential heat capacity. Similarly, seawater and rivers demonstrated substantial potential heat capacity. Although supermarkets are ubiquitous in urban and rural areas, their potential heat capacity is relatively low, albeit not insignificant.

Low-grade heat sources can be clustered into four categories:

- Low temperature industrial waste heat (at T< 100°C).

- Natural low temperature heat storage: sea, rivers, lakes, groundwater, ground (shallow geothermal).

- Municipal infrastructures: tunnels, sewage, and drinking water conducts.

- Condensers of refrigeration units: data centres, supermarkets, shopping malls, indoor ice rinks.

In the following section, various concepts are proposed for the integration of these sources within DH systems.

LOW-GRADE SOURCES UPGRADE TECHNOLOGIES

INTRODUCTION

This section outlines practical challenges that could arise when incorporating low-temperature heat sources into district heating (DH) grids. It then provides an overview of the primary technological concepts proposed to address these challenges, particularly considering that the target networks belong to relatively high-temperature systems, such as those of the 2nd or 3rd generation.
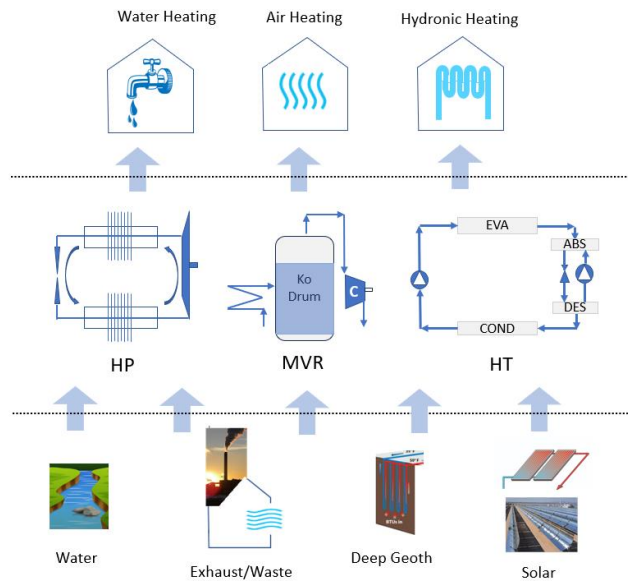
Figure 9. Concept of the decarbonized district heating system (Unige)

HEAT PUMPS

Heat pumps are attracting growing attention within the domain of district heating (DH) due to their ability to harness surplus electricity generated by non-programmable renewable sources like photovoltaics and wind turbines. Since they need an external source of energy other than heat (that is mechanical or, as usual, electrical energy), they are considered "the enabling technology" to harness low-grade heat sources as well as to use waste heat (Figure 10). Vapor compression heat pumps (VC-HP) are based on a standard inverse refrigeration cycle, used to exploit the heat released by the condenser for heating purposes.

Water-to-water heat pumps are widely favoured for their capacity to extract heat from waste energy sources of low temperatures (below 45°C), generating hot water at an elevated temperature for use in District Heating (Zhu, et al., 2023). When there is a simultaneous need for cooling alongside heating, the combined system can substantially enhance the efficiency (COP) of a district cooling and heating system.

They can operate at both ends of the DH network providing flexibility in utilizing different low-temperature heat sources, including solar thermal collectors, geothermal wells, or waste heat recovery systems but they can be used also in the customers' substations to raise the temperature level according to the needs of the served building. Furthermore, heat pumps can facilitate the seasonal storage of heat. During periods of excess renewable energy generation or low heating demand, heat pumps can convert green electricity into heat and store it for later use. This contributes to balancing the energy demand and supply in district heating networks.
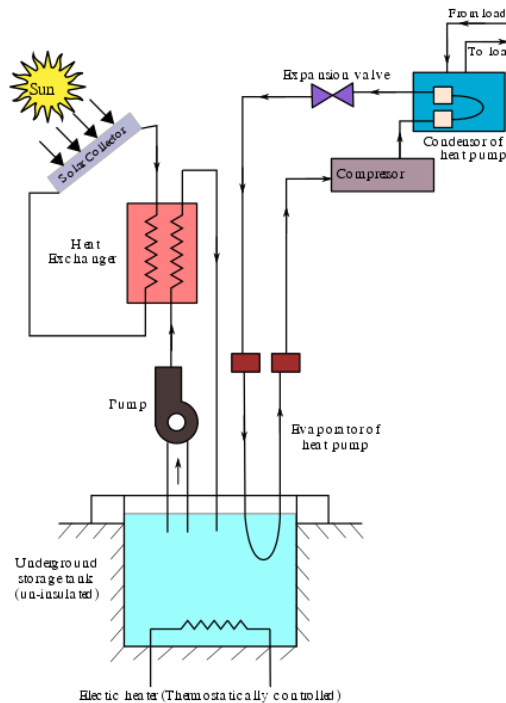
Figure 10. Schematic diagram of a Series Operated Solar Heat Pump (credit: KCVelaga, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons)

Effectively integrating heat pumps into district heating networks is a pivotal element in achieving a sustainable energy supply scenario. One of the possible applications is the use of distributed micro booster heat pumps combined with a central Heat Pump. The analysis done by in (Østergaard & Andersen, 2016) shows that the use of booster heat pumps is beneficial as it allows for improving the overall COP and decreases grid losses. The system is more flexible in acquiring different grades of sources and, generally delivering low to mid temperature heat, is less prone to heat losses along the grid pipes. The district heating (DH) system incorporating booster heat pumps demonstrated superior performance compared to a heat pump-based DH system lacking booster heat pumps in terms of operational costs and primary energy consumption. Employing booster heat pumps provides the chance to optimize both supply and return temperatures during the design phase, thereby enhancing the coefficient of performance (COP) tailored to the specific configuration, according to (Ommen, et al., 2017) and (Lund, et al., 2014).

Implementing heat pumps in DH systems presents also various challenges. Beside the high investment, existing district heating infrastructure may not be designed to accommodate the specific requirements of heat pump systems. When compared to conventional heating techniques, they could find it difficult to

provide high-temperature outputs. This may be a drawback for some DH applications that call for high-temperature heat sources and may present technical difficulties due to the requirement for appropriate system design, upkeep, and staff with the necessary skills for installation and operation. For heat pump systems in district heating to become more widely accepted, there may also be a need for technician training in order to equip them with the knowledge and skills necessary to operate more conventional heating systems.

MECHANICAL VAPOUR RECOMPRESSION

Mechanical Vapour Recompression (MVR) was primarily developed in the chemical industry, especially in processes where solution separation or concentration is required. This technology can also be applied in other sectors where concentration or evaporation processes are involved, such as in the food and beverage, pulp and paper, and wastewater treatment industries. Nevertheless, MVR technology is very versatile and can be adapted to different applications where the recovery of waste heat is beneficial because it can improve energy efficiency in process plants and offers possibilities for integrating renewable electricity and renewable heat in DH networks.

Steam remains a pivotal energy carrier across various sectors of the chemical industry, offering versatility across different pressure and temperature specifications. While high-pressure steam is used to drive turbines, low-pressure steam delivers process heating. If the pressure is too low for the steam to have direct energetic value, efficient recompressing yields a valuable energy carrier making useful a waste product.

MVR operates as an open heat pump system, where compression boosts both pressure and temperature, along with the corresponding saturation temperature. The energy needed for compression is significantly low compared to the latent heat within the steam.

The steam can be available at various temperatures depending on its origin. We will find typically high temperatures if the energy source derives from industrial processes and possibly lower if of solar or geothermal origin. In any case the state of the vapor is brought to saturated dry conditions by heating and only then is recompression applied to elevate both its pressure and its temperature. The high-pressure vapor is then use directly or as a high temperature source for subsequent distribution of heat energy. In the example reported in Figure 11, saturated dry steam (A) at a temperature of 65 °C is compressed to 1.25 bar (B) and then de-superheated to 106 °C (C) by injection of water with an increased mass flow rate (Figure 10). Steam can be used at high temperature but is often cooled to saturation to obtain a stable temperature of the carrier.
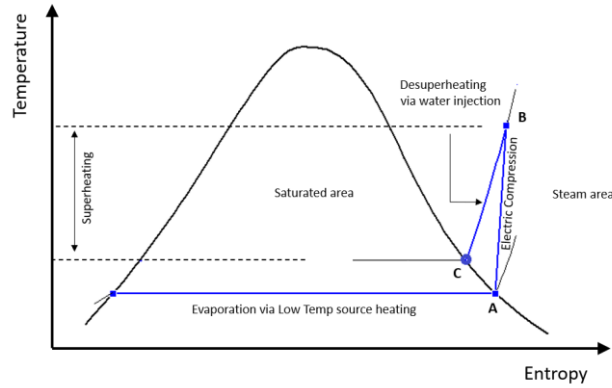
Figure 11. MVR processes. Evaporation is obtained by a low-grade heat source, de-superheating by water injection (UNIGE)

The superheating is, for a consistent part, due to the compressor isentropic efficiency, usually lower than 0.75. In dependence on the pressure gap, the compression is managed by more compressors with a decreased electric energy consumption.

By compensating the superheating by injecting boiler feed water, the final steam temperature is reached. In this way, the superheating of the steam is transformed into additional steam production.

Figure 12 schematically depicts the process of steam recompression and water injection (de-superheating) utilizing two-stage compression. Knock-out drums serve to safeguard compressor blades against erosive harm from water droplets. Introducing water between the two stages mitigates overheating, thereby enhancing efficiency. During startup, the recycle valve is essential: steam is recycled until the desired saturated dry condition is attained.

The energetic efficiency of MVR is typically quantified using the coefficient of performance (COP), akin to standard heat pumps. COP represents the ratio of the net recovered heat to the energy consumed by the compressor. In this instance, the net heat encompasses steam production, inclusive of the supplementary steam generated by water injection.
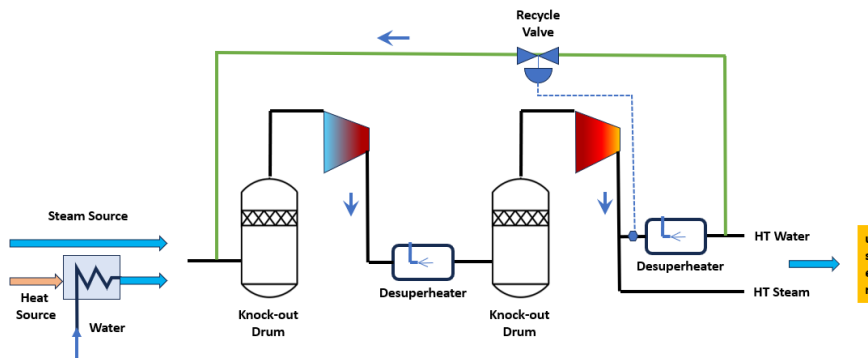
Figure 12. MVR two stage simplified plant scheme (UNIGE)

Typical economical and energy-efficient applications have a minimum COP of 3.5. Some applications of MVR prove that a COP of 10 or even higher is achievable.

To attain high COP values a low ratio of the absolute steam pressures is needed: in daily practice, the ratio is about 3, also, water injection after compression must be used.

MVR is very effective compared with other techniques. Simple electrical heating yields a COP of only 1 if it is used to reach the same exit state, that is using a circulation pump and then electric heat to high-pressure evaporation. For MVR, a wide range of compressors is available. The compressor type depends on the pressure and temperature ratios, the absolute pressure, and the volume flow. The total temperature span ranges from 10 °C to 80 °C (Zeng, et al., 2021).

The technical and financial investment risks of MVR are low. MVR is primarily interesting for processes with a surplus of low-pressure or flash steam, but systems can also be based on low temperature sources like waste or solar heat. The Payback period is found between one and three years, higher efficiency means less use of fossil fuel. MVR features the possibility of using renewable electricity for the compression process. Since the whole MVR system is always custom-made, the return on investment depends on various factors such as the capacity of the installation, the value of the input 'waste' steam and of the output steam, the electricity price. MVR demonstrates considerable economic resilience, substantiated by thorough sensitivity analyses involving fluctuations in electricity prices, input steam value, produced steam value, and investment levels. Even with a threefold ratio between electricity and gas prices per energy unit, profitability remains feasible given a favourable COP. It's not just electricity costs, but also MVR capital expenditure and natural gas prices that dictate economic feasibility. Moreover, employing renewable electricity further diminishes the carbon footprint.

Apart from the direct economic advantages to MVR users, several synergistic effects emerge. The ability to utilize renewable electricity, particularly during periods of surplus production, is very appealing. EU policy initiatives have spurred a substantial rise in variable electricity generation from renewables, leading to increased production volatility primarily due to renewable subsidies. MVR serves as an effective tool for demand-side management, facilitating balance and MVR stands as a key instrument, especially when implemented on a large scale, toward a sustainable DH.

Finally, it is worth to note that the well-established technology of MVR systems (with particular reference to steam compression) can be effectively exploited by closed cycle vapour compression cycles operated with water as working fluid, leading to very good COPs in upgrading LGERES medium temperatures (around 50÷60°C) to high temperature DH networks (110÷130°C).

Heat Transformers

When upgrading low temperature energy sources, the first choice, as seen, involves employing a vapour compression heat pump to elevate the heat to the necessary temperature. Nevertheless, the effectiveness of this option is constrained by diminished efficiency at elevated thermal lifts, resulting in increased electricity consumption. Another alternative is utilizing heat transformers (HT) (Atienza-Márquez, et al., 2020), which are devices designed to transfer heat from a lower temperature source to a higher temperature sink using an absorption thermodynamic cycle (Toppi T, et al., 2021). The following figure

shows the structure of a simple HT system compared to that of an absorption refrigerator to emphasize the fact that the HT undergoes a direct cycle opposite to the inverse cycle of the refrigerator.

Absorption Refrigerator   Heat Transformer
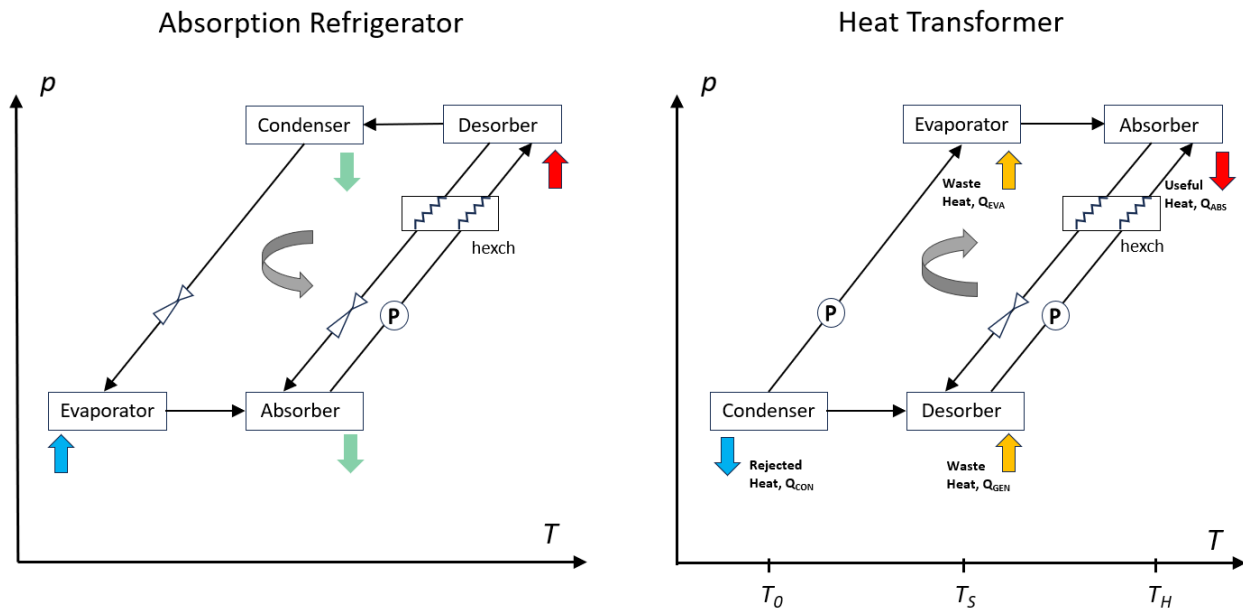
Figure 13. Comparison between an absorption refrigeration (inverse) cycle and an absorption heat transformer (direct) cycle (UNIGE)

However, the turbine is substituted by the absorber-desorber unit and high temperature heat rather than mechanical power will exit from the system (**¡Error! No se encuentra el origen de la referencia.**).

Heat transformers are highly suitable for harnessing waste heat from industrial processes, power generation, or alternative origins. They play a pivotal role in enhancing energy efficiency and present opportunities to incorporate renewable energy sources like geothermal or solar heat into district heating systems, thereby bolstering sustainability. They can be applied in decentralized district heating systems, allowing for flexibility and adaptation to local conditions. However, HTs yet encounter restrictions concerning the operational range; specifically, their thermal lift cannot surpass a certain level and, in any case, the performance is strongly influenced by this lift so finding optimal operating conditions is crucial. Since to overcome these difficulties, double cycles are implemented, heat transformers may involve complex system designs and initial costs, which could pose challenges for widespread adoption (Cudok, et al., 2021).

Temperatures involved in Heat Transformer technology vary as a function of used fluids (ammonia or Lithium Bromide) and cycle configurations. Concerning **¡Error! No se encuentra el origen de la referencia.**, from averaged data reported in (Cudok, et al., 2021), T_H ranges between 100 and 130 °C, Ts between 70 °C and 90 °C when T_0 is around 20-30 °C. So, these systems can provide temperature upgrading from 70 °C to 110 °C, that is a temperature increase up to 60°C. Cukod, in his review, underlines that the spread of this technology is not very pronounced and a smaller number of plants were realized in the period from 1990 up to 2010, followed by a revival of the technology especially in China with a capacity ranging from 0.5 to 4 MW. A top capacity of about 40 MW is reported by the manufacturer Ebara (2015).

To give some potential details, Ammonia absorption heat pumps, which use ammonia (NH3) as the refrigerant and water as the absorbent, have specific working temperature ranges depending on the application and system design. They can pose several safety problems due to Ammonia toxicity but are largely used in the refrigerant version for industrial applications. Here are the key temperature ranges for different parts of the system, based on a recent development by Ding, Lu (ZijIan, Liu et. Al, 2023):

Generator (or Desorber): The generator is where the ammonia is separated from the water by heating the solution. The typical working temperatures in the generator of heat transformers range from 60°C to 80°C, depending on the low-grade source working temperature. Higher temperatures can be used in industrial applications where waste heat or medium-temperature heat sources are available.

Condenser: In the condenser, the ammonia vapor is condensed into a liquid by releasing heat to the surroundings. The working temperatures here typically range from 10°C to 30°C, depending on the cooling medium (air or water) and ambient conditions.

Evaporator: in the evaporator the liquid ammonia absorbs heat and evaporates, exploiting again, as in the desorber, the available LGERES. The typical working temperatures in the evaporator range from 50°C to 70°C, thus being inserted in series with the desorber heat exchanger.

Absorber: In the absorber, the ammonia vapor is absorbed back into the water, releasing the useful heat. The working temperatures in the absorber usually can reach a temperature range from 100°C to 130°C, depending on the cooling medium and system design.

Applications with Lithium Bromide solutions are also conceivable, but the working temperatures are lower due to the risk of crystallization or the Lithium bromide in the water solution.

Thermal Energy Storage (TES)

The process of storing thermal energy for later use in other forms, such as heat or cold, is known as "Thermal Energy Storage.". Although it is not an energy upgrade technology, it is briefly reported here since it often represents an essential part of all the district heating networks based on fluctuating renewable energy sources. TES systems store excess heat during low-demand periods, releasing it when demand is high, contributing to load balancing, and ensuring a steady supply for district heating.

Thermal storage facilities guarantee a heat reservoir for effectively managing the dynamic features of district heating systems, such as the evolution of heat and power demand, fluctuations in energy prices, the intermittent nature of renewable sources, severe weather, and system failures. It is recommended that thermal energy storage be incorporated into district heating and cooling systems for both short- and long-term storage. In light of the scientific maturity of each type of technology, connections of sensible, latent (phase change material), and chemical heat storage are encouraged to facilitate the transition of present energy systems towards next-generation district heating (Alva, et al., 2018).
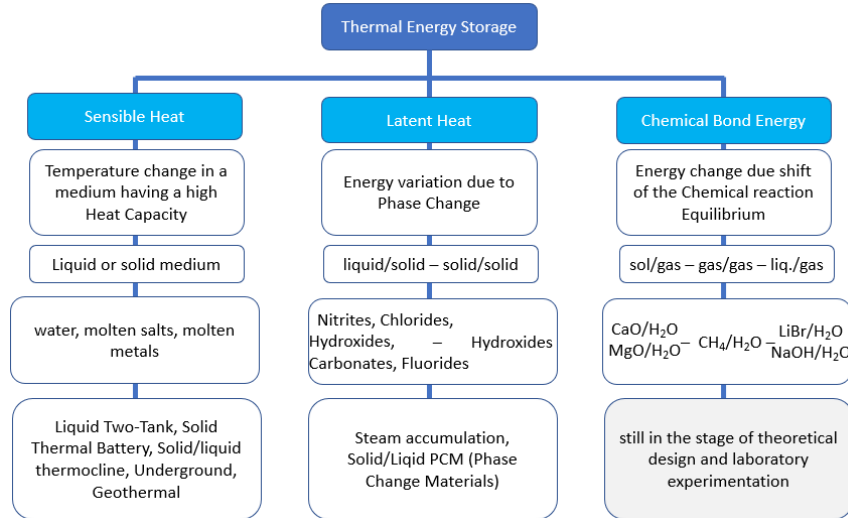
Figure 14. Common Heat Storage types and methods (Unige)

The storage of summer heat for winter heating and the storage of daytime heat for nighttime heating are two instances of Thermal Energy Storage (TES) systems. Storing thermal energy leads to alterations in the internal energy of the material, which can manifest as sensible heat, phase change latent heat, thermochemical energy, or a combination of these factors (Gil, et al., 2010) as per Figure 14.

Here are the most common working temperature ranges for different types of thermal energy storage systems:

1. Sensible Heat Storage (SHS):

- Water-based systems: 30°C to 95°C

- Molten salt systems: 150°C to 600°C

- Solid media systems (e.g., concrete, rock): 100°C to 600°C

2. Latent Heat Storage (LHS):

     - Paraffin waxes: 20°C to 70°C

     - Salt hydrates: 30°C to 120°C

     - Eutectic salts: 10°C to 150°C

High-temperature phase change materials: (PCMs): 150°C to 600°C

3. Thermochemical Energy Storage (TCES):

     - Low-temperature systems: 20°C to 150°C

     - Medium-temperature systems: 150°C to 400°C

     - High-temperature systems: 400°C to 1000°C

Applications and Corresponding Temperatures

- Building heating and cooling: Generally, use lower temperature ranges (20°C to 95°C) suitable for water-based sensible heat storage and low-temperature phase change materials.
- Industrial processes: Often require medium to high-temperature ranges (150°C to 600°C) which can be supported by molten salt systems and high-temperature phase change materials.
- Concentrated solar power (CSP): Typically uses high-temperature storage systems (150°C to 600°C) like molten salts or high-temperature PCMs.

Seasonal storage: For seasonal thermal energy storage, temperatures can range from below freezing (0°C) to high temperatures (up to 600°C) depending on the specific system and location.

The selection of a TES system and its operating temperature range depends heavily on the specific requirements of the application, the availability of materials, and economic considerations.

LOW/HIGH TEMPERATURE DISTRICT HEATING NETWORKS

INTRODUCTION

From the perspective of district heating utilization, and therefore considering the users, we can distinguish between different temperature ranges at which heat is provided, depending on its use and the suitable fluids acting as heat carriers.

With low temperature (LT), we refer to a range typically between about 30°C and 70°C, suitable for heating indoor spaces via radiant floor systems at the lower end, and for producing hot water for domestic use at the higher end of the mentioned temperature range. We also include within LT those systems with temperatures higher than 60°C but lower than 90-100°C, often referred to in literature as MTDH (Medium Temperature District Heating). In this case, the reference is to traditional building heating.

The term high temperature (HT) is used for industrial applications and centralized heating systems where heat is produced or collected by a single large structure and used to heat multiple buildings or neighbourhoods. This type of district heating, characterized by temperature from 90 °C up to 130 °C and more, which characterized much of the technology of the 20th century, is now largely outdated in much of the EU but persists in Eastern European Countries where district heating is, for historical reasons, much more developed than in Western European Countries.
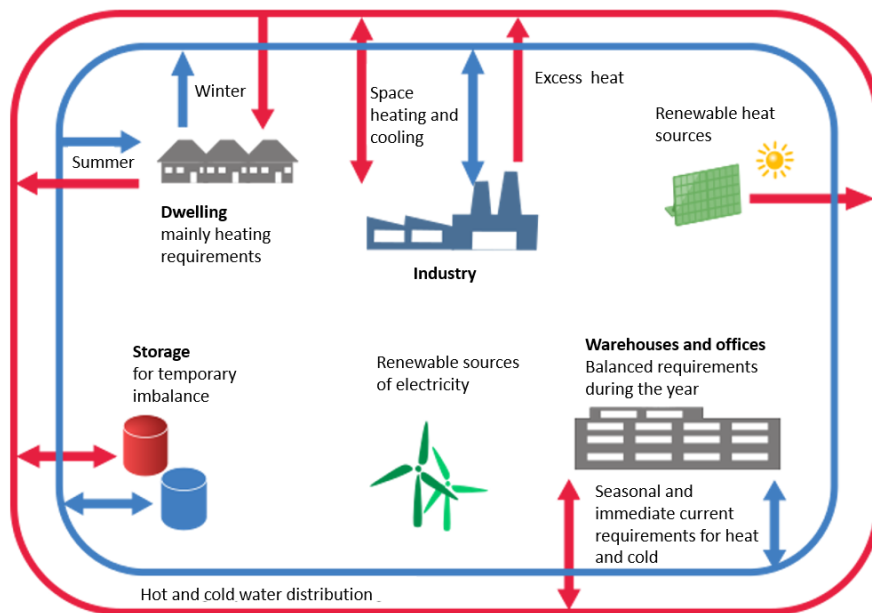
Figure 15. A circular representation of a DHC system (credit: Jirka Dl, CC BY-SA 4.0, via Wikimedia Commons)

LTDH – FLOOR HEATING, LT SPACE HEATING AND DHW

Low temperatures are a key characteristic for enabling a more efficient integration of low-carbon technologies. 70°C maximum forward flow temperature is the temperature required for thermal disinfection of domestic hot water supply, although 50°C should usually be sufficient to avoid the risk from the legionella bacteria. The label 4th generation of DH networks designates district heating networks that operate at maximum forward flow temperatures of 70 °C (Int_Energy_Agency, 2024).

However, from a user standpoint, lower temperature heat carrier fluids are used in building heating. Low-Temperature (LT) heating systems typically don't exceed 35-55°C for space heating and can involve heating indoor spaces through low-temperature radiators, radiant floor systems, or other low-temperature heat distribution devices.

LTDH presents new opportunities for increased energy efficiency and decreased use of fossil fuels on a community scale. The demand side often benefits from the availability of low-temperature heat, serving as a basis for energy-efficient Space Heating (SH) and the preparation of Domestic Hot Water (DHW). The integration of low-temperature heat into district heating systems can be achieved through the utilization of efficient large-scale heat pumps, solar thermal collectors, and biomass-fired combined heat and power plants, among other techniques.

Lower temperatures are generally employed to minimize transit losses in pipelines and to improve the overall efficiency of the energy chains utilized for DH. To get optimum efficiency, the demand side must be configured to enable the usage of low temperatures supplied by the network (e.g. via surface heating systems), in addition to the district heating and cooling networks and energy conversion needing to be at their best. Because of this, implementing solutions with a high proportion of renewable energy sources necessitates modifying the architectural and technological infrastructure. Both surplus and renewable energy sources can adequately fulfil energy requirements, particularly when captured efficiently at lower temperatures. By considering buildings and building supply systems as integral components of an energy network, synergies are optimized, especially at the community level. To develop advanced low temperature heating, several challenges about matching the available energy from the supply side with the demand caused by Space Heating and Domestic Hot Water on the building side need to be solved.

At the consumer level, there are three ways to get a low-temperature heating. Larger emitters (radiators), heavier insulation, and low-temperature regulation.

Other advantages in using and implementing low temperature district heating networks are the possibility to implement plastic instead of traditional more expensive DH metal-based pipes, more easy integration of low temperature heat sources like thermal collectors, deep geothermal wells, and low temperature waste heat. Because low temperature DH can achieve low heat losses and great overall system performance, fewer resources would be used. Other practical benefits are a Slower corrosion rate, less thermal shock to the system, cleaner air due to slow air motion at the emitters, and lower noise.

In the higher temperature range of LTDH, between 60°C and 90-100°C, we find traditional user-side heating methodologies such as mid-temperature emitters. The heat sources for building heating can include low-temperature district heating, heat pumps, geothermal systems, or other technologies that provide heat at moderate temperatures, providing that the temperature is upgraded by the correct technology to meet the various characteristic user demand.

HT-DH – Floor Heating, LT Space Heating and DHW

Centralized heating refers to a system where heat is centrally produced in a large facility or thermal plant and then distributed to multiple buildings or users. The temperatures involved in centralized heating often range between 90°C and 130°C and more. Distribution can occur through a network of pipelines connecting the thermal plant to the serviced buildings. Such a system can be utilized to heat an entire

urban area or neighbourhood. For industrial purposes, some processes require higher temperatures to operate efficiently, and centralized heating can provide this thermal energy at temperatures up to 150°C. In extensive district heating networks, the temperature of the heat transfer fluid may need to be higher to cover heat losses along the network. Cogeneration systems, which simultaneously produce heat and electricity, may require higher temperatures to maximize efficiency. In such cases, steam or high-pressure water can be used as heat transfer fluids.

Some energy districts integrate various heat sources and generation technologies. The combination of cogeneration plants, advanced heat exchangers, and other technologies may necessitate higher temperatures to ensure overall system efficiency. In all these instances, the choice of heat transfer fluid often depends on the specific project characteristics and local requirements. In many cases, pressurized water (p< 5 bar) serves as the primary heat transfer fluid for centralized heating at temperatures up to 150°C. However, specialized fluids like thermal oil or other advanced heat transfer fluids can also be used to achieve higher temperatures without reaching the boiling point. Some district heating systems use steam as a medium for heat distribution instead of water. This is to achieve higher supply temperatures, which are often necessary for industrial processes. Steam-based systems are already present in a large number of structures. Because of its great energy density, steam works especially well in industrial or large-scale buildings where it can effectively provide the required heat.

Even if more recent technologies are more efficient, they might not be appropriate in all situations. There are situations where it makes more sense to use already-existing steam systems rather than completely overhauling them to increase efficiency. It is the case of the district heating systems currently performing in the Eastern European Countries (2nd-3rd generation), where accurate technological retrofitting is needed to adapt the high temperature heating to more sustainable low temperature sources.

CURRENT HEAT GENERATION TECHNOLOGY FOR HT-DH

INTRODUCTION

Several technologies are commonly used for high-temperature district heating, each with its unique advantages and applications. Focusing on heat generation technologies that do not rely on renewable sources, the following are highlighted:

1) Natural gas and coal boilers
2) Fossil fuel Combined Heat and Power (CHP)

Coal heaters have historically been used, particularly in regions where coal is abundant and readily available. Coal-fired boilers and CHP combust coal to produce heat, as well as electric energy in the case of CHP, which is then distributed through the district heating network to provide heating and hot water to buildings and facilities. However, due to environmental concerns, particularly regarding air pollution and greenhouse gas emissions, there has been a global shift away from coal. Coal combustion releases pollutants including sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter, and carbon dioxide (CO_2), contributing to air quality problems and climate change. As governments and utilities move towards cleaner and more sustainable energy sources, the usage of coal for district heating has significantly decreased in several countries, including North America and Europe. Because of their reduced emissions and ability to integrate renewable energy sources, natural gas, biomass, and waste-to-energy technologies are becoming more and more popular choices.

Anyway, coal boilers and CHP are still in use in some regions, such as Eastern European Countries, but the recognition of the need to phase out or at least reduce coal use in favour of more environmentally friendly heat generation technologies is growing. This transition is driven by environmental regulations and the increasing availability and affordability of renewable energy sources.

COAL AND GAS BOILER DISTRICT HEATING

Despite the different fuel, heating boiler systems can be schematically represented in the same way, also when feeding a DH network. The same for CHP. Regarding these last, Figure 16 shows two possible adaptations to district heating, opportunely simplified. On the left (A), the more common of the two, a standard Rankine cycle is modified to include a dedicated condenser, usually in the deaerator line (3). The steam is extracted at a pressure ranging from 2.0 up to 2.7 bar (corresponding to saturation temperatures of 120°C – 130°C) or more. The cold side of the condenser is crossed by a water mass flow which represents the heat transfer fluid of the district heating network. This mode is also called "extraction condensing system" (Zhao, et al., 2019). The other system (B) avoids the intermediate condenser, but the turbine exhaust steam feeds a condenser unit at about 0.6 up to 1.5 bar of pressure in dependence on the desired water temperature on the district heating network. It is also known as "low vacuum" system or "high back pressure" (HPB) system. By doing this, the loss of exhaust heat is eliminated with better overall performance. To obtain this configuration, the backpressure of the last turbine is increased by removing the last stages of the blades. When comparing it to the traditional CHP system, the HPB system features significantly lower heating steam temperatures. This makes it more suitable for low temperature district heating.

Both systems can effectively harness and benefit from energy derived from low-grade sources such as solar, geothermal, waste heat, and others.
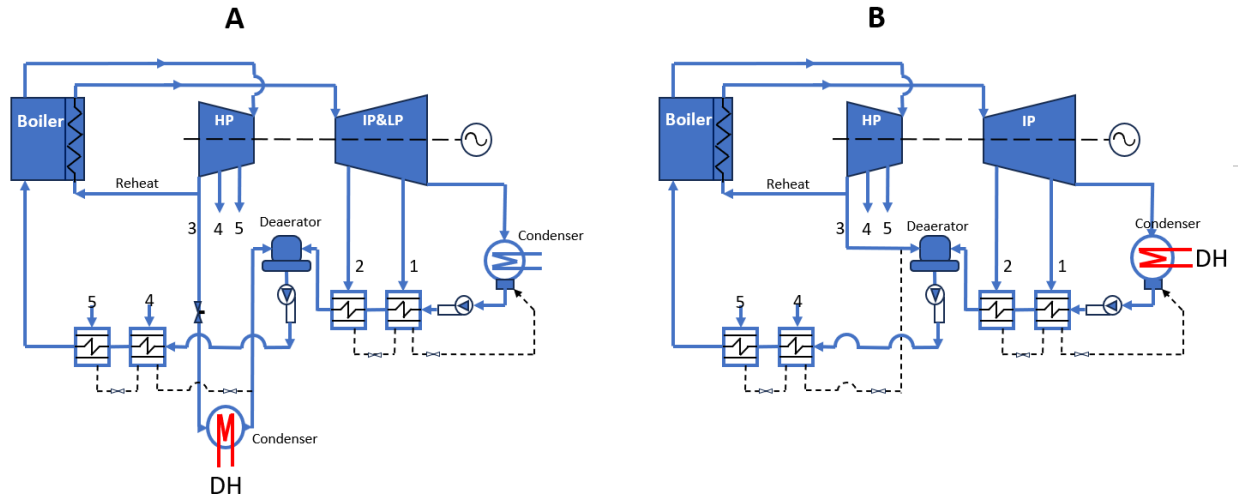
Figure 16. Two CHP configurations for district heating. On the left, the classic extraction condensing system (A) with low back pressure at the condenser. On the right, the high back pressure CHP (B) (UNIGE)

Often district heating is provided by a simple fossil-fired boiler. Regardless of the configuration or the supply temperature level, these systems can always be advantageously supplemented by low-grade sources, reducing fossil fuel consumption and thus pollution. Typically, these systems produce more or less pressurized hot water, and in the primary loop, the water state is liquid. However, some versions generate steam at various temperatures (and pressures) that can be used on heating lines at different temperatures. Both methane CHP and simple boilers can be fuelled by biogas after the required adaptations. It is underlined that, when possible, the substitution of fossil fuels with biofuels (if correctly produced) is the easier way to reduce the carbon footprint.

As an example, Figure 17 shows a steam boiler (also for power generation and CHP units) which is adaptable for wide ranges of fuels such as natural gas, LPG, biogas, methane gas, diesel, heavy oil etc. The steam capacity ranges from 500 kg/h to 20 t/h.

Figure 17. Fire Tube Steam Boiler Winsketel (credit: Diemareng, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons)

L2H Low2HighDH

INTRODUCTION

Renewable sources, like solar and geothermal, can also be profitably integrated also in old coal systems to partially substitute coal or can be part of upgrading technologies able to completely replace fossil fuels.

First, it will be necessary to distinguish the type of intervention starting from a situation reliant on completely fossil sources (Figure 18). This type of intervention, applicable starting from the current implementation of district heating (0), will either involve integrating renewable sources into existing generation facilities (A) previously powered exclusively by fossil fuels, e.g. CHP systems, or simple boilers, or completely replacing available heat sources with renewable ones (B). This last option will probably require, to correctly integrate with HT-DH, one or more upgrading technologies capable of raising the temperature to the required levels.

Current and expected HT District Heating Technology
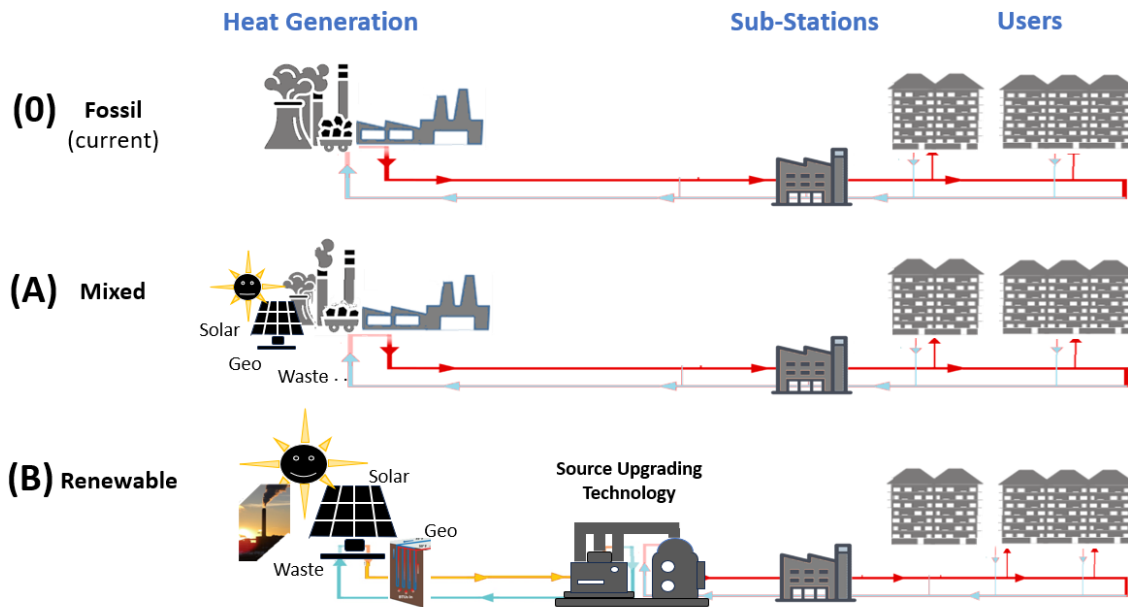
Figure 18. Alternative transition paths from current fossil-fuelled DH (UNIGE)

INTEGRATION STRATEGIES FOR LGERES-AIDED COMBINED HEAT AND POWER SYSTEMS

Earlier in this document, focus has been put on LGERES and upgrading technologies. Here, we articulate solution (A) which allows us to keep the old network virtually unaltered. Only the heat generation plant will be affected. By considering the plant design of the previous section, a simple coal-fuelled CHP system providing district heating is considered as depicted in Figure 16 (A). Various methods of low-grade energy integration are proposed (Wu & Han, 2023).

The first integration strategy is to directly insert the LGERES in the DH network, as per Figure 19 A. The low-grade source is set up alongside the DH condenser and it is employed to warm a portion of the water in the primary DH circuit. This simple scheme is easy to implement but requires the temperature of the LGERES to be consistent with that of the DH network. It allows some regulation of the DH network by the valve system and the output temperature will be between that of the LGERES and the one provided by the DH condenser.

In the second integration strategy, illustrated in Figure 19 (B), a solar field is positioned parallel to feedwater heaters (FWH) 1 and 2. Solar energy is employed to preheat feedwater and to substitute the first two extraction steam stages, which operate at the lowest pressure. This integration strategy emphasizes the incorporation of heat at low temperature before the inlet of the condensed steam in FWH-3.
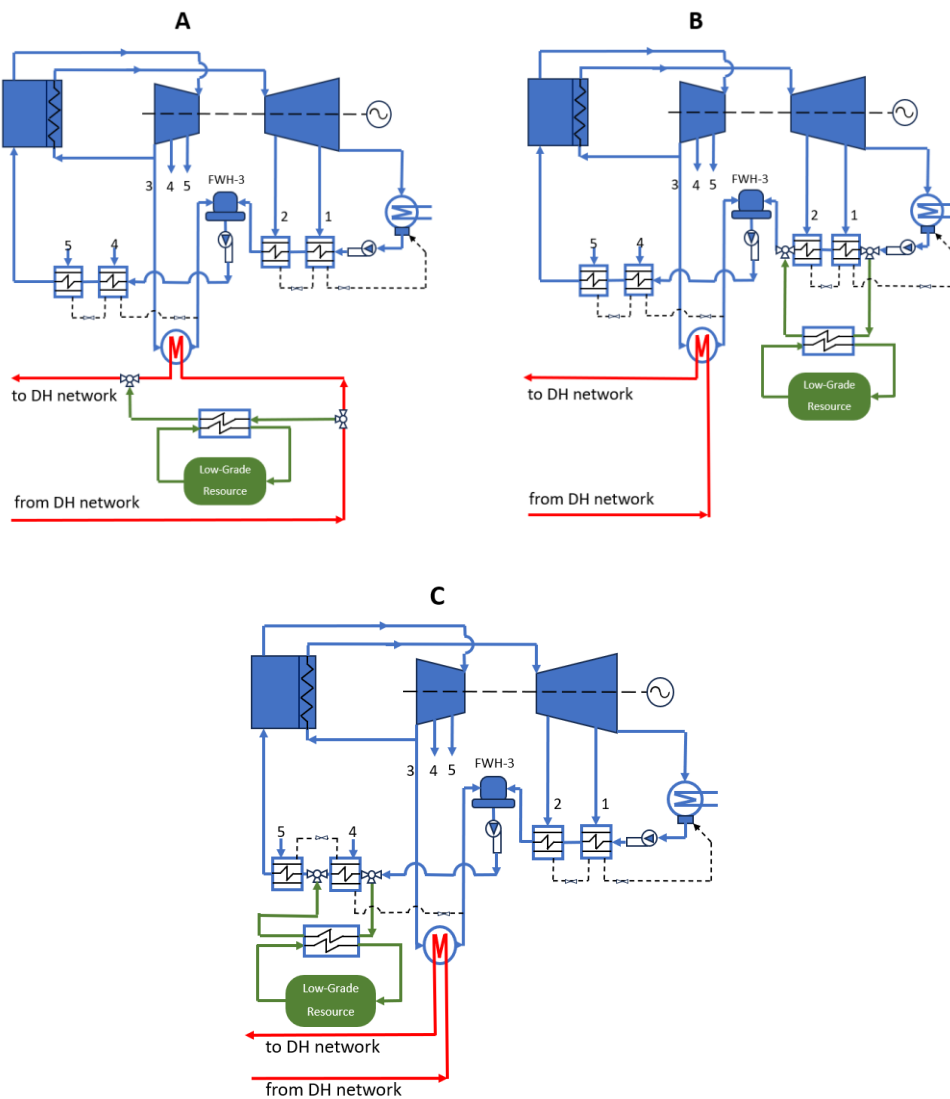
Figure 19. Basic LGERES integration strategies in pre-existing CHP district heating systems (UNIGE)

In the 3rd integration strategy, depicted in Figure 19 (C), the solar field is positioned parallel to FWH-4. Solar energy is utilized to preheat feedwater through an oil/water heat exchanger and to substitute the 4th-stage extraction steam. This integration strategy highlights the incorporation of LGERES heat after the inlet of the condensed steam in FWH-3.

The above strategies have been illustrated only as examples of LGERES integration. Usual steam CHP plants have more feedwater heaters, and the insertion of the integration heat can be done at various temperature levels depending on the available source and in parallel with one, two, or more feedwater heaters. High temperature integration can be also applied in the reheat line.

With proper adjustments, these strategies can also be applied in the case of direct boiler DH. The concept involves using LGERES heat to preheat water, thereby reducing reliance on fossil fuels.

ANALYSIS OF TECHNOLOGIES/STRATEGIES FOR LGRES-COUPLED HT DISTRICT HEATING

Several potential solutions to integrate or retrofit actual HT-DH technology can be adopted, based on the combination of the following elements:

- reference system:
  - CHP or Boiler
  - Operating temperature of the HT-DH network (which are here assumed always in the range 110÷130 °C for delivery and 60÷80 °C on the return line)
- main Low Grade Energy Resources (LGERES) or Renewable Energy Resources (RES) available:
  - solar (medium and high temperature solutions)
  - waste heat (low, medium and high temperature)
  - geothermal (with specific reference to ground heat source; hot water of vapour geothermal can be used the same way as waste heat)
  - biomass (solid, biogas, …)
  - other (specific sources which could be envisaged, none in this document)
- specific upgrading technologies needed to exploit the LGERES:
  - TES – Thermal Energy Storage, always needed when non continuous energy sources are exploited (such as solar, intermittent waste or sewage, and so on)
  - Vapour Compression Heat Pumps (VC-HP)
  - Absorption Heat Pumps (ABS-HP) also known as "heat transformers"
  - Mechanical Vapour Recompression systems (MVR), be they in open cycle configuration (for water vapour delivery) or in water vapour compression heat pump closed cycle (steam VC-HP).
- Other technologies (specified in the data sheet)
- Stand-alone RES: this is the case when the RES temperature is sufficiently high to satisfy the temperature heating needs (such as "solar through" high temperature concentration collectors).

In each data sheet a short system description is available, comparing the old system to the new LGERES integrated one.

The other practical alternative between *centralized* and *non-centralized* LGERES exploitation has been introduced.

The Centralized solution is completely developed in the central DH distribution and has the advantage to be implemented by the plant operators with high power levels and it does not directly involve the municipality or other relevant stakeholders.

The *non-centralized* solution represents a distributed energy exploitation, which has the benefit to present less impact and to involve the population in environmental sustainability issues. It has the disadvantage to need municipality or governmental agreements and can rely on rather small power installed per unit (which means higher installation and maintenance costs). In this last case, a detailed technical and financial analysis can help the municipality to assess incentives for many private, small, distributed initiatives.

For completeness the centralized solutions here listed does not involve only LGERES upgrade systems, but also retrofitting of exiting central installation, by means of LGERES not necessarily directly applied to the DH network.

To understand better the thermal coupling of users, LGERES and upgrading technologies one can refer to Figure 20, where the central temperature scale represents the application temperature needed (simply the "user temperature"), which depends on the insertion point of the LGERES into the HT-DH network and on the technological solution adopted. On the left of such temperature scale the main possible LGERES solutions are depicted, with their corresponding available temperature ranges, grouped based on continuous or non-continuous energy resources. This last need always the adoption of thermal energy storage (TES) at an adequate temperature, while continuous one could take advantage from the use of TES (in terms of regulation and control capabilities) but the use of TES is not mandatory. On the left of Fig. 20 the main upgrading technologies so far described are placed, with their more common temperature field of application. Even if this figure is by far qualitative, it is certainly useful to understand which LGERS can be used for given working temperature of the application and which upgrading technology can be used to reach the same delivery temperature level. For instance if our working temperature is around 120°C, the sketch of figure 20 clearly shows that the only solar technology able to satisfy such high temperature is the parabolic solar through, while if we want to exploit just the ground or external environment (around 5÷10°C) energy resources (air, rivers or lakes) not only a vapour compression heat pump (VC-HP) is necessary, but also a second upgrading technology must be coupled in series, such as an absorption heat pump (ABS-HP) which could be very often insufficient, or even a steam VP-HP or MVR.
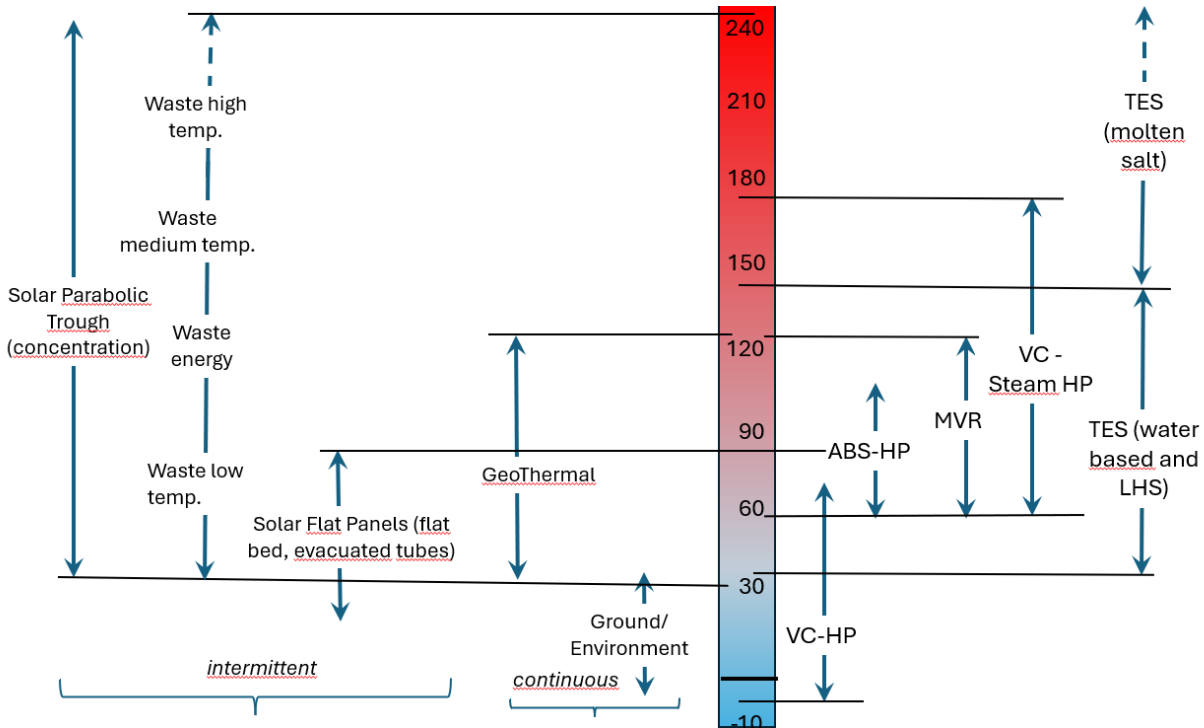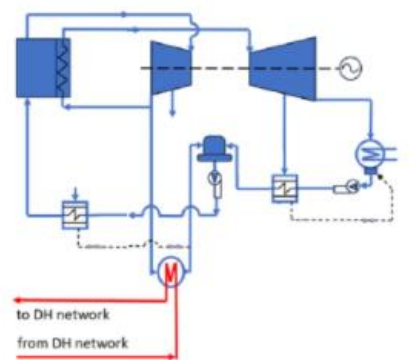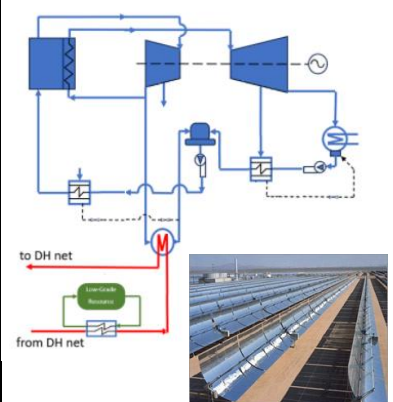

Figure 20. Coupling HT-DH working temperatures (central temperature scale) to some LGERES (on the left) and possible upgrading technologies (on the right). Direct biomass and biogas combustion processes not included (credit: UNIGE)

In what follows several examples of technical solution/integration strategy are summarized in the form of simplified data sheets.

01	**Technical Solution/Integration Strategy n. 01** **Medium /high temperature** **Solar integration (parabolic solar through) with TES in CHP systems**

Basic reference Technology ☐ Boiler ☒ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None (in the CHP economizer)	Main exploited LGERES ☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	Upgrading Technology ☒ TES ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)

New concept with direct solar integration

The considered LGERES does not need specific thermal upgrading technology, since the working temperature is usually sufficiently high, thanks to solar concentration. The use of TES (Thermal Energy Storage) is always needed to correctly couple the HT-DH needs to the solar source.

The considered simplified CHP configuration (traditional vapour cycle coal fired, on the left) uses steam extraction before the low-pressure turbine, to support the DH heat demand. It is possible to install an LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line, covering a desired % of the DH thermal needs. It can function as an integration, taking on a portion of the assigned DH demand, or as a net addition of thermal power. The actual amount (portion) depends on the temperature availability of the new source and the % saving on the installed RES power (solar field surface, filed costs, and so on).

The control strategy determines the actual emission and fossil fuel savings (FFS), depending on the possibility to operate the plant at a reduced electrical power output, or the turbine power must be fixed. Proper Thermal Energy Storage (TES) is always mandatory.

The FFS of the base system can be incremented of 10%-15%. Assuming for reference the "business as usual" fossil fuel consumption, the savings in respect to the base system can reach 15-20% when implemented as integration. When operating with a net addition of power, and therefore providing

thermal powers for district heating greater than the original one, these indicators are no longer very useful.

Main Parameters

LGERES technology: Solar Parabolic through

TRL: 10 – Well established and available technology

Operating temperature of the LGERES: up to 220°C.

Operating temperature of the integration: up to CHP intermediate temperature (economizer).

Expected performance: FFS (Fossil Fuel savings) of the order of 15÷20%

Installation costs: 3500 ÷ 6000 €/kW$_{t,peak}$ (reference peak insolation 1000W/m^2)

Energy costs: The cost of thermal energy from parabolic solar trough systems can vary depending on several factors, including the initial investment cost, system efficiency, maintenance costs, and the local solar resource. Typically, the cost of thermal energy from parabolic trough solar systems is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., euros per megawatt-hour, €/MWh).

Strength	Weakness
- Ease of integration with the existing DH plant - Possibility to increase the thermal power supplied to the users - Substantial FFS	- In "integration" mode, it does not allow for high fossil fuel savings. - It does not allow for the efficient exploitation of high-temperature sources

Main Recommendations

- Reasonably recommended use also with moderate LGERES temperatures (<110°C).

- Recommended when an increase of the DH thermal power is desired

- Not recommended for use with high temperature LGERES sources

In the high temperature range (availability of LGERES over 140°C) a direct insertion on the delivery line of the HT-DH network is suggested, leading up to 100% FFS for the DH and a great increase of CHP electrical power and efficiency (by means of proper retrofitting).

02	**Technical Solution/Integration Strategy n. 02 Medium /high temperature ground HP coupled to Absorption HP with TES in CHP plants**

Basic reference Technology ☐ Boiler ☒ CHP ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☐ None (in the CHP plant)	Main exploited LGERES ☐ Solar ☒ Geoth. ☐ Waste ☐ Biomass ☐ Other	Upgrading Technology ☐ TES + ☒ VC-HP ☐ MVR ☒ ABS-HP ☐ Other ☐ None

Intervention strategy (location):   ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)	New concept with ground HP integration
	Heat transformer ground HP

The considered solution is similar to solution n.1 (traditional steam cycle, coal fired, on the left), but exploit a cascade of thermal upgrading technologies, starting from the ground heat source (temperature about 5÷10°C all over the year) with VC-HP to get a 60÷70°C source which can be upgraded by means of a heat transformer up to the working temperature of about 100÷110°C. The use of TES (Thermal Energy Storage) is always needed to couple correctly the HT-DH needs and the LGERES to the CHP operation.

The LGERES exploitation adopt the same embodiment as the one of the data sheet n.1 with the heat exchanger in green used to pre-heat the DH return line, covering the desired share of the DH thermal needs. Due to temperature constraints, it can be used as an integration, taking on a portion of the assigned DH demand. The actual amount depends on the temperature availability of the new source (ground HP + ABS-HP) and the relative saving on the installed cascade heat pump system.

Assuming for reference the "business as usual" fossil fuel consumption, the savings in respect to the base system can reach 15-20% when implemented as integration. When operating with a net addition

of power, and therefore providing thermal powers for district heating greater than the original one, proper indicators must be defined in the detailed analyses.

Main Parameters
LGERES technology: ground heat pump (ground VC-HP) + Absorption Heat pump (ABS-HP).
TRL: 9÷10 – Well established and available technology with some difficulties to be applied in actual application. ABS-HP pilot plants should be envisaged and well come.
Operating temperature of the LGERES: bottoming ground VC-HP up to 70°C (COP of the order of 3.8 with exergy efficiency of 0.5). Topping heat transformer up to 110°C (exergy efficiency of the order of 0.35). Specific performance parameters must be defined in detailed analyses.
Operating temperature of the integration: up to 110°C, at the intermediate pressure economizer of the CHP.
Expected performance: FFS (Fossil Fuel savings) of the order of 15÷20% (limited due to the CHP mode of operation).
Installation costs: 500 ÷ 900€/kW$_t$ (thermal power delivered at the upper temperature) + ground field heat exchanger (quite variable depending on the layout, size, and ground nature).
Energy costs: The cost of thermal energy from ground source heat pump is rather low in the long term, however some additional cost must be added to account for relatively high maintenance costs for the combined system. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh).

Strength	Weakness
- Ease of integration with the existing DH plant. - Possibility to increase the thermal power supplied to the users. - Good saving indicators.	- In "integration" mode, it does not allow for high fossil fuel savings. - the use of heat transformers is not so well spread - Its cost is strongly affected by the ground field heat exchanger configuration.

Main Recommendations
- Reasonably recommended for use with moderate temperature LGERES (<110°C). **- Recommended when an increase of the DH thermal power is desired** **- Not possible to reach the highest working temperatures of the HT-DH network** **- Some adaptation of the CHP plant could be necessary. One pilot plant could be envisaged.**

03	**Technical Solution/Integration Strategy n. 03 geothermal HP + high temperature steam HP integration for CHP systems**

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☐ Boiler ☒ CHP ☐ New Integration point/ DH temperatures ☒ Supply/ 120°C ☐ Return/ 60°C ☐ None	☐ Solar ☒ Geothermal ☐ Waste ☐ Biomass/biogas ☐ Other	☒ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)	New concept with ground energy integration

Since the working temperature of ground source heat pumps is <70°C, the coupling of MVR technology in closed cycle configuration (steam heat pump) offers temperatures up to 160°C, sufficient to be used on the delivery side of the DH network. TES (Thermal Energy Storage) could be useful to enhance control system management in the coupling of CHP operations to DH needs.

The considered simplified CHP configuration (traditional vapour cycle coal fired, on the left) uses steam extraction before the low-pressure turbine, to support the DH heat demand. The LGERES, in green in the schema on the right, support the DH delivery line by means of integration technology and covers a desired % of the DH thermal. Fine tuning operation of the CHP is guaranteed. It can function as an integration, taking on a portion of the assigned DH demand, or as a net addition of thermal power, leaving to the return line of the DH network just the function of cooling the CHP. The actual amount depends on the temperature availability of the new source and the % saving on the installed RES power (ground field, field costs of the ground heat exchanger, and so on). It is also possible to by-pass the CHP system (dotted red line), increasing the CHP efficiency and directly using the electrical power to operate the HP cascade for 100% DH services.

Assuming for reference the "business as usual" fossil fuel consumption, the savings in respect to the base system can reach 15-20% when implemented as integration.

Main Parameters

LGERES technology: geothermal heat pump + steam compression heat pump

TRL: 10 – Well established and available technology, but detailed engineering design is needed

Operating temperature of the LGERES with integration: up to 150÷170°C°.

Operating temperature of the integration: up to the DH delivery temperature. The DH return line can still be used for CHP intermediate temperature economizer cooling (no CHP plant changes needed). In by-pass configuration some changes in CHP are mandatory.

Expected performance: FFS (Fossil fuel savings) of the order of 15÷20%, or even more, excluding electrical consumptions of the HP systems, which evaluation must be carefully considered, based on actual working temperatures (the order of magnitude of the total COP_{HP} is up to 2.4).
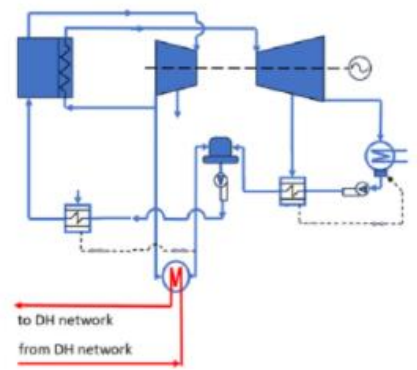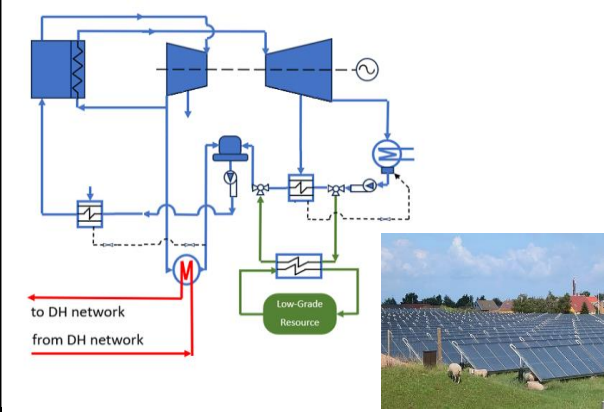
Installation costs: 350 ÷ 400 €/kW (HP) + 400 ÷ 500€/kW (steam HP) + ground field heat exchanger (strongly variable based on the configuration) for steam heat pumps[1].

Energy costs: Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., euros per megawatt-hour, €/MWh).

Strength	Weakness
- Ease of integration with the existing DH plant and good coupling also with high temperatures. - Possibility to increase the thermal power supplied to the users. - Good saving indicators.	- In "integration" mode, it does not allow for high fossil fuel savings.
Main Recommendations	
- Reasonably recommended use also with moderate LGERES temperatures (<110°C). **- Recommended when an increase of the DH thermal power is desired** **- Also applicable with high temperature DH delivery**	

---

[1] https://oilon.com/en-gb/products/oilon-chillheat-s-600-s-2000/

04	Technical Solution/Integration Strategy n. 04. Medium temperature Solar integration (flat bed, evacuated tubes) with TES in CHP systems

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☐ Boiler ☒ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None (inside the CHP)	☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)

New concept wirh direct solar integration in CHP

The considered LGERES does not need specific thermal upgrading technology, as far as the CHP condenser temperature is low. The solar panel working temperature is usually sufficiently high, and the insertion point has relatively low temperature. The use of TES (Thermal Energy Storage) is always needed to correctly couple the CHP needs to the solar source.

The considered CHP base configuration (same as data sheet 1,2 and 3 -traditional coal fired, on the left) uses the steam extraction from the low-pressure steam turbine to pre-heat the condenser liquid outlet. It is possible to install an LGERES thermal field, in green in the schema on the wright, on the mid pressure line, in parallel to the first set of feedwater heaters, covering a desired (small) % of the CHP thermal needs. The actual amount of integration is small due to the position of the insertion point and the LEGERES source must provide low temperature energy, below 60÷80°C. The actual amount (portion) depends on the temperature availability of the new source and the % saving on the installed RES power (solar field surface, filed costs, and so on).

The control strategy determines the actual emission and fossil fuel savings (FFS), but it is generally rather small: assuming for reference the "business as usual" fossil fuel consumption, the savings in respect to the base system can reach 2-3%.

Main Parameters

LGERES technology: Flat bed solar collectors/evacuated tubes solar collectors

TRL: 10 – Cheap, well established and available technology

Operating temperature of the LGERES: up to 60 °C (flat plate) ÷100 °C (evacuated tubes).

Operating temperature of the integration: usually up to CHP condenser temperature and firs set feedwater heaters.
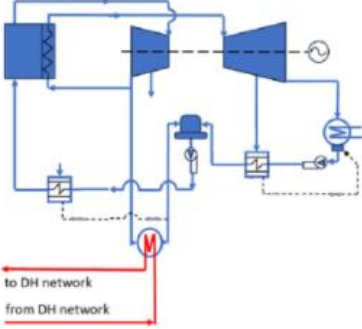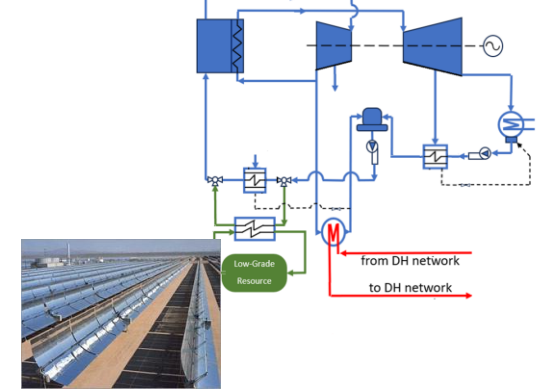
Expected performance: FFS (Fossil fuel savings) of the order of 2÷3%

Installation costs: 350 ÷700€/kW$_t$ (thermal power delivered at the upper temperature) + TES

Energy costs: The cost of thermal energy from flat bed solar collectors is not so high, even if some additional cost must be added to account for the relatively high maintenance costs for the evacuated tubes configuration. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh).

Strength	Weakness
- It can be directly implementable with very low temperature sources, down to 35 °C.	- Limited fossil fuel savings. - Limited amount of power integration. - It does not allow an efficient integration.
Main Recommendations	
- Not recommended	

05	**Technical Solution/Integration Strategy n. 05. high temperature Solar integration (parabolic solar through) with TES in CHP systems**

Basic reference Technology ☐ Boiler ☒ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None (inside the CHP)	Main exploited LGERES ☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	Upgrading Technology ☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)

New concept wirh direct solar integration

The considered LGERES does not need specific thermal upgrading technology, since the working temperature is usually sufficiently high, thanks to solar concentration. The use of TES (Thermal Energy Storage) is always needed to correctly couple the plant thermal needs to the solar source.

The considered CHP configuration (traditional coal fired, on the left) uses the steam extraction from the vapour steam turbine before going to the low-pressure turbine, to support the DH heat demand. It is possible to install an LGERES thermal field, in green in the schema on the right, on the high-pressure line, in parallel to the high temperature set of feedwater heaters, covering a desired % of the boiler thermal needs. The feedwater heaters contribution can be totally excluded.

This configuration can function as the boiler preheater, when implemented with LGERES sources capable to provide temperature from 130°C up to 250 °C, but it can partially or completely substitute the boiler if the added source can provide temperatures up to the max temperature of the plant (e.g., 500°C÷600°C). So, the amount of integration can also be very high.

The actual emission and fossil fuel savings (FFS), generally high, will be function of the above said mode of operation: preheating or boiler substitution. In the case of preheating, the FFS of the base system can be incremented up to about 20%.

Obviously, when the boiler is completely substituted by the LGERES the saving will reach 100%.

Main Parameters

LGERES technology: Solar Parabolic through

TRL: 10 – Well established and available technology

Operating temperature of the LGERES: up to 260°C.

Operating temperature of the immission: up to 250°C (preheating)/500 °C (boiler replacement).

Expected performance: FFS (Fossil fuel savings) of the order of 20% depending on the level of integration (100% if boiler replacement is possible).

Installation costs: 3500 ÷ 6000 €/kW$_{t,peak}$ (reference peak insolation 1000W/m^2) + CHP substitution costs

Energy costs: The cost of thermal energy from parabolic solar trough systems can vary depending on several factors, including the initial investment cost, system efficiency, maintenance costs, and the local solar resource. Typically, the cost of thermal energy from parabolic trough solar systems is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., euros per megawatt-hour, €/MWh).

Strength	**Weakness**
- It can completely replace the use of fossil fuel. - Very good saving indicators.	- Not easily implementable as in the DH return line (strong changes in the CHP plant). - It does not allow for the exploitation of low-temperature sources.

Main Recommendations
- Recommended both for both complete or partial fossil fuel replacement. **- Requires mid to high temperature sources (Not applicable for use with moderate temperature sources, <140°C).**

06	Technical Solution/Integration Strategy n. 06. Medium-high temperature WASTE HEAT integration with TES in CHP systems

Basic reference Technology ☐ Boiler ☒ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None	Main exploited LGERES ☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	Upgrading Technology ☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – condensing CHP (simplified)

New concept with direct wastw heat integration

The use of TES (Thermal Energy Storage) is always needed to correctly couple the CHP plant thermal needs to the waste heat source.

The considered CHP configuration (traditional coal fired, on the left) uses the steam extraction from the vapour steam turbine before going to the low-pressure turbine, to support the CHP heat needs. It is possible to install an industrial waste thermal connection, in green in the schema on the right, on the high-pressure line, in parallel to the high temperature set of feedwater heaters, covering a desired % of the boiler thermal needs. The feedwater heaters contribution can be totally excluded (increasing the electrical energy production).

This configuration can function as the boiler preheater, when implemented with waste heat sources capable to provide temperature from 130°C up to 250 °C (such as Exhaust gases from engines and turbines, heat from drying ovens, chemical reactors) , but it can partially or completely substitute the boiler if the added source can provide temperatures up to the max temperature of the plant (e.g., 500°C÷600°C) (such as waste from exhaust gases from industrial furnaces, kilns, incinerators). So, the amount of integration can also be very high.

The actual emission and fossil fuel savings (FFS), generally high, will be function of the above said mode of operation: preheating or boiler substitution. In the case of preheating, the FFS of the base system can be incremented up to about 10%.

Obviously, when the boiler is completely substituted by the LGERES the saving will reach 100%.

Main Parameters

LGERES technology: industrial waste heat

TRL: 10 – Well established and available technology

Operating temperature of the LGERES: up to 400°C and above (depends on which industry is involved).

Operating temperature of the immission: up to 250°C (preheating)/500 °C (boiler replacement).

Expected performance: FFS (fossil fuel savings) of the order of 20% (100% if boiler replacement is possible).

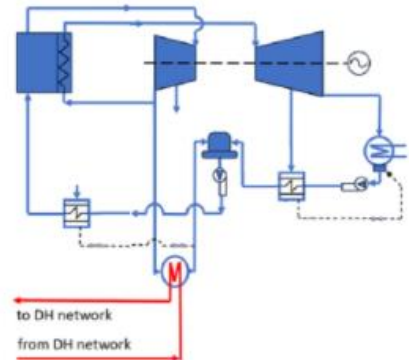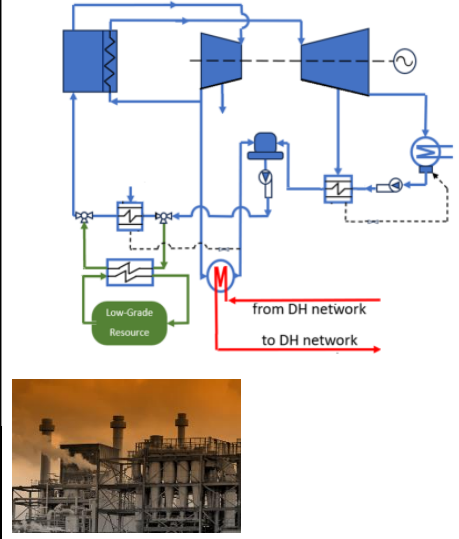**Installation costs:** It can be low (some plant arrangements and few heat exchangers), it is linked to the specific situation.
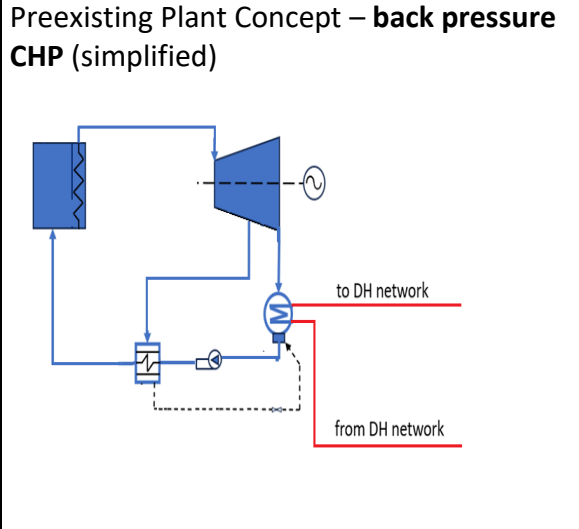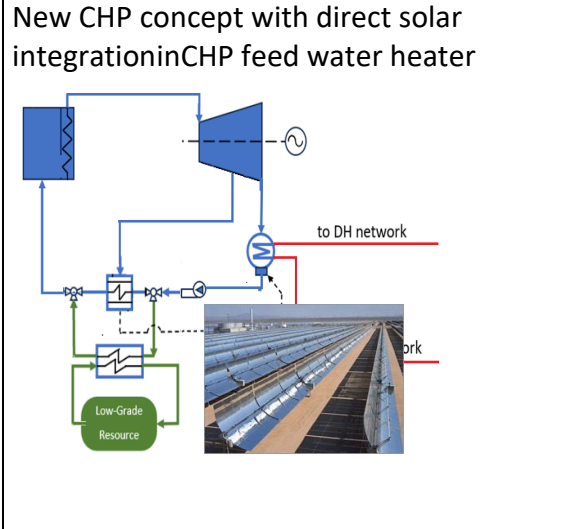
Cost of energy: to be determined for the specific case since it is linked to the installation cost.

Strength	Weakness
- It can completely replace fossil fuel use. - Very good saving indicators.	- Not easily implementable as in the DH return line - It does not allow for the exploitation of low-temperature sources.

Main Recommendations

- **Recommended both for complete or partial fossil fuel replacement.**

- **Requires mid to high temperature sources (Not applicable for use with moderate temperature sources , <140°C).**

07	Technical Solution/Integration Strategy n. 07. Medium to high temperature Solar integration (parabolic solar through) with TES in CHP Back Pressure systems

Basic reference Technology ☐ Boiler ☒ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None	Main exploited LGERES ☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	Upgrading Technology ☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location):   ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – **back pressure CHP** (simplified)

New CHP concept with direct solar integrationinCHP feed water heater

The considered CHP configuration (traditional coal fired, on the left) is a backpressure system with a single turbine and uses the steam condensation at a relatively high-pressure to assure the DH heat demand. In respect to the previous extraction/condensing configurations, the backpressure system does not disperse heat into the environment and therefore exhibits a global energetic efficiency equal to one. On the other hand, it has usually low to very-low energy conversion (electric) efficiency, due to the high condensing temperature and to the low isentropic efficiency of the turbine, which is often adapted by removing the last blade rotors (no fluid flow optimization).

It is possible to install an LGERES thermal field, in green in the schema on the right, on the high-pressure line, in parallel to the feedwater heater set, covering a desired % of the DH thermal needs. The feedwater heaters contribution can be totally excluded. It can function as the boiler preheater, when implemented with LGERES sources capable to provide temperature from 130°C up to 250 °C, but it can partially or completely substitute the boiler if the added source can provide temperature up to the max temperature of the plant (e.g., 500°C-600°C). So, the amount of integration can also be very high. The actual emission and fossil fuel savings (FFS), generally high, will be function of the above said mode of operation: preheating or boiler substitution. In the case of preheating, the FFS

of the base system can be incremented up to about 18%, higher compared to the extraction/condensing CHP. Obviously, when the boiler is completely substituted by the LGERES the saving will reach 100%.

Main Parameters
LGERES technology: Parabolic Solar Through **TRL:** 10 – Well established and available technology **Operating temperature of the LGERES:** up to 220°C **Operating temperature of the integration:** up to CHP intermediate temperature (economizer) (around 200°C). **Expected performance:** FFS (fossil fuel savings) of the order of 15÷20% **Installation costs:** 3500 ÷ 6000 €/kW$_{t,peak}$ (reference peak insolation 1000W/m^2) **Energy costs:** The cost of thermal energy from parabolic solar trough systems can vary depending on several factors, including the initial investment cost, system efficiency, maintenance costs, and the local solar resource. Typically, the cost of thermal energy from parabolic trough solar systems is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., euros per megawatt-hour, €/MWh).

Strength	Weakness
- It can completely replace fossil fuel use. - Very good saving indicators.	- Rather low cycle efficiency but the system is preexisting. - Usually it provides lower DH temperature (<100 °C) than extraction CHP.

Main Recommendations
- **Recommended for partial fossil fuel replacement (complete replacement only for high temperatures, such as concentration solar technology).** - **Requires mid to high temperature sources (Not implementable for use with moderate temperature sources (<130°C)).**

08	**Technical Solution/Integration Strategy n. 08. Ground Heat Pump integration + steam heat pump with TES in CHP Back Pressure systems**

Basic reference Technology ☐ Boiler ☒ BP-CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None	Main exploited LGERES ☐ Solar ☒ Geoth. ☐ Waste ☐ Biomass ☐ Other	Upgrading Technology ☒ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – **back pressure CHP** (simplified)

New CHP concept with ground source integration

The considered CHP configuration (traditional coal fired, on the left) is a backpressure system with a single turbine and uses the steam condensation at a relatively high-pressure to assure the DH heat demand. In respect to the previous extraction/condensing configurations, the backpressure system does not disperse heat into the environment and therefore exhibits a global energetic efficiency equal to one. On the other hand, it has usually low to very-low energy conversion (electric) efficiency, due to the high condensing temperature and to the low isentropic efficiency of the turbine, which is often adapted by removing the last blade rotors (no fluid flow optimization).

It is possible to install a ground geothermal field, in green in the schema on the right, on the high-pressure line, in parallel to the feedwater heater set, covering a desired % of the CHP thermal needs. The feedwater heaters contribution can be totally excluded. It can function as the boiler preheater, with the steam HP, coupled to the traditional geothermal heat pump, able to guarantee temperatures from 130°C up to 180 °C. The actual emission and fossil fuel savings (FFS), generally high, will be function of upgrading efficiency and preheating efficiency. The FFS of the base system can be incremented up to about 20%, but the electrical consumption of the two heat pumps must be considered. Final calculations must be performed for detailed analysis.

Main Parameters

LGERES technology: ground heat pump (VC_HP) + steam compression heat pump (MVR)

TRL: 10 – Well established and available technology, but detailed engineering design is needed

Operating temperature of the LGERES with integration: up to 150÷170°C.

Operating temperature of the integration: up to the pre-heater working temperatures in the CHP. (CHP plant changes needed).

Expected performance: FFS of the order of 15÷20%, or even more, excluding electrical consumptions of the HP systems, which evaluation must be carefully considered, based on actual working temperatures (the order of magnitude of the total COP_{HP} is 2.5).
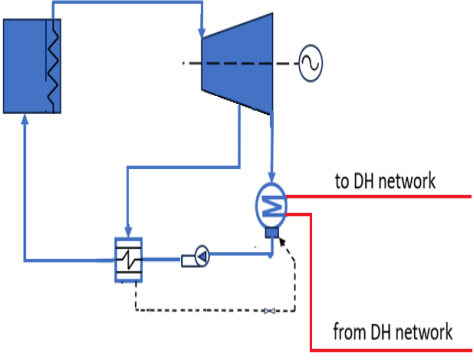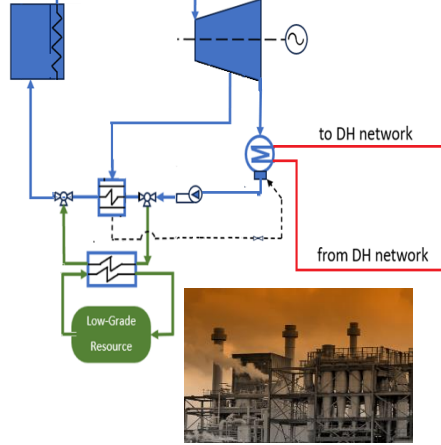
Installation costs: 350 ÷ 400 €/kW_t (VC-HP) + 400 ÷ 500€/kW_t (steam VC-HP) + ground field heat exchanger (strongly variable based on the configuration)[2].

Energy costs: Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., eros per megawatt-hour, €/MWh).

Strength	Weakness
- It can completely replace the pre-heater needs. - Very good saving indicators.	- Rather low cycle efficiency but the system is preexisting (typical back pressure CHP). - Additional important electricity consumption.

Main Recommendations
- **Recommended for partial fossil fuel replacement (20% savings) if COP of heat pumps is high.** - **Requires an important electrical energy consumption.** - **Requires mid to high temperature sources (Not implementable for use with moderate temperature sources (<130°C)).**

---

[2] https://oilon.com/en-gb/products/oilon-chillheat-s-600-s-2000/

TECHNICAL SOLUTION/INTEGRATION STRATEGY N. 09 (INDUSTRIAL WASTE SOURCE IN BP-CHP – MEDIUM HIGH TEMPERATURES)

09	**Technical Solution/Integration Strategy n. 09. Industrial waste integration + with TES in CHP Back Pressure systems**

Basic reference Technology ☐ Boiler ☒ BP-CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None (in CHP)	Main exploited LGERES ☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	Upgrading Technology ☒ TES + ☒ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location):   ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – **back pressure CHP** (simplified)

New BP-CHP concept with direct waste heat source in BP-CHP feed water heater

The considered BP-CHP configuration (traditional coal fired, on the left) is a backpressure system with a single turbine and uses the steam condensation at a relatively high-pressure to assure the DH heat demand. In respect to other extraction/condensing configurations, the backpressure system does not disperse heat into the environment and therefore exhibits a global energetic efficiency equal to one. On the other hand, it has usually low/to very-low energy conversion (electric) efficiency, due to the high condensing temperature and to the low isentropic efficiency of the turbine, which is often adapted by removing the last blade rotors (no fluid flow optimization).

It is possible to install an LGERES thermal field, in green in the schema on the right, on the high-pressure line, in parallel to the feedwater heater set, covering a desired % of the BP-CHP thermal needs. The feedwater heaters contribution can be totally excluded. It can function as the boiler preheater, when implemented with waste heat sources capable to provide temperatures from 130°C up to 250 °C, but it can partially or completely substitute the boiler if the added source can provide temperatures up to the max temperature of the plant (e.g., 500°C-600°C). So, the amount of integration can also be very high. The actual emission and fossil fuel savings (FFS) is generally high and will be function of the above said mode of operation: preheating or boiler substitution. In

the case of preheating (which should be the most common waste heat solution), the FFS of the base system can be incremented up to about 18%, higher compared to the extraction/condensing CHP. Obviously, when the boiler is completely substituted by the LGERES the saving will reach 100%. The use of TES (Thermal Energy Storage) is always needed to correctly couple the CHP plant thermal needs to the waste heat source.

Main Parameters
LGERES technology: industrial waste heat
TRL: 10 – Well established and available technology
Operating temperature of the LGERES: up to 400°C and above (depends on which industry is involved). Most actual available temperatures below 205°C.
Operating temperature of the immission: up to 250°C (preheating)/500 °C (boiler replacement).
Expected performance: FFS of the order of 15-20% (100% if boiler replacement is possible)
Installation costs: very cheap (some plant arrangements and few heat exchangers installation)

Strength	Weakness
- Can completely replace the use of fossil fuel - Very good saving indicators	- Rather low cycle efficiency (intrinsic feature of preexisting BP-CHP). - Usually provides lower DH temperature (<100 °C) than extraction CHP

Main Recommendations
- **Recommended both for complete and partial fossil fuel replacement.** - **Requires mid to high temperature sources (Not implementable for use with moderate temperature sources (<130°C)).**

10	Technical Solution/Integration Strategy n. 10 . Generic LGERES on the return line of CHP Back Pressure systems		
	Basic reference Technology ☐ Boiler ☒ BP-CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	**Main exploited LGERES** ☐ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☒ Other	**Upgrading Technology** ☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – **back pressure CHP** (simplified)

New CHP concept with direct LGERES heat source on DH return line

The considered CHP configuration (traditional coal fired, on the left) is a backpressure system with a single turbine and uses the steam condensation at a relatively high-pressure to assure the DH heat demand at 120°C. In respect to other extraction/condensing configurations, the backpressure system does not disperse heat into the environment and therefore exhibits a global energetic efficiency equal to one (all the combustion energy is exploited). On the other hand, it has usually low/to very-low energy conversion (electric) efficiency, due to the high condensing temperature and to the low isentropic efficiency of the turbine, which is often adapted by removing the last blade rotors (no fluid flow optimization).

It is possible to install a generic LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line. Unfortunately, the backpressure system is inherently less flexible than the extraction/condensing systems. The condenser is designed to give a definite amount of Heat and if it decreases as the LGERES increases the return line temperature on the CHP plant, the condenser cannot condensate any more properly and only a small degree of regulation is allowed by changing

the mass flow rate extracted from the turbine. Furthermore, the heat rejection at the condensed cannot be reduced, unless a corresponding reduction in the electrical power of the plant is accepted, and even in that case severe regulation problems persist.

As a consequence, the LGERES can supply very small integration heat power. The saving indicators are affected very marginally.

Main Parameters
LGERES technology: any available at temperatures up to 130°C
TRL: 10 – Well established and available technology
Operating temperature of the LGERES: up to 130°C
Operating temperature of the integration: up to CHP condenser temperature (around 130°C).
Expected performance: FFS of the order of 2÷3% (with no or little reduction of electrical power generation)
Installation costs: depends on LGERES employed
Energy costs: The cost of thermal energy from LGERES systems can vary depending on several factors, including the initial investment cost, system efficiency, maintenance costs, and the local resource. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., euros per megawatt-hour, €/MWh)

Strength	Weakness
- none	- Very low contribution and saving

Main Recommendations
- **Not recommended, unless great electric power reductions are accepted.**

TECHNICAL SOLUTION/INTEGRATION STRATEGY N. 11 (CHP: FLAT PLATE SOLAR PANEL + STEAM VC-HP ON THE DH RETURN LINE)

11	**Technical Solution/Integration Strategy n. 11 Medium temperature flat bed solar panel coupled to steam HP with TES on the DH return line to CHP systems**

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☐ Boiler ☒ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	☒ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location):   ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)	New concept with solar field + steam Heat Pump

The considered CHP configuration (traditional coal fired, on the left) uses the steam extraction from the vapour steam turbine before going to the low-pressure turbine, to support the DH heat demand. It is possible to install an LGERES thermal field, for instance a low temperature (50 °C) flat bed solar field, in green in the schema on the right, to pre-heat the DH return line, covering a desired % of the DH thermal needs.

Due to the low temperature of the supply of this LGERES, lower to that of the return line, an upgrading technology, in the form of a steam heat pump, is implemented to elevate the water temperature up to the range 80 °C-100 °C or more. In this way, part of the district heating power is provided by the solar source, part by the compressor power and the rest by the extraction condenser of the CHP. Decreasing the thermal power extraction from the CHP offers an increase in the expected electrical power output, thus compensating in part the compressor electrical consumption.

The axial flow steam compressor used in this type of heat pump have typically an efficiency around 0.8, resulting in COP value from 3.5 up to 4. The upgrading system can provide also the full DH need with consistent fuel saving. In this case the FFS of the system is high, but considering only the heating

demand, this is 80% satisfied by green sources, the rest coming from the compressor. Due to the upgrade capability of the water steam heat pump, the DH system can be implemented also as a stand-alone DH solution, without serving a preexisting CHP.

Main Parameters

LGERES technology: flat bed or evacuated tubes solar collectors + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES)

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: bottoming solar field up to 60÷70°C, steam HP up to 120-140°C (COP of the order of 4.5 with standard machine - exergy efficiency of 0.5). Specific performance parameters must be defined in detailed analyses.

Operating temperature of the integration: up to 120°C (can be used in the form of CHP economizer integration, or as a stand-alone solution).

Expected performance: FFS of the order of 50÷60% (limited due to the CHP mode of operation). Up to 75% in stand-alone solution.

Installation costs: 1500 ÷ 3000€/kW$_t$ (thermal power delivered at the upper temperature). This is the cost of the thermal field + steam HP

Energy costs: The cost of thermal energy from heat pumps is rather low in the long term, however some additional cost must be added to consider relatively high maintenance costs for the combined system. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh).

Strength	Weakness
- Ease of integration with the existing DH plant and possibility to install as a standalone application on the DH network - Possibility to increase the thermal power supplied to the users - Good saving indicators (especially for the stand-alone configuration)	- It needs an additional electric source for the compressor. - It must be coupled to low temperatures.

Main Recommendations

- Reasonably recommended for use low temperature (<60°C).

- Also Recommended when an increase of the DH thermal power is desire

12	**Technical Solution/Integration Strategy n. 11 Medium temperature flat bed solar collectors coupled to Absorption Heat Pump with TES on the DH return line to CHP systems**

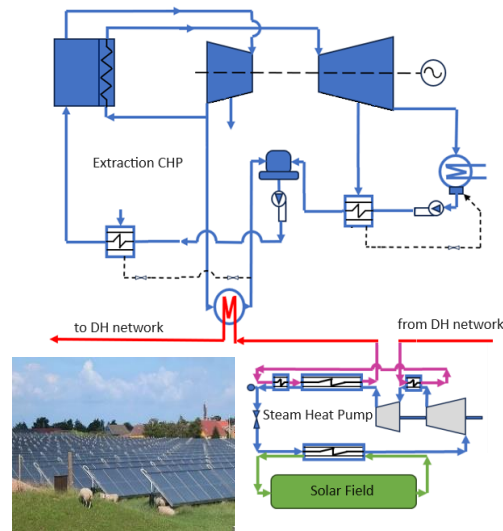| Basic reference Technology	Main exploited LGERES	Upgrading Technology
☐ Boiler ☒ CHP . ☐ New	☒ Solar ☐ Geoth.	☒ TES + ☐ VC-HP
Integration point/ DH temperatures	☐ Waste ☐ Biomass	☐ MVR ☒ ABS-HP
☐ Supply/ 120°C ☒ Return/ 60°C	☐ Other	☐ Other ☐ None
☐ None		

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)	New concept with solar field + steam Heat Pump

The considered CHP configuration (traditional coal fired, on the left) uses the steam extraction from the vapour steam turbine before going to the low-pressure turbine, to support the DH heat demand. It is possible to install an LGERES thermal field, for instance a low temperature (60 °C) flat bed solar field, in green in the schema on the right, to pre-heat the DH return line, covering a desired % of the DH thermal needs.

Due to the low temperature of the supply of this LGERES, lower to that of the return line, an upgrading technology, in the form of an heat transformer (Absorption heat pump), is implemented to elevate the water temperature up to the range 80 °C-100 °C. In this way, the heating power provided by the solar source is used both for heating the DH network and to operate the BAS-HP (in the desorption process), without any significative electrical consumption. Decreasing the thermal power extraction from the CHP economizer offers a net increase in the electrical power output, thus also increasing the CHP efficiency and the FFS.

The drawback is that a great amount of thermal energy at 60°C is needed, thus increasing a lot the surface of the solar field. In this case the FFS of the system exceeds 45%. The standalone configuration

is not so easy to be implemented since the upper temperature of the ABS-HP could be not sufficient for high temperature (120°C) DH.

Main Parameters
LGERES technology: flat plate solar field + Absorption Heat pump (ABS-HP)+TES
TRL: 9÷10 – Well established and available solar technology with some difficulties to be applied in actual application with ABS-HP. ABS-HP pilot plants could be envisaged and well come.
Operating temperature of the LGERES: bottoming solar panel up to 60°C. Topping heat transformer up to 110°C (exergy efficiency of the order of 0.35). Specific performance parameters must be defined in detailed analyses.
Operating temperature of the integration: up to 110°C, at the intermediate pressure of the economizer of the CHP.
Expected performance: FFS of the order of 35÷45% (limited due to the CHP mode of operation).
Installation costs: 2500 ÷ 4000€/kW$_t$ (thermal power delivered at the upper temperature) + (quite variable depending on the layout, size, and solar field nature).
Energy costs: The cost of thermal energy from absorption heat pumps should be rather low in the long term, however some additional cost must be added to consider relatively high maintenance costs for the combined system and great field surfaces needed. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh).

Strength	Weakness
- Ease of integration with the existing DH plant - Possibility to increase the thermal power supplied to the users - Good saving indicators and very low electric energy consumption	- Great amount of thermal energy needed at 60°C (great surface of solar collectors) - the use of heat transformers is not so well spread - Its cost is strongly affected by the field costs of the solar collectors

Main Recommendations
- Recommended for use with moderate temperature sources (<60°C). **- Recommended when an increase of the DH thermal power is desired** **- Not possible to reach the highest working temperatures of the HT-DH network**

13	**Technical Solution/Integration Strategy n. 13 HIgh temperature parabolic through solar collectors inside the boiler coupled to TES**

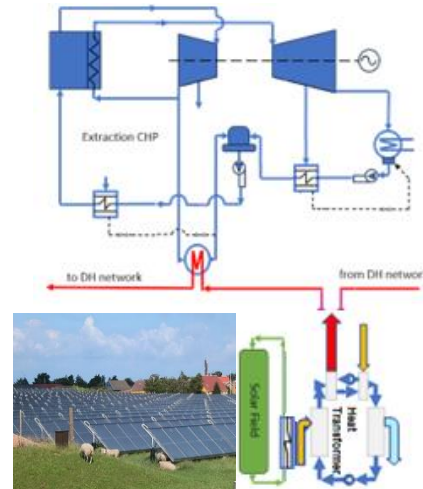| Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None (inside boiler system)	☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)

Boiler with high temperatrue solar field (parabolic through)

The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C. In respect to CHP configurations, there is not electric energy production, so that the heating system is easier to be controlled. Also, involved temperatures and pressures are lower.

It is possible to install an LGERES thermal field, in green in the schema on the right, as the preheater (economizer), covering a desired % of the DH thermal needs. To function this way, the LGERES sources must be capable to provide temperatures in the range 90°C÷ 110 °C, e.g. from a typical flat plate solar source, but it can completely substitute the boiler if the added source can provide about 130°C. So, the amount of fossil energy substitution can be very high.

The size of the LGERES source cannot exceed that of the original system, it cannot saturate the capacity of the heat exchanger. The fossil fuel savings (FFS) or the original boiler increases up to 100% as a function of the above said mode of operation: preheating or boiler substitution. Obviously, when the

boiler is completely substituted (not easily in the case of solar energy, but some industrial waste solution could be possible) by the LGERES the saving and emission reduction will reach 100%.

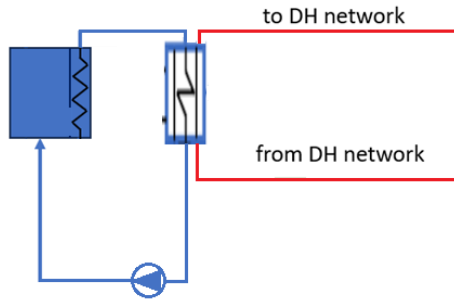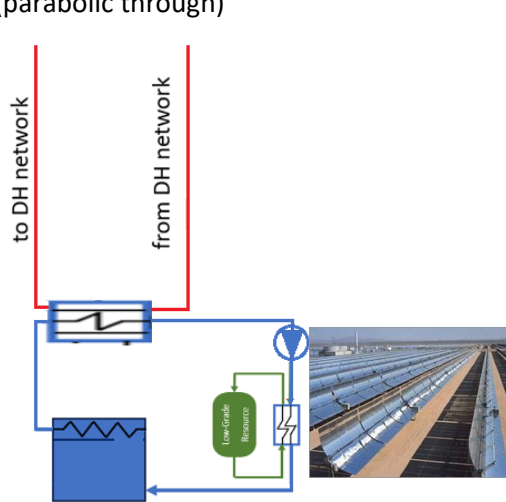| Main Parameters |
|---|
| **LGERES technology:** concentration parabolic solar collectors + high temperature TES |
| **TRL:** 10 – Well established and available solar technology |
| **Operating temperature of the LGERES:** up to 220÷240°C |
| **Operating temperature of the integration:** up to 200°C, depending on the main heat exchanger configuration. |
| **Expected performance:** FFS of the order of 40÷50% (limit due to the TES size and boiler integration needs). |
| **Installation costs:** 2000 ÷ 4000€/kW$_t$ (thermal power delivered at the upper temperature) + (quite variable depending on the layout, size, and solar field nature). Auxiliary costs (piping, heat exchangers, should be added) |
| **Energy costs:** The cost of thermal energy from parabolic solar trough systems can vary depending on several factors, including the initial investment cost, system efficiency, maintenance costs, and the local solar resource. Typically, the cost of thermal energy from parabolic trough solar systems is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g, euros per megawatt-hour, €/MWh). |

Strength	Weakness
- Ease of integration with the existing DH plant - Can replace fossil fuel use for more than 50% - Very good saving indicators	- Has small range of operating temperatures - TES and boiler (at least a small one) integration management are crucial - -Good maintenance is needed

Main Recommendations
- Recommended both for partial fossil fuel replacement. **- Requires mid temperature sources (Not implementable for use with moderate temperature sources (<80°C)).**

14	Technical Solution/Integration Strategy n. 14 Boiler pre-heating or substitution with biomass combustion

Basic reference Technology ☒ Boiler ☐ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None (inside boiler system)	Main exploited LGERES ☐ Solar ☐ Geoth. ☐ Waste ☒ Biomass ☐ Other	Upgrading Technology ☐ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)

Boiler integration or substitution with biomass or biogas burner

The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main DH exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

The considered traditional fossil fuelled configuration, is integrated, or completely substituted, by a green fuelled system. Coal, Oil, and natural gas are replaced by biogas or biomass. The main advantage is the elimination of non-green sources with net zero CO_2 emission. Since the combustion process is similar and produce similar amount of CO_2, for this approach to work the biofuel utilized must be produced in an eco-system able to remove the same amount of CO_2 from the ambient.

For example, the combustion wood cannot simply come from a pre-existing forest but the forest itself must have been planted and managed in such a way to result in additional CO_2 removal compared to the "no action" scenario (in practice, we need a doubled surface forest: one half for cut and burning, the other half for CO_2 sequestration). If this is the case, the considered system provides 100% CO_2 emission reduction in respect to the original plant, obtained with small or almost no plant modification.

Main Parameters

LGERES technology: biomass or biogas burner

TRL: 10 – Well established and available combustion technology

Operating temperature: rather high in principle, up to 220÷240° is sufficient.

Operating temperature of the integration: up to 200°C, depending on the boiler and main heat exchanger configuration.
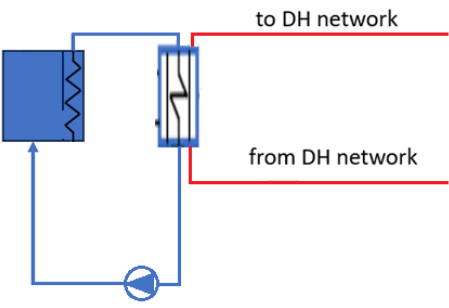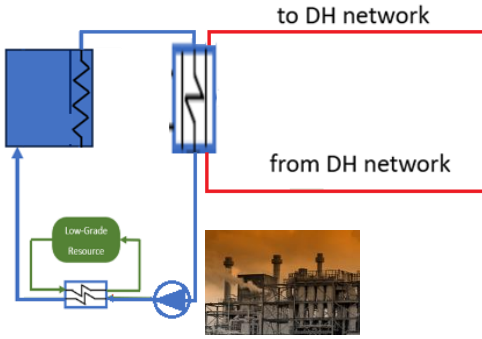
Expected performance: FFS up to 100% (with net zero emission, if the constraints so far described are satisfied).

Installation costs: 50 ÷ 100€/kW$_t$ (thermal power delivered at the upper temperature)

Energy costs: The cost of thermal energy from biogas and biomass burners is very low, even if higher in respect of oil. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., euros per megawatt-hour, €/MWh). It also includes installation and financial costs.

Strength	Weakness
- Easy to integrate with the existing DH plant. - It can completely replace fossil fuel use. - Very good saving indicators and very cheap installation.	- Biofuel is more expensive than fossil fuel. - Biomass requires large field surfaces.
Main Recommendations	
- **Recommended if properly applied**	
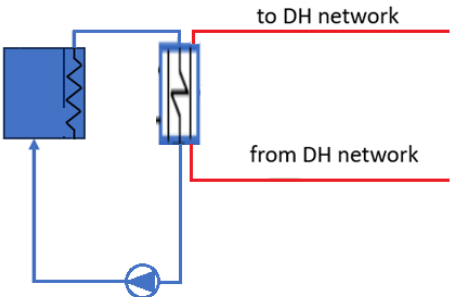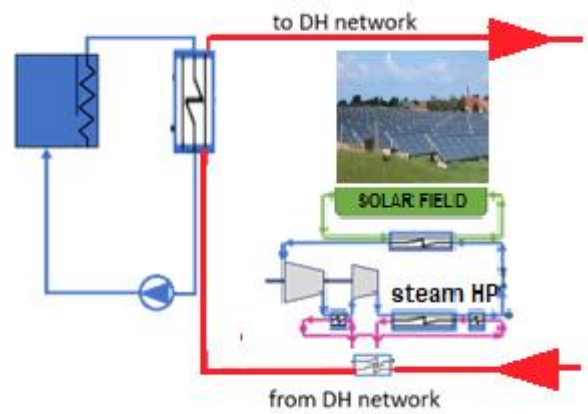
TECHNICAL SOLUTION/INTEGRATION STRATEGY N. 15 (BOILER PRE-HEATING OR SUBSTITUTION WITH INDUSTRIAL WASTE INTEGRATION)

15	**Technical Solution/Integration Strategy n. 15. Boiler pre-heating or substitution with industrial waste heat**

Basic reference Technology ☒ Boiler ☐ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None (inside boiler system)	Main exploited LGERES ☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	Upgrading Technology ☐ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)	Boiler integration with medium-high temperature industrial waste heat

The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

It is possible to install a LGERES thermal source, in green in the schema on the right, as the preheater (economizer), covering a desired % of the boiler thermal needs. To function this way, the LGERES sources must be capable to provide temperatures in the range 90°C÷ 110 °C, typical of medium-high temperature industrial waste heat (e.g. Exhaust gases from engines and turbines, heat from drying ovens, chemical reactors, and medium-pressure steam condensate), but it can completely substitute the boiler if the added source can provide about 130°C and the power level of the coupled industry is sufficient. So, the amount of fossil energy substitution can be very high.

The size of the LGERES source cannot exceed that of the original system, it cannot saturate the capacity of the heat exchanger. The fossil fuel savings of the original boiler increases up to 100% as a function of the above said mode of operation: preheating or boiler substitution. Obviously, when the boiler is completely substituted (not so easily in the case of intermittent energy source, but with some industrial waste solution it could be possible) the fossil fuel savings and emission reduction will reach 100%.

Main Parameters
LGERES technology: waste heat sources, industrial waste heat
TRL: 10 – Simple and well-established available technology
Operating temperature of the LGERES: up to 220÷240°C (depends on the waste source)
Operating temperature of the integration: up to 200°C, depending on the main heat exchanger configuration.
Expected performance: FFS up to 100%, in the limits of thermal power availability of the coupled waste heat source.
Installation costs: 500 ÷ 1500€/kW$_t$ (thermal power delivered at the upper temperature). Depending mainly on the distance between the sources.
Energy costs: Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g, euros per megawatt-hour, €/MWh). It includes also installation and financial costs.

Strength	Weakness
- Easy to integrate with the existing DH plant - It can replace fossil fuel use potentially up to 100% - Very good saving indicators	- Need industrial agreements - It is not easy to find high-power, high temperature waste heat sources - Distance between the DH network and the waste heat source

Main Recommendations
- **Recommended both for partial or total fossil fuel replacement.** - **Requires mid temperature waste sources (Not implementable for use with moderate temperature sources (<90°C)).**

TECHNICAL SOLUTION/INTEGRATION STRATEGY N. 16 (BOILER INTEGRATION OR SUBSTITUTION WITH FLAT BED SOLAR COLLECTORS WITH STEAM COMPRESSION HEAT PUMP)

<table>
<tr>
<td rowspan="2">16</td>
<td colspan="3">Technical Solution/Integration Strategy n. 16 Boiler pre-heating or substitution with flat bed solar collectors + steam HP (MVR) + TES</td>
</tr>
<tr>
<td>Basic reference Technology
☒ Boiler ☐ CHP . ☐ New
Integration point/ DH temperatures
☐ Supply/ 120°C ☒ Return/ 60°C
☐ None</td>
<td>Main exploited LGERES
☒ Solar ☐ Geoth.
☐ Waste ☐ Biomass
☐ Other</td>
<td>Upgrading Technology
☒ TES + ☐ VC-HP
☒ MVR ☐ ABS-HP
☐ Other ☐ None</td>
</tr>
<tr>
<td colspan="4">Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network</td>
</tr>
<tr>
<td colspan="4" align="center">Overall System Description</td>
</tr>
<tr>
<td colspan="2">Preexisting Plant Concept – simple boiler (simplified)

</td>
<td colspan="2">Boiler integration with medium-low temperature solar field + steap HP + TES

</td>
</tr>
<tr>
<td colspan="4">The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

It is possible to install an LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line. If the solution is the simplest flat bed solar field, the thermal integration would be very low, therefore a proper upgrading technology is required. In this case a vapour compression steam heat pump (maximum operating temperature of about 150°C). TES is mandatory.

The FFS of the base system can be incremented up to 100%. The boiler contribution is proportionally decreased while the power of the LGERES increases. At most, the boiler can be turned off. Otherwise, the systems can contribute to the overall power and the total DH capacity increased if needed.

This solution is applicable also locally, in decentralized substations.</td>
</tr>
<tr>
<td colspan="4" align="center">Main Parameters</td>
</tr>
</table>

LGERES technology: flat bed or evacuated tubes solar collectors + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES)

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: bottoming solar field up to 60÷70°C, steam HP up to 120-140°C (COP of the order of 4.5 with standard machine-assuming exergy efficiency of 0.5). Specific performance parameters must be defined in detailed analyses.

Operating temperature of the integration: up to 120°C (can be used in the form of burner integration, or as a stand-alone solution with small burner integration).

Expected performance: FFS of the order of 45÷50% (limited due to the CHP mode of operation). Up to 100% in stand-alone solution.

Installation costs: 1500 ÷ 3000€/kW$_t$ (thermal power delivered at the upper temperature). This is the cost of the thermal field + steam HP

Energy costs: The cost of thermal energy from heat pumps is rather low in the long term, however some additional cost must be added to consider relatively high maintenance costs for the combined system. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh).

Strength	Weakness
- Easy to integrate with the existing DH plant - It can replace fossil fuel use potentially up to 100% - Very good saving indicators	- It needs accurate engineering design - Not suitable for retrofitting adding a CHP system
Main Recommendations	
- **Recommended both for partial or total fossil fuel replacement.** - **Recommended when an increase of the DH thermal power is desired**	

L2H Low2HighDH

TECHNICAL SOLUTION/INTEGRATION STRATEGY N. 17 (BOILER INTEGRATION OR SUBSTITUTION WITH CONCENTRATION SOLAR COLLECTORS (PARABOLIC TROUGH WITH HIGH TEMPERATURE TES))

17	**Technical Solution/Integration Strategy n. 17 Boiler pre-heating or substitution with concentration solar collectors (parabolic trough) with high temperature TES**

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)

Boiler integration with parabolic trough solar field + high temperature TES

The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

It is possible to install an LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line. If the solution is the concentration solar trough solar field, the thermal integration can be very high, provide CO_2 a high temperature thermal energy storage (TES) is installed.

The FFS of the base system can be incremented up to 100%. The boiler contribution is proportionally decreased while the power of the LGERES increases. At most, the boiler can be turned off, being used only as a small thermal integration. The solar systems can contribute to the overall power and the total DH capacity even increased if needed.

This solution is applicable also locally, in decentralized substations.

Main Parameters

LGERES technology: concentration parabolic trough solar collectors + Thermal Energy Storage (TES)

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: up to 180-240°C. Specific performance parameters must be defined in detailed analyses.

Operating temperature of the integration: up to 240°C (can be used in the form of burner integration, or as a stand-alone solution with small burner integration).
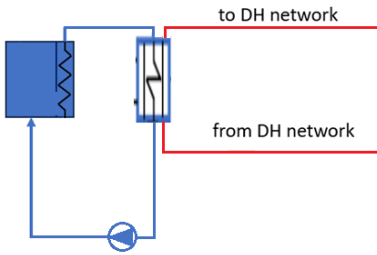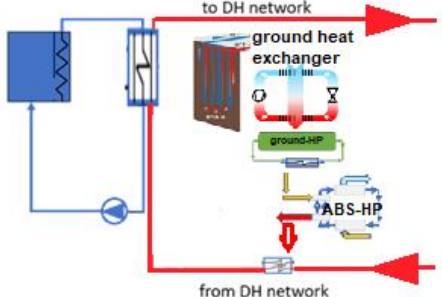
Expected performance: FFS typically up to 45÷55% in stand-alone solution with small burner integration.

Installation costs: 3500 ÷ 6000 €/kW$_{t,peak}$ (reference peak insolation 1000W/m^2)

Energy costs: The cost of thermal energy from parabolic solar trough systems can vary depending on several factors, including the initial investment cost, system efficiency, maintenance costs, and the local solar resource. Typically, the cost of thermal energy from parabolic trough solar systems is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., euros per megawatt-hour, €/MWh).

Strength	Weakness
- Easy to integrate with the existing DH plant - It can replace fossil fuel use potentially up to 80% - Very good saving indicators	- It needs accurate engineering design - TES and boiler (at least a small one) integration management are crucial - Substantial maintenance is needed
Main Recommendations	
- **Recommended both for partial and total fossil fuel replacement.** - **Recommended when an increase of the DH thermal power is desired**	

18	**Technical Solution/Integration Strategy n. 18 Boiler integraton with ground HP + ABS-HP on the DH return line**

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☐ Solar ☒ Geoth. ☐ Waste ☐ Biomass ☐ Other	☐ TES + ☒ VC-HP ☐ MVR ☒ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler	Boiler integration with ground HP + ABS.HP
(simplified)	

The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

It is possible to install an LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line. If the solution is ground field heat pump (max temperature of about 70°C), the thermal integration would be very low, due to the HP operating temperatures, therefore a proper upgrading technology is required. In this case an absorption heat transformer (maximum operating temperature of about 100÷110°C). TES is optional, bat could help system regulation. In this way, the heating power provided by the solar source is used both for heating the DH network and to operate the ABS-HP (in the desorption process), without any significative electrical consumption. Decreasing the thermal power by combustion in the boiler lead to a very good total FFS. The drawback is that a great amount of thermal energy at 60°C is needed to operate the ABS-HP, thus increasing a lot the surface of the solar field. The standalone configuration (with no boiler) is not so easy to be implemented, since the upper temperature of the ABS-HP could be not sufficient for high temperature (120°C) DH.

The FFS of the base system can be incremented up to 100%. The boiler contribution is proportionally decreased while the power of the LGERES increases. The systems can contribute to the overall power and the total DH capacity can be increased if needed.

This solution is applicable also locally, in decentralized substations.

Main Parameters
LGERES technology: ground heat pump (ground VC-HP) + Absorption Heat pump (ABS-HP)
TRL: 9÷10 – Well established and available technology with some difficulties to be applied in actual upgrading solutions. ABS-HP pilot plants should be envisaged and well come.
Operating temperature of the LGERES: bottoming ground VC-HP up to 70°C (COP of the order of 3.8 with exergy efficiency of 0.5). Topping heat transformer up to 110°C (exergy efficiency of the order of 0.35). Specific performance parameters must be defined in detailed analyses.
Operating temperature of the integration: up to 110°C, reducing the temperature drop in the boiler.
Expected performance: FFS of the order up to 45%÷50%.
Installation costs: 500 ÷ 900€/kW$_t$ (thermal power delivered at the upper temperature) + ground field heat exchanger (quite variable depending on the layout, size and ground nature).
Energy costs: The cost of thermal energy from ground source heat pump is rather low in the long term, however some additional cost must be added to consider relatively high maintenance costs for the combined system. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh), including installation and capital costs.

Strength	Weakness
- Ease of integration with the existing DH plant - It can replace fossil fuel use potentially up to 85% - Very good saving indicators	- It needs accurate engineering design - The use of heat transformers is not so well spread - Its cost is strongly affected by the ground field heat exchanger configuration.

Main Recommendations
- Reasonably recommended for partial fuel replacement.   **- Recommended when an increase of the DH thermal power is desired**   **- Very high installed heat powers of the ground-HP are needed to operate the ABS-HP**

19	**Technical Solution/Integration Strategy n. 19. Boiler pre-heating or substitution with medium/low teperature WASTE Heat + steam HP (MVR) + TES (optional)**

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	☐ TES + ☒ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station   ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)	Boiler integration with medium/low temperature solar field + steap HP + TES (optional)

The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

It is possible to install an LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line. To function this way, the LGERES sources must be capable to provide temperatures in the range 90°C÷ 110 °C, typical of medium-high temperature industrial waste heat (e.g. Exhaust gases from engines and turbines, heat from drying ovens, chemical reactors, and medium-pressure steam condensate), but it cannot completely substitute the boiler if the added source cannot reach about 130°C. Furthermore, the power level of the coupled industry must be enough. If the solution is a low/medium temperature (industrial) waste heat, the thermal integration would be very low, therefore a proper upgrading technology is required. In this case a vapour compression steam heat pump (maximum operating temperature up to about 150°C). TES is optional, depending on the continuous or intermittent regime of the waste heat source.

The FFS can be incremented up to 100%, the same for the fuel saving, the boiler contribution is proportionally decreased while the power of the LGERES increases. At most, the boiler can be turned off. Otherwise, the systems can contribute to the overall power and the total DH capacity increased if needed.

This solution is applicable also locally, in decentralized substations, near the waste heat source.

Main Parameters
LGERES technology: waste heat sources + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES)
TRL: 10 – Well established and available technology. Need accurate engineering design.
Operating temperature of the LGERES: waste source in the range 60÷90°C, steam HP up to 120-140°C (COP of the order of 4.5 with standard machine-assuming exergy efficiency of 0.5). Specific performance parameters must be defined in detailed analyses.
Operating temperature of the integration: up to 120°C (can be used in the form of burner integration, or as a stand-alone solution with small burner integration). The main data driving potential application is based on temperature and power level of the waste heat source.
Expected performance: FFS typically about 50%, but the use of MVR and its electrical energy consumption must be considered. Smaller FFS are expected if the waste heat source is intermittent.
Installation costs: 500 ÷ 1500€/kW$_t$ (thermal power delivered at the upper temperature). This is the cost of the steam HP + fluid lines to connect the waste heat plant.
Energy costs: The cost of thermal energy from heat pumps is rather low in the long term, however some additional cost must be added to account for relatively high maintenance costs for the combined system. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh).

Strength	Weakness
- Easy to integrate with the existing DH plant - It can replace fossil fuel use potentially up to 100% - Very good saving indicators	- It needs accurate engineering design - It is not easy to find high-power, high temperature waste heat sources - Distance between the DH network and the waste heat source

Main Recommendations
- **Recommended both for partial or total fossil fuel replacement.**

20	**Technical Solution/Integration Strategy n. 20 Boiler pre-heating or substitution medium temperatrue LGERES + steam HP (MVR) + TES**

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP . ☒ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	☒ TES + ☐ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminates (simplified)

Boiler integration with medium temperature LGERES + steap HP + TES

This data sheet summarizes the potential substitution of traditional burners with a completely LGERES at medium temperature (not less than 50÷60°C).

The considered traditional coal fired configuration is completely substituted by an LGERES source. It is possible to install a low-grade thermal source, for instance a low temperature (50÷60 °C) solar field, in green in the schema on the right, to heat the DH return line, covering a desired % of the DH thermal needs. Due to the low temperature supplied by the LGERES, lower than that of return line, an upgraded technology, in the form of a steam heat pump, is implemented to elevate the return water temperature up to the range 110 °C-120 °C of delivery to the DH network. In this way, a portion of the district heating power is provided by the solar source, the other by the compressor power. The temperature increase provided by the LGERES guarantee a good working and efficiency of the MVR. The axial flow steam compressor used in this type of heat pump have typically an efficiency around 0.8, resulting in COP value from 3.5 up to 4. This upgrading arrangement provides the full DH needs with consistent fuel saving of the order of 70%-100% depending on the implementation (the electrical consumption of the HP cycle must be carefully considered). The system can work also with other low-grade sources like intermittent waste heat coming from shopping mall.

This solution is applicable also locally, in decentralized substation operating as an independent DH subnetwork.

Main Parameters
LGERES technology: medium temperature LGERES + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES).
TRL: 10 – Well established and available technology. Need accurate engineering design.
Operating temperature of the LGERES: at least 50÷60°C, steam HP up to 120-140°C (COP of the order of 4.5 with standard machine, assuming exergy efficiency of 0.5). Specific performance parameters must be defined in detailed analyses.
Operating temperature of the upgrading: up to 140°C. The use of a high temperature TES is mandatory.
Expected performance: FFS of the order of 80% in respect of traditional boiler, up to 100% for complete boiler substitution case.
Installation costs: 1500 ÷ 3000€/kW$_t$ (thermal power delivered at the upper temperature). This should be the cost of LGERES + steam HP + TES
Energy costs: The cost of thermal energy from heat pumps is rather low in the long term, however some additional cost must be added to weigh up relatively high maintenance costs for the combined system and the cost of a big high temperature TES. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh), including installation and capital costs.

Strength	Weakness
- Ease of integration with the existing DH plant - It can replace fossil fuel use potentially up to 80% - Very good saving indicators	- It needs accurate engineering design - It needs electric energy (for the compressors) - Good high temperature TES
Main Recommendations	
- **Recommended for extensive fossil fuel replacement.**	

21	**Technical Solution/Integration Strategy n. 21. Boiler substitution by means of aerobic digestor + steam HP (MVR) + TES (optional)**

Basic reference Technology ☒ Boiler ☐ CHP . ☒ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	Main exploited LGERES ☐ Solar ☐ Geoth. ☐ Waste ☒ Biomass ☐ Other	Upgrading Technology ☐ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminates (simplified)	New concept: Boiler substitution with medium temperature aerobic digestor + steam HP + TES

The considered traditional coal fired configuration is completely substituted by an LGERES source represented by an aerobic digestor which represents a low-grade thermal source at about 70°C. Due to the low temperature supplied by the LGERES, similar to that of return line, an upgrading technology, in the form of a steam heat pump, is implemented to elevate the water temperature up to the range 110 °C-120 °C. In this way, a portion of the district heating power is provided by the digestor, the other by the compressor power (electrical energy). The axial flow steam compressor used in this type of heat pump have typically an efficiency around 0.8, resulting in COP values from 3.5 up to 4. This upgrading arrangement provides the full DH needs with consistent fuel saving typically of the order of 80% up to 100% (complete substitution) but the electrical consumptions of the HP systems must be accounted for, which evaluation must be carefully considered, based on actual working temperatures. Usually integrated by a small burner also for regulation purpose. Due to the oxidation processes, dioxide (CO_2) and nitrous oxide (N_2O) are produced, while CO_2 is also emitted to produce the energy required for the system operation. Efforts to reduce these emissions and to capture it are possibly required

This solution is applicable also locally, in decentralized substation operating as an independent DH subnetwork.

Main Parameters

LGERES Technology: low temperature aerobic digestor + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES), optional.

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: digestor at 50÷70°C, steam HP up to 120÷140°C (COP of the order of 4. with standard machine, assuming exergy efficiency of 0.5). Specific performance parameters must be defined in detailed analyses.

Operating temperature of the upgrading: up to 140°C. The use of a good high temperature TES is not mandatory (and not shown in the figure), but welcome.

Expected performance: FFS of the order of 70% to 100% (complete substitution) in respect of traditional boiler.

Installation costs: 500 ÷ 1000€/kW$_t$ (thermal power delivered at the upper temperature). The aerobic digestor is assumed to be already existent, or any way supported by municipal funding.

Energy costs: The cost of thermal energy from heat pumps is rather low in the long term, however some additional cost must be added to consider relatively high maintenance costs for the combined system. Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g. euros per megawatt-hour, €/MWh), including installation and capital costs.
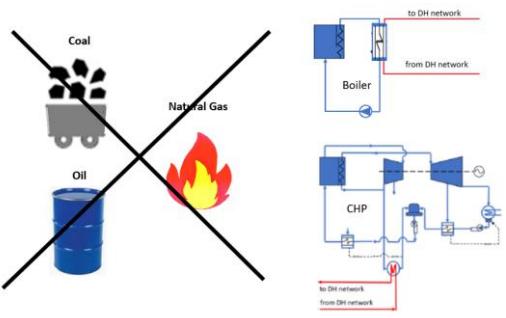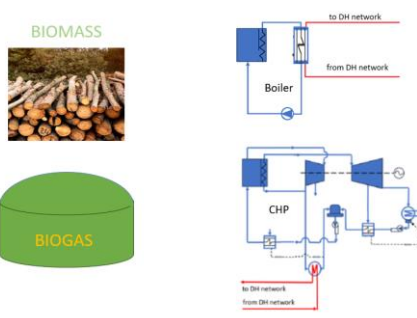
Strength	Weakness
- Very good saving indicators - In principle, it does not need a thermal storage system.	- It needs electric energy (for the compressors) - The produced CO_2 should be captured
Main Recommendations	
Recommended with preexisting aerobic digestor only	

TECHNICAL SOLUTION/INTEGRATION STRATEGY N. 22 (BOILER SUBSTITUTION WITH GEOTHERMAL HEAT PUMP + STEAM COMPRESSION HEAT PUMP (MVR CLOSED CYCLE))

Page | 86

22	**Technical Solution/Integration Strategy n. 22. Boiler substitution with Ground source Heat Pump + steam heat pump (MVR closed cycle)**

Basic reference Technology ☒ Boiler ☐ CHP . ☒ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	Main exploited LGERES ☐ Solar ☒ Geoth. ☐ Waste ☐ Biomass ☐ Other	Upgrading Technology ☐ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location):　☒ central heat station　　☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminated (simplified)	New concept : Boiler substitution with Ground source Heat Pump + steam heat pump (MVR closed cycle) integration

This data sheet summarizes the potential substitution of traditional burners with a completely LGERES at low temperature (down to 5÷10°C).

The considered traditional coal fired configuration is completely substituted by an LGERES source represented by the ground, aided by a geothermal heat pump. This system transforms and upgrades ambient heat from ground at about 10 °C to a more manageable and valuable temperature of 50°÷60C, which however still represents a low-grade thermal source. So, the output of this first stage must be further upgraded by means of some technology: an absorption heat pump, an MVR or a water steam heat pump (in figure) to reach the higher temperatures required by the DH network, up to 110 °C÷120 °C. A fraction of the district heating power is provided by the ground, the other by the electric power consumed by the compressors. Although the modern heat pumps involved are characterized by high COPs, the combination of the two upgrades usually gives a global COP not higher than 2.5. The presented arrangement provides a fuel saving of the order of 70% up to 100% in case of complete substitution. Fine calculations must be performed for detailed analysis.

This technical solution can be applied also locally, in decentralized substation operating as an independent DH subnetwork.

Main Parameters
LGERES technology: ground heat pump (VC_HP) + steam compression heat pump (MVR close cycle).
TRL: 10 – Well established and available technology, but detailed engineering design is needed.
Operating temperature of the LGERES with integration: the first stage geothermal heat pump reaches 50÷60°C, the other MVR closed cycle goes up to 150÷170 C°.
Operating temperature of the integration: up to the pre-DH working temperatures.
Expected performance: FFS up to 100%, but the electrical consumptions of the HP systems must be accounted for, which evaluation must be carefully considered, based on actual working temperatures (the order of magnitude of the total COP_{HP} is 2.5).
Installation costs: 350 ÷ 400 €/kW$_t$ (VC-HP) + 400 ÷ 500€/kW$_t$ (steam VC-HP) + ground field heat exchanger (strongly variable based on the configuration)[3].
Energy costs: Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., eros per megawatt-hour, €/MWh).

Strength	Weakness
- Good saving indicators - Consolidated technology - It does not need a thermal storage system, unless different intermittent sources are used (solar, waste)	- It needs an external electric source for the compressors. - Complex upgrading technology (detailed engineering design is needed).

Main Recommendations
- Recommended for use with very low temperature sources (10°C)

---

[3] https://oilon.com/en-gb/products/oilon-chillheat-s-600-s-2000/

TECHNICAL SOLUTION/INTEGRATION STRATEGY N. 23 (BOILER: FOSSIL FUEL SUBSTITUTION WITH BIOMASS OR BIOGAS FUELS)

23	Technical Solution/Integration Strategy n. 23. Substitution of fossil fuels with biomass or biogas fuels in boilers

Basic reference Technology ☒ Boiler ☐ CHP . ☒ New Integration point/ DH temperatures ☐ Supply/ 120°C ☐ Return/ 60°C ☒ None (just fuel change)	Main exploited LGERES ☐ Solar ☐ Geoth. ☐ Waste ☒ Biomass ☐ Other	Upgrading Technology ☐ TES + ☒ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location):   ☒ central heat station   ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel to be eliminated (simplified, e.g.)	New concept: fuel substitution with biomass or biogas (simplified, e.g.)

This data sheet summarizes the potential substitution of fuels in traditional boiler (burners).

The considered traditional fossil fuelled configuration, simple Boiler or CHP system, is completely substituted by a green fuelled system. Coal, Oil and natural gas are replaced by biogas or biomass. The main point to favour this implementation is the elimination of non-green sources with a complete elimination of net CO_2 emission. Since the combustion process is similar and produce similar amount of CO_2, for this approach to work the biofuel utilized must be produced in way that removes the same quantity of CO_2 from the ambient. For example, the used wood cannot simply come from a pre-existing forest but the forest itself must have been planted and managed in such a way as to result in additional CO_2 removal compared to the "no action" scenario. If this is the case, the considered system provides 100% CO_2 emission reduction in respect to the original plant, obtained with small or nothing plant modification.

This technical solution can be applied also locally, in decentralized substation operating as an independent DH subnetwork.

Main Parameters
LGERES technology: ground heat pump (VC_HP) + steam compression heat pump (MVR close cycle).   **TRL:** 10 – Well established and available technology, but detailed engineering design is needed   **Operating temperature of the LGERES with integration:** the first stage geothermal heat pump reaches 50÷60°C, the other MVR closed cycle goes up to 150÷170°C°.   **Operating temperature of the integration:** up to the pre-DH working temperatures.   **Expected performance:** FFS of the order of 60%, or even more, including the electrical consumptions of the HP systems, which evaluation must be carefully considered, based on actual working temperatures (the order of magnitude of the total COP_{HP} is 2.5).   **Installation costs:** 350 ÷ 400 €/kW$_t$ (VC-HP) + 400 ÷ 500€/kW$_t$ (steam VC-HP) + ground field heat exchanger (strongly variable based on the configuration)[4].   **Energy costs:** Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., eros per megawatt-hour, €/MWh).
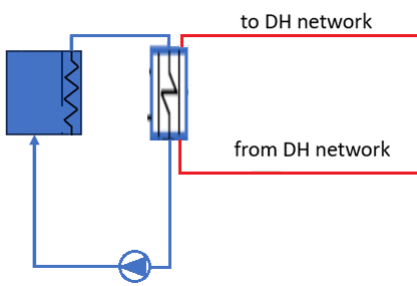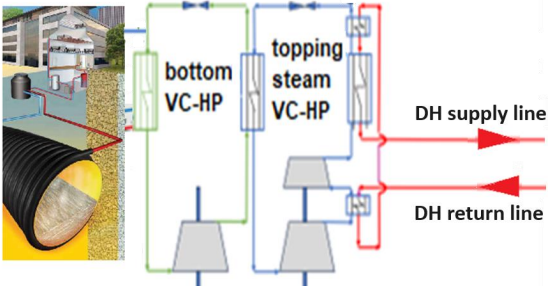
Strength	Weakness
- - Very Good saving indicators - Consolidated technology - It practically doesn't system modifications)	- biofuel must be obtained with proper procedure. - biofuel is more expensive than fossil fuel

Main Recommendations
Recommended if properly applied

---

[4] https://oilon.com/en-gb/products/oilon-chillheat-s-600-s-2000/

24	**Technical Solution/Integration Strategy n. 24. Boiler integration with sewage waste heat + Heat Pump + steam heat pump (MVR closed cycle)**

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP . ☒ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	☐ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminated (simplified)

New concept : Boiler substitution with sewage waste heat + Heat Pump + steam heat pump (MVR closed cycle) integration

This data sheet summarizes the potential substitution of traditional burners with a completely LGERES at low temperature (down to 15÷20°C).

The considered integration is based on an in-tube heat exchanger for sewage water exploitation (typically in local district or building solutions) coupled to VC-HP system, (the sewage water is usually a higher temperature of environment, say 15°C on average, and the VC-HP can reach temperatures of about 60°C). Once the local temperature is the same of the return line of the DH network, a topping steam VC-HP (MVR closed cycle), up to 150°C can be added, be it in the central station or locally. The availability of sewage waste heat is supposed to be 15% of the DH heating power. Higher values are unlikely.

Despite the availability of "free" heat power from the sewage heat exchanger, the upgrading process is energy-intensive and, for each MW_{th} supplied to the user, an electric power from 0.3 to 0.4 MWe are needed by the devices' compressors.

Some plant retrofit is necessary to maximize performance. The use of is necessary, due to the discontinuous availability of environmental energy from waste sewage water.

Since electric power is needed the Fossil fuel saving ranges from 20% to 30%, but it could be higher if the electricity used to operate the compressors is "green".

This technical solution can be applied also locally, in decentralized substation operating as an independent DH subnetwork.

Main Parameters

LGERES technology: heat pump (VC_HP) + steam compression heat pump (MVR close cycle)

TRL: 10 – Well established and available technology, but detailed engineering design is needed

Operating temperature of the LGERES with integration: the first stage geothermal heat pump reaches 50÷60°C, the other MVR closed cycle goes up to 150÷170 C°.

Operating temperature of the integration: up to the pre-DH working temperatures.

Expected performance: FFS up to about 30%, including the electrical consumptions of the HP systems, which evaluation must be carefully considered, based on actual working temperatures (the order of magnitude of the total COP_{HP} is 2.5).

Installation costs: $350 \div 400$ €/kW$_t$ (VC-HP) + $400 \div 500$€/kW$_t$ (steam VC-HP) + sewage waste heat exchanger.

Energy costs: Typically, the cost of thermal energy is measured in terms of the levelized cost of heat (LCOH), which is the average cost of producing one unit of heat over the lifetime of the system, expressed in terms of cost per unit of energy (e.g., eros per megawatt-hour, €/MWh).

Strength	Weakness
- Good saving indicators - Consolidated technology - It does not need a thermal storage system, unless different intermittent sources are used (solar, waste).	- It needs an external electric source for the compressors. - Complex upgrading technology (detailed engineering design is needed).

Main Recommendations
- Recommended for use with very low-mid temperature sources (10°C-20°)

ANALYSIS CRITERIA AND ENERGY AND FINANCIAL KPI

INTRODUCTION

In this section, we aim to specify the methodology used to implement simplified energy models of heat sources for District Heating networks, starting from the users' needs in terms of thermal power and temperature, and then tracing back to the energy source to be sized, i.e., characterized in terms of thermal source power and working temperatures. This source could be low-grade, or an existing traditional source in the case of retrofitting, which involves partial or complete preservation of the original heat/energy source. Combined Heat and Power (CHP) are highly efficient solutions for simultaneously generating electricity and thermal energy from a single fuel source. So, it is not unlikely that the district heating plant to be addressed has a CHP as thermal source or, at the very least in early plants, a simple boiler with a considerable number of years of active service ahead. As shown in detail in previous sections, and in the report D2.1 of the Low2HighDH WP2, the three target countries Lithuania, Poland, and Slovakia, even with very different DH situations, has roughly 50% CHP and 50% boiler thermal sources for their DH networks.

Besides the source and users, the network can feature two types of systems: energy integration systems and temperature upgrading systems. The following paragraphs present the energy modelling aspects of the network and proceed by outlining the energetic and economic/financial performance parameters used for its characterization. Even if quite simplified and based mainly on global benchmark characteristics of systems and components, this energy model is detailed enough to have an idea of the main Key Performance Indexes (KPI) of each potential solution, to guide the managers and project partners decisions about the best choice to be done in their country and which specific solution is worth to be deepened and applied.

The model will be applied to 10 specific cases to assess their overall performance.

DH NETWORK BASIC THERMAL MODELLING

The methodology proceeds according to the following steps:

- According to Figure 21, a known thermal power consumption by the users, $\dot{Q}_{DH}$, is assumed along with a heat loss from the network. Starting from the received power and summing up the dissipation, $\dot{Q}_{Loss}$, the required power at this level (let us say the demand side), which will be slightly higher, can be obtained as $\dot{Q}_{NET}$. At the same time, by imposing the known supply and return temperatures (T_{DH} and T_{Ret}), the flow rate can be derived, as shown by the steady state energy balance equations.

$$\dot{Q}_{DH} = \dot{m}\left(T_{DH} - T_{Ret}\right) \tag{1}$$

$$\dot{Q}_{DH} = \dot{Q}_{NET} - \dot{Q}_{Loss} \tag{2}$$
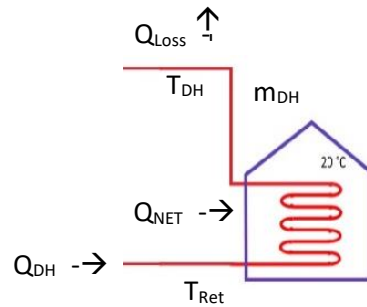
Figure 21 - Demand side of the DH network. Heat powers, temperatures, and DH mass flow rate in evidence (credit: Unige)

- Continuing to trace the network backward towards the energy source, we will encounter temperature upgrading systems, as per Figure 22, and power integration systems. The temperature upgrading might be placed either before or after the power integration systems (see later), depending on various factors. Temperature upgrading systems are typical in a LOW2HIGH system, where a low-grade thermal source, usually at a low temperature, must be upgraded to supply a high-temperature heating to the user. Power integration, on the other hand, is used when the so-called "primary" source is unable to meet the users' energy demands covering 100% of heating needs. In such a case the support of one or more supplementary sources is required. Furthermore, LGERES integration is welcome to decrease fossil fuel consumption. It is also conceivable that the DH system is designed to use multiple sources, integrating several different sources that may already be available and suitable for use in that precise actual context.
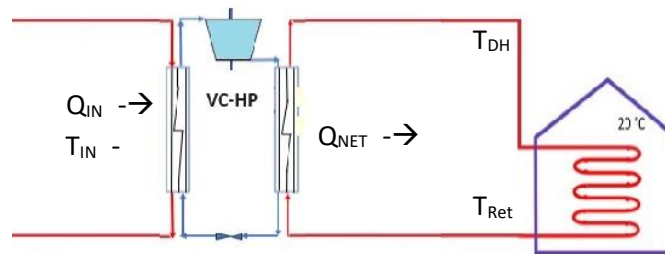
Figure 22 - Part of the DH network highlighting a temperature upgrading device, in this case a heat pump (credit: Unige)

To focus on a specific configuration, we will assume that, tracing backward, the temperature upgrading system is first encountered. Again, integration will be placed on the return line or in the supply line depending primarily on the relative temperatures. This does not affect the modelling procedure and setup. Thus, as previously discussed, we know the temperatures at the user end and will have an average temperature, currently unknown, which we could set as a trial value at the input of the upgrading tool. This tool typically consists of heat pumps, mechanical vapor recompression, or absorption heat pumps. Unlike T_{DH} and T_{Ret}, an average inlet/outlet temperature will be assumed at the interface of the heat exchangers, always referring to the external heating line. The thermal, Q_{in}, and mechanical (if present) power inputs to the upgrading tool will be a function of still unknown quantities such as the COP of the machine and the inlet temperature, T_{in}, which we have seen as a guess value. We will delve deeper into the methodology underlying the COP calculation later.
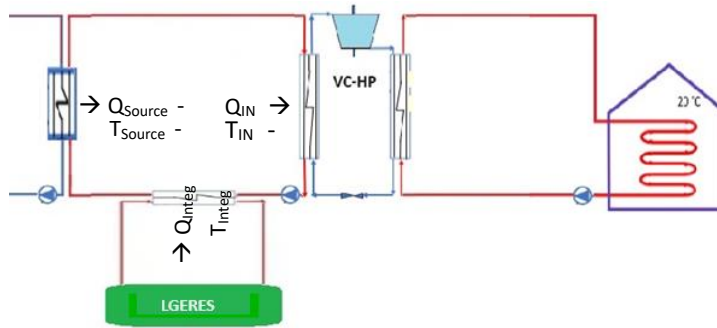
Figure 23- Part of the DH network with LGERES integration before the upgrading and applied on the return line (credit: Unige)

- After that, we proceed with thermal integration, see Figure 23. If present, it is often applied on the return line of the district heating network. The application on the return line or on the supply line depends essentially on the temperature of the integration relative to that of the source. Moreover, the integration could be upstream or downstream of the temperature upgrading devices also due to location constraints. This integration might involve a renewable thermal source, such as a solar field, a geothermal source, or waste heat from industrial or other processes. The integration could be direct, as shown in Figure 23, or it might also have undergone a dedicated upgrade using, as before, a heat pump device of the previously mentioned type. The power and supply temperature characteristics of the integration are generally known. The temperature of the primary source is also generally known, but the associated power is not. From this perspective, we assume that T_{integ} and Q_{integ} are known (or somehow calculated) so that, to proceed, a guess value for T_{in} is assumed and Q_{in} will be derived, which will allow for the calculation of the necessary Q_{source}. If required, an iterative process is automatically applied by the Excel sheet, since, sometimes, not all variables can be derived sequentially, one after the other. In this last case, two or three iterations will be needed to bring the calculation algorithm to convergence.

As said, the temperatures used by the model are the average inlet/outlet temperatures of the heat exchangers on the water side, i.e., on the DH network side.

Modelling of Temperature Upgrading systems

Each upgrading element is modelled by defining a COP (Coefficient of Performance) and calculating various energy elements, which may include thermal powers at the input and output, and possibly mechanical/electrical powers as in the case of traditional vapor compression heat pumps. Additionally, for systems like heat transformers (absorption devices), we might have heat input at an intermediate temperature and high-temperature thermal power output, but also the release of a significant amount of heat at ambient temperature. This fact must always be considered when discussing the potential application of absorption heat pumps, as one of the critical aspects of these machines is the dissipation of low-temperature heat, which necessitates oversizing the upstream sources.

To model these systems, we need to identify all energy quantities, whether thermal or mechanical powers. With reference to Figure 24 these quantities are linked by the first law of thermodynamics and performance coefficients, efficiencies, or COPs for these types of devices. These coefficients can be expressed, as we will see, as a function of the various temperatures involved. These COPs, which will

represent the model of the upgrading tool, can be defined by referring to the performance of an ideal Carnot cycle operating between the same internal (not source) temperatures of the given cycle. For example, a simple heat pump will have a COP characterized by an amplification ratio between the mechanical power input and the cooling power input (the refrigeration effect), or the heating power output (the heating effect). Once the energy exchange elements are identified, we also will have all the necessary components to associate a primary energy consumption with the considered device

COP definition and use

The reference is always the ideal COP of the Carnot machine, a cycle that appears as a rectangular shape in the *T-S* plane (temperature-entropy thermodynamic plane of the working fluid), which will be the most efficient possible, temperatures given, according to the second law of thermodynamics. There is always some discretion in selecting the reference temperatures that characterize this cycle, primarily due to the intended use of the COP in view of a useful comparison with the actual cycle. From a strictly thermodynamic point of view, the temperatures of the Carnot cycle should correspond to the temperatures of the thermal sources for the real cycle. However, in this case, the ratio between the COP Carnot value and the actual COP also accounts for exergetic dissipation that occurs in the exchange process, particularly dependent on the quality of the heat exchangers.

If one wants to focus on the vapor compression cycle, this characteristic can be, though a bit improperly, avoided by directly referring to the phase transition temperatures of the fluid at the evaporator and condenser, respectively T_{eva} and T_{cond}. The ratio between the actual COP and the Carnot COP provides a parameter called the second law efficiency (η_{II}), which effectively characterizes the machine's performance (Scarpa, et al., 2013) (Scarpa, et al., 2013) (Tagliafico, et al., 2014). For a given device, this parameter, if expressed as indicated above, is relatively constant during the operations of the device. So, we can express the COP as η_{II} multiplied by the Carnot COP as:

$$COP_{\mathrm{Refrig}} = \eta_{II} \cdot COP_{Carnot} \tag{3}$$

However, since we are adopting the "heat pump" view, we will write:

$$COP = 1 + \eta_{II} \cdot COP_{Carnot} \tag{4}$$

$$COP = 1 + \eta_{II} \cdot \frac{T_{eva}}{T_{cond} - T_{eva}} \qquad \text{with temperature in Kelvin} \tag{5}$$

$$COP = 1 + \chi\rho_c \cdot \frac{T_{eva}}{T_{cond} - T_{eva}} \tag{6}$$
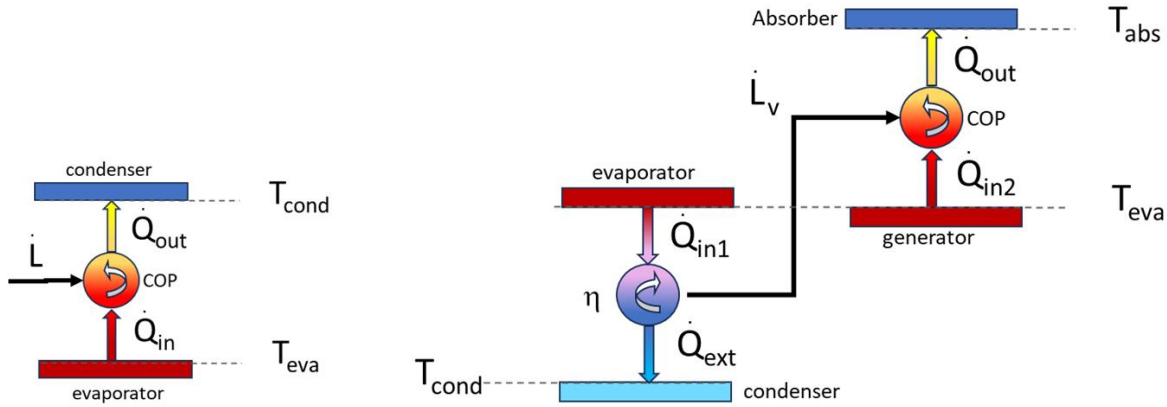
Figure 24 – Two-temperature schematic representation of a simple vapor-compression heat pump, on the left, and of a three-temperature absorption heat pump made by two devices, on the right (credit: Unige)

The most variable part will be the Carnot COP, while η_{II}, as per Eq. 6, will depend primarily on the isentropic efficiency of the compressor (ρ_c), the characteristics of the fluid, the cycle configuration, and the operating conditions. In any case, η_{II} shoes little variation, around 0.5, but it is higher for large compressors with high ρ_c, and it naturally depends on the plant size which is related to the compressor efficiency.

Validation

This type of representation, this modelling has been validated by comparing the results obtained with this simplified model, implemented in an Excel spreadsheet, with those obtained using specialized thermodynamic software for solving direct and inverse cycles. The model used is shown in the following Figure 25. The left figure (A) shows a schematic of a water (steam) vapor compression heat pump operating at various temperatures.

This type of heat pump is suitable for high temperatures and is usually used as the second stage of a cascade system. Additionally, a two-stage compressor was used to improve performance, along with inter-cooling and sub-cooling achieved using the return flow from the district heating system.
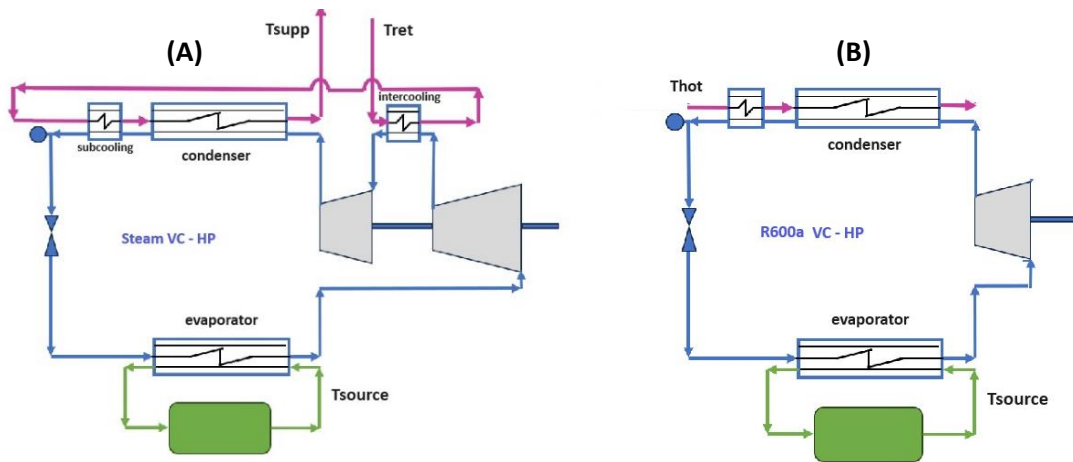
Figure 25- Model schematics used to validate the Carnot/η_{II} representation of the devices. Steam VC-HP double compression water heat pump on the left (A). Simple R600a VC-HP on the right (credit: UNIGE)

In the associated table, we can see the comparison between the COP (Coefficient of Performance) values resulting from both simulations: the one conducted using the model implemented in Excel and the more sophisticated one obtained using the complete thermodynamic model. By keeping constant the supply temperature, T_{supply}, at 120°C and the return temperature from the heating network, T_{RET}, at 60°C, the lower source temperature, T_{source}, was varied between 50°C and 70°C. Percentage errors were found to be less than 3%.

In the second table, the results for the low-temperature heat pump using R600a (Figure 25 (B)) are presented. This type of device is used at low temperatures, typically as the first stage before a subsequent stage of either a Steam HP, Heat Transformer, or MVR. In this case, the source temperature, T_{source}, was kept constant at 20°C, and the temperature on the hot side (typically the evaporator of the next stage) was varied between 50°C and 70°C. Percentage error exceeded 7% in the worst case.

For both machines, an isentropic efficiency of 0.7 was assumed for the compressor. The temperature differences in the heat exchangers were assumed to match those of the Excel model, with a source inlet-outlet difference of 15°C. The η_{II} values were adjusted to achieve balanced performance.

Table 2 - Validation process. Comparison between simple model of Eq.5 and a complete thermodynamic model. The table refers to high Temp Steam heat pump reported in Figure 25(A). T_{supply}= 120 °C, T_{return}= 60 °C.

T_{source} [°C]	COP	COP Simplified	Difference
50	3.15	3.23	2.6%
55	3.37	3.41	1.2%
60	3.61	3.60	-0.2%
65	3.89	3.82	-1.6%
70	4.20	4.07	-3.0%

Table 3 – Validation process. The same of Table 1 with reference to the R600a heat pump of Figure 25(B) used as first stage temperature upgrade. T_{source} = 20 °C

T_{hot} [°C]	COP	COP Simplified	Difference
50	4.09	3.82	-6.6%
55	3.68	3.56	-3.3%
60	3.34	3.34	0.0%
65	3.05	3.16	3.6%
70	2.79	3.00	7.4%

Absorption heat pump

In the case of an absorption heat pump or a heat transformer, a three-temperature level description will be followed, combining a power cycle associated to a virtual work L_v (not physically present in the absorption heat pump, but ideally performed by the absorption/desorption processes) and a cooling cycle as illustrated in Figure 24 (right).

For simplicity, considering a single intermediate temperature T_{eva}, we can distinctly write the previously defined parameters for each of the two cycles (the direct one and the inverse one).

$$\dot{L}_v = \eta \, \dot{Q}_{in1} \qquad\qquad \eta = \eta_{mII}\left(1 - \frac{T_{cond}}{T_{eva}}\right) \tag{7}$$

$$\dot{Q}_{out} = \dot{L}_v + \dot{Q}_{in2} = (1 + COP_F)\cdot \dot{L} \qquad\qquad COP_F = \eta_{II}\left(\frac{T_{eva}}{T_{abs} - T_{eva}}\right) \tag{8}$$

$$\dot{Q}_{in2} = COP_F \cdot \dot{L}_v \tag{9}$$

Defining the following as the merit parameter for an absorption heat pump:

$$\eta_{ABS} = \frac{Q_{out}}{Q_{in1} + Q_{in2}} \tag{10}$$

For the Heat Transformer (HT) It will be

$$\eta_{HT} = \frac{(1 + COP_F)\cdot L_v}{L/\eta + COP_F \cdot L_v} \qquad = \frac{\eta(1 + COP_F)}{1 + \eta COP_F} \qquad \eta < \eta_{ABS} < 1 \tag{11}$$

The physical interpretation of this result emphasizes the fact that the heat transformer exploits a large amount of heat at an intermediate level (T_{eva}, which is the temperature at which the low-grade energy resource is available) to upgrade it to a higher temperature level T_{abs}, but with a lower available total amount. A lot of the low-grade energy resource is discharged to the lowest environmental temperature (represented by T_{cond} in the right side of Figure 24).

Let us observe that the schemes of Figure 24 try to keep the nomenclature to understand the thermodynamic processes but change the application meanings of the working temperatures. Indeed, in the same figure, T_{eva} represents the low-grade energy resource temperature, but in the vapor compression heat pump on the left T_{cond} represent the heat temperature after upgrading (that is the district heating working temperature), while on the right it is the lower heat transformer temperature (that is the environmental temperature). In the schema on the right the district heating working temperature is represented by T_{abs}.

The trend as a function of COP$_F$, shown in the following Figure 26, recommends high values of COP$_F$ and efficiency. In fact, in terms of temperatures, to achieve high values of η_{HT} (the fraction 1-η_{HT} will be dissipated towards the environment), and considering that the source temperature Text and Tout are generally fixed, high values of Tin will obviously be required, resulting in small temperature increase (upgrade). In any case, given the temperatures involved in the virtual machine, the values of η are very small, sometimes less than 0.1, and as a consequence low values of η_{HT}, resulting in the dissipation of large amounts of heat into the environment, from 50% up to 80%. Therefore, the practical use of heat transformers can be highly problematic, unless very cheap (or free) and large amounts of energy are available at the intermediate temperature of the heat transformer (T_{eva} in Figure 24, right).

In the case of the Absorption Heat Transformer, the model expressed by Eqs. 7-11 will be less accurate due to the complexity of the transformations and because the phase-change temperatures at constant

pressure no longer occur at a constant temperature but exhibit a significant gradient, known as glide. This glide makes it difficult to apply the simple models used previously, which provide acceptable results for traditional heat pumps.
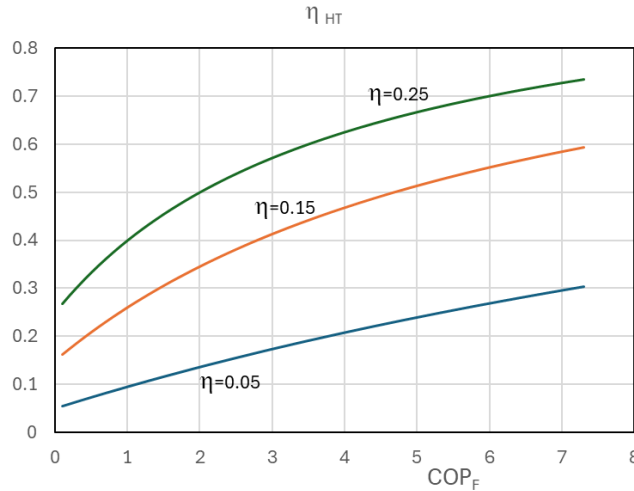
Figure 26 – Dependence of the overall efficiency of the absorption heat pump on η (the virtual machine efficiency) and COP$_F$ (the inverse cycle heat transformer efficiency), i.e., on the three temperatures involved. The considered temperature values are in the actual operating range of low-grade energy resources.

Since we will refer to the temperatures on the network side and not to the internal cycle temperatures, we will use a notation such as, for example, for a standard heat pump:

$$COP_{HP} = 1 + \eta_{II} \cdot \frac{T_{in} - \Delta T_{eva}}{T_{out} - \Delta T_{cond} - (T_{in} - \Delta T_{eva})} \tag{12}$$

Where the magnitude of the temperature difference at the heat exchangers, typically around 5÷10°C, will be inversely proportional to the quality (and Capex, through UA) of the installed heat exchangers.

Usually, the temperature drop in the HEX (given the heat transfer duty Q) depends on two main characteristics, the heat transfer efficiency, U (W/m^{2}K) (which is fixed based on technology and fluid involved) and size A(m^2). The bigger is UA, the lower is the temperature drop. To achieve very small temperature drops (which leads to good quality HEX) big values of A must be adopted, which means bigger and expensive HEXs.

In the case where an integration source is present based on LGERS, as briefly sketched in Figure 27, the inlet temperature, necessary for calculating the COP, is found as previously mentioned.
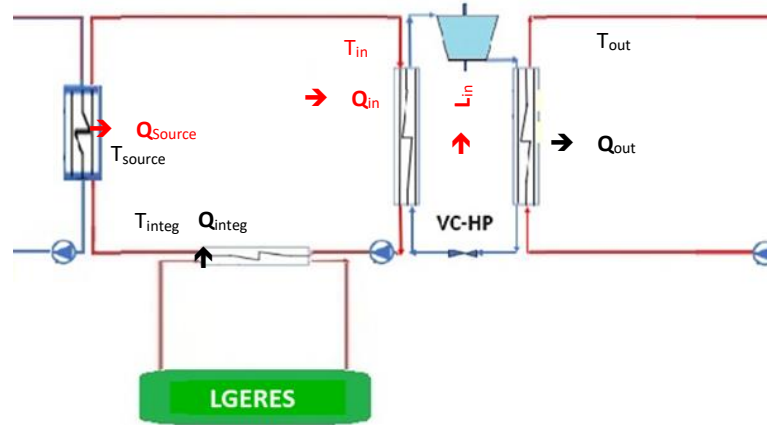
Figure 27 – Highlight on the quantity involved in the process. Calculated quantities in red (credit: UNIGE)

The complete model implementation follows the scheme reported in Figure 28, which includes the possible simultaneous presence of two upgrades on the main line and two on the possible integration.
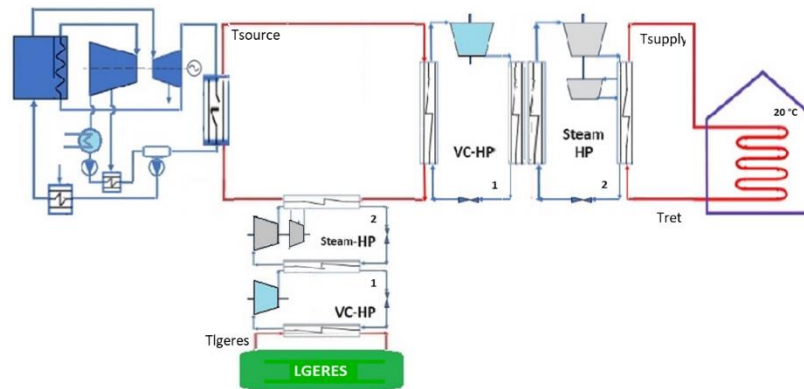
Figure 28 – DH net schematic in case of CHP retrofitting. The possible temperature upgrades are shown only for completeness (Credit: UNIGE)

Once the energy contributions of all devices have been obtained, the various performance indices of the plant can be calculated, both in terms of performance and in terms of primary energy consumed and CO_2 emissions.

The model presented so far, summarized in Figure 28, allows for the description of a wide range of cases, such as the representation of the merging of two distinct renewable sources. In the specific analysis of the following ten cases, a simplified model can be used that does not include upgrades on the main DH line but only locally on the low-grade source. This model is represented by Figure 29 and can be applied both in the case of using an existing thermal plant (Boiler or CHP) or by using only the low-grade source as the sole source.
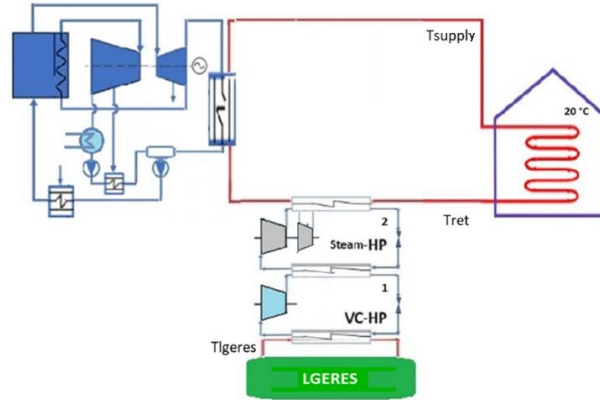
Figure 29 - DH simplified net schematic in case of CHP retrofitting. The temperature upgrades are applied only on the low-grade sources (credit: UNIGE)

ENERGY PERFORMANCE INDICATOR

A distinction is made between fossil fuel sources and the other sources. We call the first Non-Renewable Energy Sources **(NRES)** and the latter, including nuclear sources, Renewable Energy Sources **(RES).**

To assess the efficiency and effectiveness of DH systems, identifying areas for improvement, and ensuring that the system operates within optimal parameters, some key Energy performance indicators (EPIs) are introduced:

- Thermal Efficiency
- NRES Primary Energy Factor for Heat
- RES Energy Share
- Fossil Fuel Energy savings
- NRES fossil fuel savings
- Carbon intensity

Since we are discussing a synthetic model, some of the above parameters here mentioned become irrelevant and will be excluded. In the literature, various definitions of these indicators are used also depending on local legislation of a Country. Here, we have arbitrarily adopted the following definitions:

Ep is the primary energy associated to a source before any conversion to secondary or usable energy forms like electricity or heat. Primary and secondary energy are related by the conversion factors usually reported using the symbol f.

If Heat is the usable form of energy, the following coefficients are assumed

For RES $f_H = 1$

For NRES $f_H = 1/\eta_H = 1/0.9$

Where $\eta_H = 0.9$ is the overall burner conversion efficiency

If Electric Energy is the usable form of energy, then

For RES $\qquad f_{el\,i} = 1$ excluding nuclear energy for which $f_{el} = 1/\eta_{nuke}$

For NRES $\qquad f_{el\,i} = 1/(\eta_{el\,i} \cdot \eta_H)$

where η_H account for the first conversion in Heat and $\eta_{el\,i}$ account for the conversion from Heat to Electric energy. That is, $\eta_{el\,i}$ is the average efficiency of the i-th non-renewable source plant type (related to the i-th fuel: coal, gas, oil).

These are conversion factors related to the single source or bunch of sources of the same kind. To calculate, as an example, the overall primary conversion factor, PEF, for the Electric energy production of a Country, the share (sh) of electric energy associated to each source must be accounted for. That is

$$f_{el} = \sum_i \left(sh_i \cdot f_{el\,i} \right)$$

These factors are usually applied also to group sources of the same nature, for instance

$$f_{el} = sh_{RES} \cdot f_{el\,RES} + sh_{NRES} \cdot f_{el\,NRES}$$

f_{el} is the average primary energy factor (PEF) for **electric energy** in that Country,

sh_{RES} is the **share of electric energy** coming from renewable sources in the given Country while

With

$$f_{el\,RES} = \frac{\sum_i \left(sh_i \cdot f_{el\,i} \right)_{RES}}{\sum_i \left(sh_i \right)_{RES}} \qquad\qquad f_{el\,NRES} = \frac{\sum_i \left(sh_i \cdot f_{el\,i} \right)_{NRES}}{\sum_i \left(sh_i \right)_{NRES}}$$

And

$$sh_{RES} = \sum_i \left(sh_i \right)_{RES} \qquad\qquad sh_{NRES} = \sum_i \left(sh_i \right)_{NRES} \qquad\qquad sh_{RES} + sh_{NRES} = 1$$

In case of absence of the nuclear energy share, it will be

$$f_{el} = sh_{RES} + (1 - sh_{RES}) \cdot f_{el\,NRES}$$

Occasionally, the following formula ca be found in the literature

$$f_{el} = f^*_{el\,RES} + f^*_{el\,NRES}$$

But in this case, the inverse of the terms *f** are no more average efficiencies.

Thermal Efficiency – it measures the efficiency of converting input energy into usable heat. It is typically expressed as the ratio of useful heat output to the total energy input (from outside the system). In the simplest case it only accounts for heat losses in the heat generation plant and in the DH network. If other device or sub-systems are part of the heating system, other terms are to be accounted for. If the source id a "extraction-condensing" CHP then a great amount of heat is dispersed to environment in the low-pressure condenser. If an absorption heat pump is used as the upgrading temperature device, again much heat is dispersed in the environment. Both energy integration and upgrading systems will contribute with heat or mechanical energy input to the overall Thermal Efficiency of the system.

From here on, only electric/mechanical contribution coming from outside the DH system are considered.

In symbols we have:

$$\eta_{th} = \frac{Q_{DH}}{\sum_i Q_{in\ i} + \sum_j L_{in\ j}}$$

Non-Renewable Primary Energy Factor (NRPEF) for Heat - Indicates the amount of non-renewable primary energy (nuclear energy excluded) required to deliver one unit of **thermal energy to the end-user**. Lower NRPEF values indicate a more sustainable system, as less non-renewable (fossil) primary energy is needed to produce the required thermal energy.

$$f_{p,DH} = \frac{\sum_i Ep_{NRES\ \dot{Q}_{in\ i}} + \sum_j Ep_{NRES\ \dot{L}_{in\ j}}}{Q_{DH}}$$

Where the terms $Ep()$ represent the primary energy associated with the non-renewable energy inputs $\dot{Q}_{in}$ and $\dot{L}_{in}$.

$$f_{p,DH} = \frac{f_H Q_{NRES} + sh_{NRES} f_{el,NRES} \sum_j L_{in\ j}}{Q_{DH}}$$

f_H and $f_{el,NRES}$ as defined

Renewable Energy Share – The fraction of input energy generated from renewable sources. A higher share of renewable + nuclear energy indicates a more sustainable district heating system. The selected index accounts for the share of renewable energy in electric Energy production of the given Country.

$$R_{sh} = \frac{\sum_i Q_{RES\ i} + sh_{RES} \sum_j L_{in\ j}}{\sum_i Q_{in\ i} + \sum_j L_{in\ j}} = \eta_{th} \quad \frac{\sum_i Q_{RES\ i} + sh_{RES} \sum_j L_{in\ j}}{Q_{DH}}$$

Waste sources are considered renewable sources.

Fossil Fuel Savings (FFS)– a local index, which expresses the fossil fuel fractional savings, is derived from a comparison between the considered system and a reference system. If the actual system uses a pre-existing fossil source, such as a boiler or a CHP, the comparison is made against that source coupled with

a simple DH network, with no integrations or upgrades. Otherwise, the reference plant is a district heating network heated by a simple boiler. It is related to the local decrease in CO_2 emissions, but there are better specific indexes.

$$FFS = \frac{Q_{NRES\_ref} - Q_{NRES}}{Q_{NRES\_ref}} = 1 - \frac{Q_{NRES}}{Q_{NRES\_ref}}$$

Primary Fossil Fuel Energy Savings (PFFES) – a global index. Like the previous, it expresses the Primary fuel fractional savings as the ratio of primary energy related to fossil fuel saved by the system in comparison with the base reference for that system, divided by Primary Fuel Energy consumed by the base system. In formulas:

$$PFFES = \frac{Ep_{NRES\_ref} - Ep_{NRES}}{Ep_{NRES\_ref}}$$

Differently from the previous, it also accounts for the conversion to produce the electric energy needed to operate the upgrading devices.

$$PFFES = 1 - \frac{f_H \cdot Q_{NRES} + sh_{NRES} f_{el,NRES} \sum_j L_{in\ j}}{f_H \cdot Q_{NRES\_ref}}$$

Carbon intensity - CO_2 Emissions in t/MWh: Measures the amount of CO_2 emitted per unit of thermal energy delivered. This indicator helps in assessing the environmental impact of the district heating system. Renewable energy sources as solar thermal, produce next to no CO_2 emissions, so their carbon intensity value is very low, and we assume it equal to zero. We evaluate a local emission index that only involves fossil fuel utilized in the heat generation plant (reference is made to coal), which can be related to possible costs of CO_2 tax/bonds, and a global index also accounting for CO_2 emissions related to the Electric energy possibly used in the temperature upgrading devices, e.g., heat pumps. This last is more related to the entire environmental impact. The two indices are obtained as:

$$CI_{local} = \frac{f_H e_{CO_2\ x} \cdot Q_{NRES}}{Q_{DH}}$$

$$CI_{global} = \frac{f_H e_{CO_2\ x} \cdot Q_{NRES} + \left(\sum_k e_{CO_2\ k} \frac{sh_{NRES\ k}}{\eta_{el\ k} \cdot \eta_H}\right)\left(\sum_j L_{in\ j}\right)}{Q_{DH}}$$

$e_{CO_2\ k}$ is the CO_2 emission factor of the fuel associated to the k-th non renewables source of heat used in Electric energy production while $e_{CO_2\ x}$ refer to the fuel used in the burner of the DH system, if present.

In the present context, the analysis output will be limited to the following parameters:

- Thermal Efficiency
- RES Energy Share
- Fossil Fuel Energy savings

- Carbon intensity

That is:

$$\eta_{th} = \frac{Q_{DH}}{\sum_i Q_{in\ i} + \sum_j L_{in\ j}} \tag{13}$$

$$R_{sh} = \eta_{th} \frac{\sum_i Q_{RES\ in\ i} + sh_{RES} \sum_j L_{in\ j}}{Q_{DH}} \tag{14}$$

$$FFS = 1 - \frac{Q_{NRES}}{Q_{NRES\_ref}} \tag{15}$$

$$CI_{local} = \frac{f_H e_{CO_2\ x} \cdot Q_{NRES}}{Q_{DH}} \tag{16}$$

$$CI_{global} = \frac{f_H e_{CO_2\ x} \cdot Q_{NRES} + \left(\sum_k e_{CO_2\ k} \frac{sh_{NRES\ k}}{\eta_{el\ k} \cdot \eta_H} \right) \left(sh_{NRES} \sum_j L_{in\ j} \right)}{Q_{DH}} \tag{17}$$

In addition, the electric energy consumption (from RES/NRES sources) will be given.

The following numerical data[5] are considered in the calculation for the different countries considered:

Table 4 – Share of Power Generation Sources

Electric Energy Share	Lithuania	Poland	Slovakia
Fossil (sh_{NRES})	0.24	0.73	0.15
Nuclear	0.00	0.00	0.62
Renewable (sh_{RES})	0.76	0.27	0.85

Table 5 – Share of Fuels in Power Generation

Non-renewable share sh_{NRES}	Lithuania	Poland	Slovakia
coal	0.000	0.786	0.224
gas	0.321	0.110	0.386
oil	0.354	0.039	0.128
biogas	0.007	0.002	0.008
wood	0.318	0.062	0.255

Table 6 – Average carbon emission factors for different sources.

Emission factor	e_{CO2} [t/MWh]

---

[5] Data are retrieved from https://ourworldindata.org/electricity-mix or estimated according to the given definitions.

Coal	0.354
CH$_4$	0.20196
Oil	0.249
Biogas	0.197
Wood	0.403

Table 7 – Average efficiency for power plant according to the considered primary energy source.

Average Efficiency	η_i
Coal	0.34
CH$_4$	0.50
Oil	0.40
Biogas	0.50
Wood	0.34

ECONOMIC PERFORMANCE INDICATOR

District heating systems provide thermal energy to various type of buildings through a network of insulated pipes. These systems utilize various heat sources as solar, biomass, geothermal, waste heat, and fossil fuels and can greatly enhance energy efficiency and reduce greenhouse gas emissions. To grant the successful implementation and operation of district heating plants, a thorough economic and financial analysis is essential. In this context, we will limit ourselves to outline the main performance parameters used for the economic and financial characterization of the system. The model will be applied to 10 specific cases to assess their overall feasibility.

Standard methods of economic and financial analysis for district heating plants involve several key steps and tools, including:

- **Capital Cost Expenditure (C$_0$)[CAPEX]**: This involves calculating the initial investment required for setting up the retrofitting, the integration and the upgrading of the preexisting district heating system, including costs for equipment, design, construction, land acquisition (e.g. solar integration), and connection to the distribution network. This cost is greatly influenced by the LGERES source selected and can also be particularly low if the plant utilizes a pre-existent fossil source to be partially integrated by other sources. Among the utilizable sources, the presence of industrial o residential heat source (with the right supply temperature) located near the plant will allow a further containment of the investment cost.

- **Operating and Maintenance Costs [OPEX]**: Estimating the ongoing expenses related to fuel, labour, maintenance, administrative overheads, and other operational activities is crucial for understanding the long-term financial requirements.

- **Revenue Forecasting**: Projecting potential income from the sale of thermal energy to customers. This includes considering different tariff structures, potential subsidies, and incentives provided by governments or regulatory bodies. In the specific cases to be developed, these incomes will not be considered since the target of the analysis is to calculate an order of magnitude of the levelized

cost of thermal energy (LCOH), while other indices, hereafter reported for completeness, will not be reported since they are strongly affected by actual market parameters and potential incentives which must be specified in a more detailed financial analysis. These data will be necessary in the specific solutions which will be adopted in each Country. Also, the reference plant is assumed to produce the same amount of Heat, and only the LCOH will be calculated.

- **Net Present Value (NPV) and Internal Rate of Return (IRR)**: These financial metrics are critical for assessing the project's profitability. NPV calculates the difference between the present value of cash inflows and outflows. Investment cost and dismantling cost are to be considered. Since NPV calculations consider the time value of money, you need to discount the future dismantling costs to their present value using the appropriate discount rate.

  IRR identifies the discount rate at which the NPV equals zero, indicating the project's expected return.

  The following formulas are used

  $$NPV = -C_0 + \sum_{k=1}^{N} \frac{C_k}{(1+r)^k} \qquad ,\text{M€} \qquad (18)$$

  $$0 = -C_0 + \sum_{k=1}^{N} \frac{C_k}{(1+IRR)^k} \qquad (19)$$

  Where C_0 is the initial investment cost of the project and C_k are the cash flows relative to the year k. *r* is the discount rate.

- **Profitability Index (PI)**: it is defined as the present value of future cash flows divided by the initial cost of the project and it is a useful tool for classifying projects as it allows quantification of the amount of value created per unit of investment. A profitability index of 1 indicates breakeven. Any value below 1 would indicate that the present value of future cash flows of the project is less than the initial investment. As the value of the profitability index increases, so does the financial attractiveness of the proposed project.

  $$PI = \frac{\sum_{k=1}^{N} \frac{C_k}{(1+r)^k}}{C_0} \qquad (20)$$

- **Discounted Payback Period (DPP)**: Estimating the duration needed for the investment to generate sufficient cash flow to recover the initial capital outlay. By discounting future cash flows thus recognizing the time value of money. The DPP is not recommended when selecting mutually exclusive alternatives as it does not account for different investment sizes.

  $$0 = -C_0 + \sum_{k=1}^{DPP} \frac{C_k}{(1+r)^k} \qquad ,\text{yrs.} \qquad (21)$$

- **Levelized Cost of Heat (LCOH)**: LCOH is a relevant and commonly used indicator for district heating systems. It represents the average cost per unit of heat produced over the lifetime of the heating

system, accounting for all the costs associated with its installation, operation, maintenance and, possibly, dismantling. This comprehensive approach helps in understanding the true cost of providing heat over the system's lifespan. LCOH allows for the comparison of different heat generation technologies and fuel sources on a consistent basis. Stakeholders can assess the economic viability of a district heating project since LCOH helps in determining whether the project can provide heat at a competitive price compared to alternative heating solutions.

$$LCOH = \frac{-C_0 + \sum_{k=1}^{N} \frac{S_k}{(1+r)^k}}{\sum_{k=1}^{N} \frac{H_k}{(1+r)^k}} \qquad ,€/MWh_{Th} \qquad (22)$$

Where C_0 is the initial investment cost of the project and S_k are the expenditures relative to the year k, and H_k are the produced amount of heat per year. In case of concurrent production of electric energy (e.g. CHP source), various methods are used to portion and assign the expenditures. Usually LCOH is measured in €/MWh$_{Th}$ and represents the cost in euros of 1 thermal MWh delivered to the network. The order of magnitude of LCOH is in the range 30 to 100€/MWh, depending on the Country, on the energy policy, on the main thermal sources, and so on.

In the present context, the analysis output will be limited to the following parameters:

- CAPEX
- LCOH

The following numerical data have been assumed for CAPEX calculations, assuming the same mean values for Lithuania, Poland and Slovakia. All the data are specific with respect to the power of the device, thermal power delivered for all heating systems and electrical power for power co-generation plants.

The CAPEX includes the cost of the components included in the plants and the design & construction costs. It is assumed a share of 60% and 40% of the total CAPEX respectively. Furthermore, the yearly maintenance cost is estimated as the 2% of the capex.

The CAPEX values reported in Table 8 have been considered (European Commission, DG JRC,, 2017) in the proposed calculations.

Table 8 – CAPEX for the different technologies analysed.

Considered System	CAPEX (€/kW)
LGERES	
Solar Trough	2000
Solar Panel	560
Ground Geothermal	1200
Deep Geothermal	3000
Waste	400
Reference Heating System	
Boiler	100
CHP-Ex (Expansion)	1350
CHP -Bp (back pressure)	1000
Upgrading Technology	
VC-HP	600
Steam-HP	700
ABS-HP	400
MVR	550

The considered OPEX consist in maintenance cost, fuel cost, electricity cost and CO_2 cost. Depending on the specific case only some of them can be present. The discount rate is set at **a fixed yearly value of 5% and whereas for fuel and CO_2 a yearly increase of the cost of 0.5%.** According to the hypothesis on the cost escalation financial results can change.

The energy, fuel and CO_2 data costs were obtained and adapted from (ENERDATA, 2023) and Eurostat. As for fossil fuels, only coal or gas are considered since they are the most common in DH systems. Other fuels can be used, as shown in previous Tables.

Table 9 – Energy costs for the different target markets.

ENERGY COSTS	Lithuania	Poland	Slovakia
electric energy [€/kWh$_{El}$]	0.15	0.18	0.19
green electric RECS energy [€/kWh$_{EL}$]	0.18	0.216	0.228
Coal [€/kWh$_{TH}$]	0.025	0.025	0.025
Gas [€/kWh$_{TH}$]	0.0357	0.0413	0.0634
CO_2 emissions [€/ton]	70	70	70

From the initial set comprising 24 possible strategies for integrating existing DH (District Heating) networks, 10 cases have been further investigated due to their interesting energy and economic aspects. Specifically, the detailed cases are related to the following solutions:

5, 11, 13, 17, 18, 19, 20, 21, 22, and 24.

The first **two** solutions represent a retrofit using the existing CHP (Combined Heat and Power) plant employed in the district heating network. The next **four** solutions are suitable for use in systems based on simple boilers, while the last **four** involve the partial or complete replacement of the primary source with LGERES (Low-Grade Energy RESource).

These 10 cases have undergone a more in-depth energy and economic analysis, using the modelling approach described in the previous section. The focus was on identifying solutions that could achieve fossil fuel savings (%) and as low as possible LCOH (€/MWh$_{TH}$) with an associated reduction in direct CO_2 emissions (described by the Carbon Intensity parameter, ton/GWh$_{TH}$/year). Additionally, the impact of the external electricity demand required by temperature upgrade systems was examined, since this parameter directly affects the electricity consumption and therefore the carbon emission parameters and the operating costs parameters. The possibility to use "green certified electricity supply" has been considered too, with direct impact on carbon emission reduction and increase in the electricity bill (which means increase in the operating cost of the upgraded solution). This electricity requirement, typical of heat pumps, necessitates extending the analysis to consider the different characteristics of the energy mix in the three countries under consideration and their respective market situation: Lithuania, Poland, and Slovakia.

Each summary table reports the general DH data of the specific case (DH user demand, LGERS operating temperature, thermal contribution required to LGERER, – Elgeres – the percentage of verified green electricity supply – REC% - the local fuel – natural gas or standard coal -the mean operating hours per year and the size of the thermal energy storage, in terms of heat capacity MWh, if present).

DETAILED ANALYSIS N.1 (TECH.SOL. N. 05) - **EXTRACTION CHP**: SOLAR CONCENTRATION HIGH TEMPERATURE PARTIAL OR COMPLETE SUBSTITUTION OF THE HIGH–PRESSURE ECONOMIZER

CASE 1

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☐ Boiler ☒ CHP . ☐ New Integration DH temperature ☐ Supply / 120°C ☐ Return / 60°C ☒ None (inside the CHP)	☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station   ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)

New concept wirh direct solar integration

The base system to retrofit uses steam extraction before the low-pressure turbine, to support the DH heat demand. The new solution uses a high-temp solar field in parallel to the high temperature set of feedwater heaters, thus covering a desired % of the CHP boiler thermal needs (Boiler pre-heater). The solution can provide simple boiler pre-heating if the available LGRES temperature is up to 150 °C but can provide deep heating with higher temperature. To this purpose, the evaporator pressure of the CHP must correspond to saturation temperature of 230-240 °C (30-35 bar) to allow the LGRES hot fluid to cause the phase change in the boiler. In these conditions, the fuel saving can reach 50% and more.

Similar results can be obtained if high temperature waste is available. The main difference pertains to the possible presence of a thermal energy storage in case of intermittent source.

The considered LGERES does not need specific thermal upgrading technology, since the working temperature is usually sufficiently high, thanks to solar concentration. The use of TES (Thermal Energy Storage) is needed to correctly couple the plant thermal needs if the source is time varying (e.g. solar source).

The considered CHP configuration (traditional coal fired, on the left) uses the steam extraction from the vapour steam turbine before going to the low-pressure turbine, to support the DH heat demand. It is

possible to install an LGERES thermal field, in green in the schema on the right, on the high-pressure line, in parallel to the high temperature set of feedwater heaters, covering a desired % of the boiler thermal needs. The feedwater heaters contribution can be totally excluded.

This configuration can function as the boiler preheater, when implemented with LGERES sources capable to provide temperature from 130°C up to 250 °C, but it can partially or completely substitute the boiler if the added source can provide temperatures up to the max temperature of the plant (e.g., 500°C÷600°C). So, the amount of integration can also be very high.

The actual emission and fossil fuel savings (FFS), generally high, will be function of the above said mode of operation: preheating or boiler substitution. In the case of preheating, the FFS of the base system can be incremented up to about 30%.

Obviously, when the boiler is completely substituted by the LGERES the saving will reach 100%.

Financial estimation does not include land cost associated to the solar field deployment.

Main Parameters

LGERES technology: Solar Parabolic through

TRL: 10 – Well established and available technology

Operating temperature of the LGERES: up to 260°C.

Operating temperature of the integration: up to 250°C (preheating)/500 °C (boiler replacement).

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.0	200	5	0%	natural gas	4380	15

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
El_{NRES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
RES Share (%)	19.7%	0	19.7%	0	19.7%	0
FFS (%)	19.7%	0	19.7%	0	19.7%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	457.9	570.1	457.9	570.1	457.9	570.1
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	457.9	570.1	457.9	570.1	457.9	570.1
CAPEX (M€/MW$_t$)	1.03	1.35	1.03	1.35	1.03	1.35
LCOH (€/MWh$_t$) - 20yrs.	60	51	63	54	78	71

(*) including Green certified electricity supply

LGERES = Low Grade Energy RESource	
BAU = Business As Usual (Reference)	
Strength	**Weakness**
- It can completely replace the use of fossil fuel - Very good saving indicators	- Not easily implementable as in the DH return line (strong changes in the CHP plant) - It does not allow for the exploitation of low-temperature sources.
Main Recommendations	
- Recommended both for complete or partial fossil fuel replacement. **- Requires mid to high temperature sources (Not applicable for use with moderate temperature sources , <140°C).**	

Case 2

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☐ Boiler ☒ CHP . ☐ New	☒ Solar ☐ Geoth.	☒ TES + ☒ VC-HP
Integration point/ DH temperatures	☐ Waste ☐ Biomass	☒ MVR ☐ ABS-HP
☐ Supply/ 120°C ☒ Return/ 60°C	☐ Other	☐ Other ☐ None
☐ None		

Intervention strategy (location): ☒ central heat station ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – extraction/condensing CHP (simplified)

New concept with **solar field + steam Heat Pump**

The considered CHP configuration (traditional coal fired, on the left) uses the steam extraction from the vapour steam turbine before going to the low-pressure turbine, to support the DH heat demand. The new solution exploits a field of flat bed solar collectors (mean temperature about 50°C) with a steam VC-HP (closed cycle MVR) up to the working temperatures of about 100 ÷ 120°C, on the DH return line. Standalone solutions are possible (steam VC-HP up to 140°C) using a by-pass return/supply control. The need of an upgrading technology is due to the low temperature of the supply of this LGERES, lower to that of the return line.

In this way, part of the district heating power is provided by the solar source, part by the compressor power and the rest by the extraction condenser of the CHP. Decreasing the thermal power extraction from the CHP offers an increase in the expected electrical power output, thus compensating in part the compressor electrical consumption. The axial flow steam compressor used in this type of heat pump have typically an efficiency around 0.8, resulting in COP value from 3.5 up to 4. The upgrading system could provide even the full DH need with consistent fuel saving. In this case (5MW solar field integration) the FFS of the system exceeds 65%. The energy share of Renewable can be further increased considering green certified supply possibilities (in this case RECs=50%). Due to the upgrade capability of the water steam heat pump, the DH system can be implemented also as a stand-alone DH solution, without serving a preexisting CHP. In fact, If the LGRES uses the bypass control, the systems can be considered separately with performance like those of following cases 7 and 8. In this scenario, the max capacity of the LGRES system no longer depends on that of the CHP and can supply an additional DH network.

Main Parameters

LGERES technology: flat bed or evacuated tubes solar collectors + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES)

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: bottoming solar field up to 50÷60°C, steam HP up to 120-140°C (COP of the order of 4 with standard machine - exergy efficiency of 0.5). Specific performance parameters must be defined in detailed analyses.

Operating temperature of the integration: up to 120°C (can be used in the form of CHP economizer integration, or as a stand-alone solution).

Financial estimation does not include land cost associated to the solar field deployment.

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.0	55	5	50%	natural gas	4380	21

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	7.57	0	5.46	0	7.96	0
El_{NRES_in} (*) (GWh/y)	1.03	0	3.14	0	0.65	0
RES Share (%)	42.2%	0	35.9%	0	43.4%	0
FFS (%)	66.9%	0	66.9%	0	66.9%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	189.0	570.1	189.0	570.1	189.0	570.1
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	208.1	570.1	265.6	570.1	201.6	570.1

CAPEX (M€/MW$_t$)	0.51	1.35	0.51	1.35	0.51	1.35
LCOH (€/MWh$_t$) - 20yrs.	70	51	80	54	87	71

(*) including Green certified electricity supply

LGERES = Low Grade Energy RESource

BAU = Business As Usual (Reference)

Strength	Weakness
- Ease of integration with the existing DH plant and possibility to install as a standalone application on the DH network - Possibility to increase the thermal power supplied to the users -Good saving indicators (in particular from the stan-alone configuration)	- It needs an additional electric source for the compressor. - It must be coupled to low temperatures.

Main Recommendations
- Reasonably recommended for use low temperature (<60°C). **- Also Recommended when an increase of the DH thermal power is desire**

DETAILED ANALYSIS N.3 (TECH. SOL. N. 13) – BOILER **PRE-HEATING OR SUBSTITUTION** WITH PARABOLIC SOLAR TROUGH INTEGRATION

Case 3

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP . ☒ New	☒ Solar ☐ Geoth.	☒ TES + ☐ VC-HP
Integration point/ DH temperatures	☐ Waste ☐ Biomass	☐ MVR ☐ ABS-HP
☐ Supply/ 120°C ☐ Return/ 60°C	☐ Other	☐ Other ☒ None
☒ None (inside boiler system)		

Intervention strategy (location): ☒ central heat station ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)

Boiler with **high temperature solar field** (parabolic through)

The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C. In respect to CHP configurations, there is not electric energy production, so that the heating system is simpler and easier to be controlled. Also, involved temperatures and pressures are lower.

The new solution uses a high-temp solar field (parabolic solar trough – potentially up to 250°C) to pre-heat the water in the boiler, covering a desired % of the DH thermal needs. To function this way, the LGERES sources must be capable to provide temperatures in the range 90°C÷ 110 °C, but it can completely substitute the boiler if the added source can provide about 140°C. So, the amount of fossil energy substitution can be very high. In this case a TES system is needed. If the integration simply acts as a pre-heater the TES can be avoided and the boiler modulate to provide the requested heat power not coming from the solar source. The adopted configuration will depend mainly on economic considerations

This kind of integration can be implemented both in the boiler loop and in the HD network line (see case 4).

The size of the LGERES source cannot exceed that of the original system, it cannot saturate the capacity of the heat exchanger. The fossil fuel savings (FFS) or the original boiler increases up to 100% as a function of the above said mode of operation: preheating or boiler substitution. Obviously, when the boiler is completely substituted (not easily in the case of solar energy, but some industrial waste solution could be possible) by the LGERES the saving and emission reduction will reach 100%.

Main Parameters

LGERES technology: concentration parabolic solar collectors + high temperature TES

TRL:10 – Well established and available solar technology

Operating temperature of the LGERES: up to 220÷240°C

Operating temperature of this integration: up to 140°C, depending, however, on the main heat exchanger configuration.

Financial estimation does not include land cost associated to the solar field deployment.

LCOH calculation is strongly influenced by the energy and fuel policy of each Country.

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.0	140	5	0%	natural gas	4380	15

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
El_{NRES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
RES Share (%)	48.0%	0	48.0%	0	48.0%	0
FFS (%)	48.0%	0	48.0%	0	48.0%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	121.6	233.8	121.6	233.8	121.6	233.8
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	121.6	233.8	121.6	233.8	121.6	233.8
CAPEX (M€/MW$_t$)	1.03	0.1	1.03	0.1	1.03	0.1
LCOH (€/MWh$_t$) - 20yrs.	51	53	54	59	68	81

(*) including Green certified electricity supply
LGERES = Low Grade Energy RESource

BAU = Business As Usual (Reference)

Strength	Weakness
- Ease of integration with the existing DH plant - Can replace fossil fuel use for more than 50% - Very good saving indicators	- Has small range of operating temperatures - TES and boiler (at least a small one) integration management are crucial - good maintenance is needed
Main Recommendations	
- Recommended both for partial fossil fuel replacement. **- Requires mid temperature sources (Not implementable for use with moderate temperature sources (<80°C)).**	

DETAILED ANALYSIS N.4 (TECH. SOL. N. 17) – BOILER **INTEGRATION OR SUBSTITUTION** WITH HIGH TEMP.

PARABOLIC SOLAR TROUGH WITH HIGH TEMPERATURE TES

Case 4

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☒ Solar ☐ Geoth. ☐ Waste ☐ Biomass ☐ Other	☒ TES + ☐ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☒ None

Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)	Boiler integration with parabolic **solar trough field + high temperature TES**
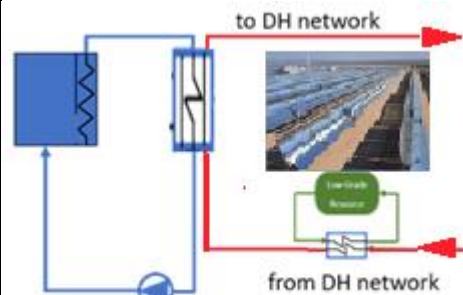
The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

It is possible to install an LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line. If the solution is the concentration solar trough solar field, the thermal integration can be very high, provided a high temperature thermal energy storage (TES) is installed.

The FFS can be incremented up to 100%. The boiler contribution is proportionally decreased while the power of the LGERES increases. At most, the boiler can be turned off, being used only as a small thermal integration. The solar systems can contribute to the overall power and the total DH capacity even increased if needed.

This solution is applicable also locally, in decentralized substations.

Main Parameters

LGERES technology: concentration parabolic trough solar collectors + Thermal Energy Storage (TES)

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: up to 180-240°C. Specific performance parameters must be defined in detailed analyses.

Operating temperature of this integration: up to 140°C (can be used in the form of burner integration as in Case 3, or as a stand-alone solution with small burner integration).

Financial estimation does not include land cost associated to the solar field deployment.

LCOH calculation is strongly influenced by the energy and fuel policy of each Country.

The use of coal as fossil fuel, opposite to the use of gas of case 3, strongly reduces the opex costs and gives the same results for the three Countries (given that the coal costs are assumed the same)

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.0	140	5	0%	coal	4380	15

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
El_{NRES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
RES Share (%)	48.0%	0	48.0%	0	48.0%	0
FFS (%)	48.0%	0	48.0%	0	48.0%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	213.1	409.7	213.1	409.7	213.1	409.7
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	213.1	409.7	213.1	409.7	213.1	409.7
CAPEX (M€/MW$_t$)	1.03	0.1	1.03	0.1	1.03	0.1
LCOH (€/MWh$_t$) - 20yrs.	51	53	51	53	51	53

(*) including Green certified electricity supply
LGERES = Low Grade Energy RESource
BAU = Business As Usual (Reference)

Strength	Weakness
- Ease of integration with the existing DH plant - Can replace fossil fuel use potentially up to 80% - Very good saving indicators	- need accurate engineering design - TES and boiler (at least a small one) integration management are crucial - good maintenance is needed
Main Recommendations	
- **Recommended both for partial or total fossil fuel replacement.** - **Recommended when an increase of the DH thermal power is desired**	

DETAILED ANALYSIS N.5 (TECH. SOL. N. 18) – BOILER **INTEGRATION OR SUBSTITUTION** WITH INDUSTRIAL WASTE HEAT + ABS-HP ON THE DH RETURN LINE

Case 5

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP ☐ New	☐ Solar ☐ Geoth.	☐ TES + ☐ VC-HP
Integration point/ DH temperatures	☒ Waste ☐ Biomass	☐ MVR ☒ ABS-HP
☐ Supply/ 120°C ☒ Return/ 60°C	☐ Other	☐ Other ☐ None
☐ None		

Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler	Boiler integration with **industrial waste + ABS-HP**
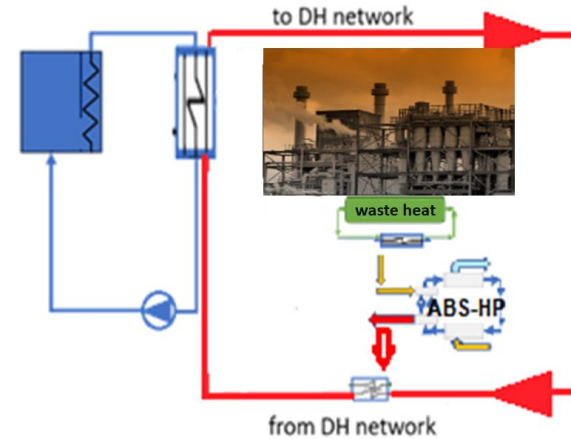
The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

The new solution uses industrial waste heat to pre-heat the DH return line. With this integration (temperature of about 70°C) a proper upgrading technology is required. In this case an absorption heat transformer (maximum operating temperature of about 100÷115°C) can be used. TES is optional but could help system regulation. In this way, the heating power provided by the waste source is used to operate the ABS-HP (in the desorption process), without any significative electrical consumption but the need of a great amount of auxiliary heat. Decreasing the thermal power by combustion in the boiler lead to a very good performance. The drawback is that a great amount of thermal energy at 60°C is needed to operate the ABS-HP, thus requiring large industrial waste. In fact, for the above given temperatures, the COP of the system is in the range 0.35- 0.5 meaning that if a power of, for instance, 1MWth is needed, the source will have to provide something like 5MWth of heat, 4 of which will be discharged into the environment. Nevertheless, if operated from a large industrial waste source, this technology will provide temperature upgraded heat at very low costs. The standalone configuration

(with no boiler) is not so easy to be implemented, since the upper temperature of the ABS-HP could be not sufficient for high temperature (120°C) DH

The FFS of the system can be incremented up to 100%. The boiler contribution is proportionally decreased while the power of the LGERES increases. The systems can contribute to the overall power and the total DH capacity can be increased if needed.

This solution is applicable also locally, in decentralized substations.

Main Parameters

LGERES technology: waste heat sources + Absorption Heat pump (ABS-HP)

TRL: 9÷10 – Well established and available technology with some difficulties to be applied in actual upgrading solutions. ABS-HP pilot plants should be envisaged and well come.

Operating temperature of the LGERES: the waste is assumed to be available at 70 °C so that the heat transformer at 110-115°C (exergy efficiency of the order of 0.15) can be used.

Operating temperature of the integration: up to 110°C, reducing the temperature gain in the boiler.

The operation of ABS-HP requires a great amount of heat to be discharged to the environment (51.6% of the heat input in this specific case). Therefore, an oversizing of the LGERES is needed.

The assumed availability of 10 MW waste heat at 70 °C is reduced to only 4.8 MW of useful effect in the DH net at 115 °C.

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.00	70	10	0%	natural gas	4380	0

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
El_{NRES_in} (*) (GWh/y)	0.00	0	0.00	0	0.00	0
RES Share (%)	64.2%	0	64.2%	0	64.2%	0
FFS (%)	46.4%	0	46.4%	0	46.4%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	125.2	233.8	125.2	233.8	125.2	233.8
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	125.2	233.8	125.2	233.8	125.2	233.8

CAPEX (M€/MW$_t$)	0.59	0.1	0.59	0.1	0.59	0.1
LCOH (€/MWh$_t$) - 20yrs.	43	53	47	59	60	81

(*) including Green certified electricity supply

LGERES = Low Grade Energy RESource

BAU = Business As Usual (Reference)

Strength	Weakness
- Ease of integration with the existing DH plant - Can replace fossil fuel use potentially up to 85% - Very good saving indicators	- needs accurate engineering design - - the use of heat transformers is not so well spread - Its cost is strongly affected by the ground field heat exchanger configuration.

Main Recommendations

- Reasonably recommended for partial fuel replacement.

- Recommended when an increase of the DH thermal power is desired

- Very high installed heat power of waste source is needed to operate the ABS-HP

DETAILED ANALYSIS N.6 (TECH. SOL. N. 19) – BOILER **INTEGRATION OR SUBSTITUTION** WITH LOW TEMP. WASTE HEAT+ STEAM COMPRESSION HEAT PUMP))

Case 6

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP . ☐ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	☐ TES + ☒ VC-HP ☐ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station   ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – simple boiler (simplified)	Boiler integration with medium/low temperature **industrial waste + steam HP + TES (optional)**
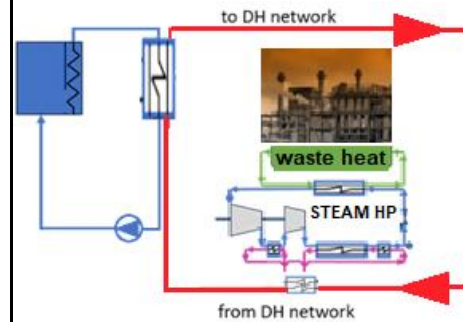
The considered boiler configuration (traditional heater gas or coal fired, on the left) is a pressurized water system providing water at about 130°C at the main exchanger (e.g. shell&coil tubular heat exchanger) while the secondary loop assures the DH heat demand at about 110 °C÷120°C.

It is possible to install an LGERES thermal field, in green in the schema on the right, to pre-heat the DH return line. To function this way, the LGERES sources must be capable to provide temperatures in the range 90°C÷ 115 °C, typical of medium-high temperature industrial waste heat (e.g. Exhaust gases from engines and turbines, heat from drying ovens, chemical reactors, and medium-pressure steam condensate), but it cannot completely substitute the boiler if the added source cannot reach about 130°C. Furthermore, the power level of the coupled industry must be enough. If the solution is a low/medium temperature (industrial) waste heat, the thermal integration would be very low, therefore a proper upgrading technology is required. In this case a vapour compression steam heat pump (maximum operating temperature up to about 150°C). TES is optional, depending on the continuous or intermittent regime of the waste heat source.

The FFS of the system can be incremented up to 100%. The boiler contribution is proportionally decreased while the power of the LGERES increases. At most, the boiler can be turned off. Otherwise, the systems can contribute to the overall power and the total DH capacity increased if needed.

This solution is applicable also locally, in decentralized substations, near the waste heat source.

Main Parameters

LGERES technology: waste heat sources + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES)

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: waste source in the range 60÷90°C, steam HP up to 120-140°C (COP of the order of 4.5 with standard machine-assuming exergy efficiency of 0.5).

The integration power requires to the from the waste source is less than in case 5 (3.8 MW instead of 10 MW) to operate with the same thermal power input to the DH network (4.8 MW). In this case 6, the use of a steam VC-HP introduces additional heat power due to electrical consumption (1 MW).

Significative differences among the Countries are due to differences in energy policies.

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.00	70	3.8	0%	natural gas	4380	0

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	3.41	0	1.21	0	3.81	0
El_{NRES_in} (*) (GWh/y)	1.08	0	3.27	0	0.67	0
RES Share (%)	44.0%	0	39.1%	0	44.8%	0
FFS (%)	46.3%	0	46.3%	0	46.3%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	125.5	233.8	125.5	233.8	125.5	233.8
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	145.4	233.8	205.4	233.8	138.7	233.8
CAPEX (M€/MW$_t$)	0.49	0.1	0.49	0.1	0.49	0.1
LCOH (€/MWh$_t$) - 20yrs.	62	53	71	59	84	81

(*) including Green certified electricity supply
LGERES = Low Grade Energy RESource

BAU = Business As Usual (Reference)

Strength	Weakness
- Ease of integration with the existing DH plant - Can replace fossil fuel use potentially up to 100% - Very good saving indicators	- needs accurate engineering design - it is not easy to find high-power, high temperature waste heat sources - Distance between the DH network and the waste heat source
Main Recommendations	
- Recommended both for partial and total fossil fuel replacement.	

DETAILED ANALYSIS N.7 (TECH. SOL. N. 20) –BOILER SUBSTITUTION WITH GENERIC MEDIUM
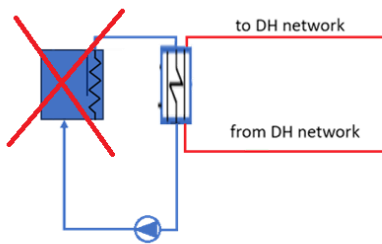TEMPERATURE LGERES AND WATER STEAM HP)

Case 7

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP ☒ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	☒ TES + ☐ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station ☐ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminates (simplified)	Boiler substitution with medium temperature **LGERES + steam HP + TES**
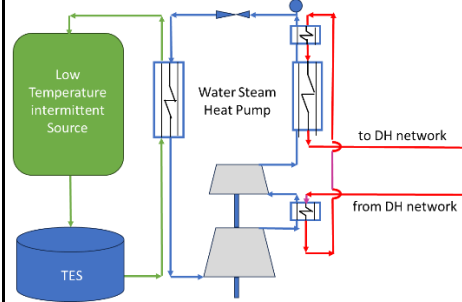
This data sheet summarizes the potential substitution of traditional burners with a completely LGERES at medium temperature (not less than 60÷70°C).

The considered traditional coal fired configuration is completely substituted by an LGERES source. It is possible to install a low-grade thermal source, for instance a low temperature (60÷70 °C) solar field, in green in the schema on the right, to heat the DH return line, covering a desired % of the DH thermal needs. Due to the low temperature supplied by the LGERES, lower than that of return line, an upgraded technology, in the form of a steam heat pump, is implemented to elevate the return water temperature up to the range 110 °C-120 °C of delivery to the DH network. In this way, a portion of the district heating power is provided by the solar source, the other by the compressor power. The temperature increase provided by the LGERES guarantee a good working and efficiency of the MVR. The axial flow steam compressor used in this type of heat pump have typically an efficiency around 0.8, resulting in COP value from 3.5 up to 4. Despite the availability of "free" power from the waste source, the upgrading process is energy-intensive and, for each MWth supplied to the user, an electric power of about 0.3 Mwe is needed by the device compressor.

The use of a good high temperature TES is mandatory when intermittent waste heat sources are exploited.

The system can work also with other low-grade sources like solar or intermittent waste heat coming from shopping mall. This solution is applicable also locally, in decentralized substation operating as an independent DH subnetwork.

Main Parameters
LGERES technology: medium temperature LGERES + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES)
TRL: 10 – Well established and available technology. Need accurate engineering design.
Operating temperature of the LGERES: at least 60÷70°C, steam HP up to 110-130°C (COP of the order of 4.0 with standard machine, assuming exergy efficiency of 0.5).

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.00	65	7.75	0%	natural gas	4380	250

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
EI_{RES_in} (*) (GWh/y)	9.06	0	3.22	0	10.13	0
EI_{NRES_in} (*) (GWh/y)	2.86	0	8.70	0	1.79	0
RES Share (%)	93.8%	0	81.0%	0	96.1%	0
FFS (%)	100.0%	0	100.0%	0	100.0%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	0.0	233.8	0.0	233.8	0.0	233.8
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	52.9	233.8	212.3	233.8	35.1	233.8
CAPEX (M€/MW$_t$)	1.31	0.1	1.31	0.1	1.31	0.1
LCOH (€/MWh$_t$) - 20yrs.	83	53	96	59	95	81

(*) including Green certified electricity supply
LGERES = Low Grade Energy Resource
BAU = Business As Usual (Reference)

Strength	Weakness
- Ease of integration with the existing DH plant	- needs accurate engineering design
- Can replace fossil fuel use potentially up to 80%	- it needs electric energy (for the compressors)
- Very good saving indicators	- good high temperature TES

Main Recommendations
- **Recommended for extensive fossil fuel replacement.**

Case 8

| Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP ☒ New Integration point/ DH temperatures ☐ Supply/ 120°C ☒ Return/ 60°C ☐ None	☐ Solar ☐ Geoth. ☐ Waste ☒ Biomass ☐ Other	☐ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location): ☒ central heat station ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminates (simplified)	New concept: Boiler substitution with medium temperature **aerobic digestor + steam HP + TES**

The considered traditional coal fired configuration is completely substituted by an LGERES source represented by an aerobic digestor which represents a low grade thermal source at about 60°C-70°C. Due to the low temperature supplied by the LGERES, similar to that of return line, an upgrading technology, in the form of a steam heat pump, is implemented to elevate the water temperature up to the range 110 °C-120 °C. In this way, a portion of the district heating power is provided by the digestor, the other by the compressor power (electrical energy). The axial flow steam compressor used in this type of heat pump have typically an efficiency around 0.8, resulting in COP values from 3.5 up to 4. Due to the relatively high temperature of the source, the electric power required by the upgrade is of the order of 0.25MWe per 1 MWth.

Due to the oxidation processes, dioxide (CO_2) and nitrous oxide (N_2O) are produced, while CO_2 is also emitted to produce the energy required for the system operation. Efforts to reduce these emissions and to capture it are possibly required.

The global CO_2 emission due to electric energy consumption can be mitigated by means of green certified electricity supply, which include implied higher opex and LCOH cost. In this specific case 8 the assume percentage of RECs is 50%.

This solution is applicable also locally, in decentralized substation operating as an independent DH subnetwork. The use of TES could be not necessary, thanks to the continuous operation of the digestor.

Main Parameters

LGERES low temperature: aerobic digestor + steam heat pump (closed loop MVR) + Thermal Energy Storage (TES), optional.

TRL: 10 – Well established and available technology. Need accurate engineering design.

Operating temperature of the LGERES: digestor at 60÷70°C, steam HP up to 110÷130°C (COP of the order of 4. with standard machine, assuming exergy efficiency of 0.5). Specific performance parameters must be defined in detailed analyses.

Operating temperature of the upgrading: up to 130°C. The use of a good high temperature TES is not mandatory (and not shown in the figure), but welcome.

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.00	65	7.75	50%	coal	4380	250

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
EI_{RES_in} (*) (GWh/y)	10.49	0	7.57	0	11.03	0
EI_{NRES_in} (*) (GWh/y)	1.43	0	4.35	0	0.89	0
RES Share (%)	93.8%	0	81.0%	0	96.1%	0
FFS (%)	100.0%	0	100.0%	0	100.0%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	0.0	409.7	0.0	409.7	0.0	409.7
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	26.5	409.7	106.2	409.7	17.5	409.7
CAPEX (M€/MW$_t$)	1.31	0.1	1.31	0.1	1.31	0.1
LCOH (€/MWh$_t$) - 20yrs.	80	53	91	53	92	53

(*) including Green certified electricity supply

LGERES = Low Grade Energy Resource

BAU = Business As Usual (Reference)

Strength	Weakness
- Very good saving indicators	- it needs electric energy (for the compressors)
- In principle, it doesn't need a thermal storage system.	- the produced CO2 should be captured

Main Recommendations
Recommended with preexisting aerobic digestor only

Case 9

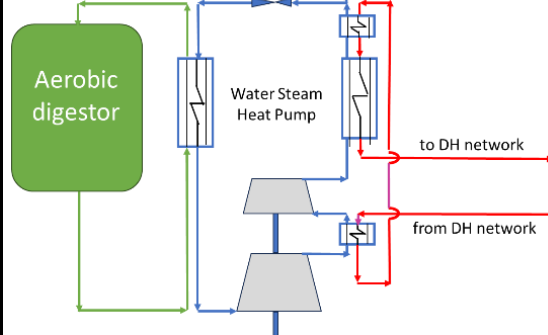| Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP ☒ New	☐ Solar ☒ Geoth.	☐ TES + ☒ VC-HP
Integration point/ DH temperatures	☐ Waste ☐ Biomass	☒ MVR ☐ ABS-HP
☐ Supply/ 120°C ☒ Return/ 60°C	☐ Other	☐ Other ☐ None
☐ None		

Intervention strategy (location): ☒ central heat station   ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminated (simplified)	New concept : Boiler substitution with **Ground source Heat Pump + steam heat pump** (MVR closed cycle) integration

This data sheet summarizes the potential substitution of traditional burners with a completely LGERES at low temperature (down to 5÷10°C).

The considered traditional coal fired configuration is completely substituted by an LGERES source represented by the ground, aided by a geothermal heat pump. This system transforms and upgrades ambient heat from ground at about 10 °C to a more manageable and valuable temperature of 50÷60 °C, with ground mean seasonal temperature of 10°C, which however still represents a low-grade thermal source. So, the output of this first stage is further upgraded by means of a **water steam heat pump** (in figure) to reach the higher temperatures required by the DH network, up to 120 °C÷130 °C. A fraction of the district heating power is provided by the ground, the other by the electric power consumed by the compressors. Although the modern heat pumps involved are characterized by high COPs, the combination of the two upgrades usually gives a global COP not higher than 2.5. The use of a double upgrade to elevate the very low temperature of the source (10°) implies a high LCOH value.

This technical solution can be applied also locally, in decentralized substation operating as an independent DH subnetwork.

Main Parameters

LGERES technology: ground heat pump (VC_HP) + steam compression heat pump (MVR close dcycle)

TRL: 10 – Well established and available technology, but detailed engineering design is needed

Operating temperature of the LGERES with integration: the first stage geothermal heat pump reaches 50÷60°C, the other MVR closed cycle can reach 120÷130°C°.

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.00	10	5.49	0%	coal	4380	0
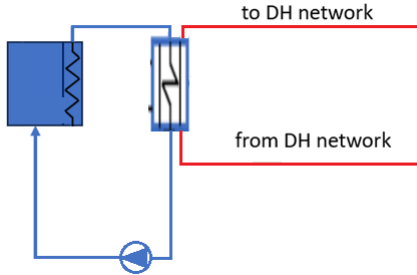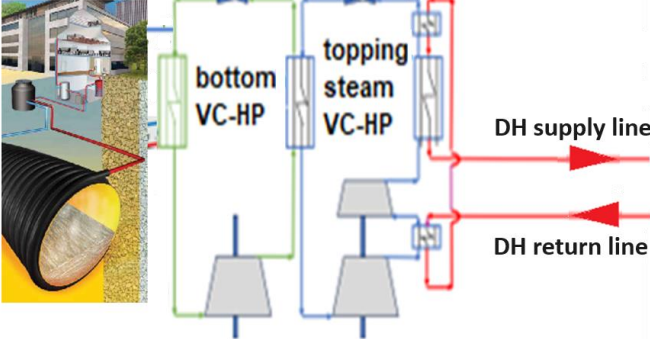
	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	16.43	0	5.84	0	18.37	0
El_{NRES_in} (*) (GWh/y)	5.19	0	15.78	0	3.24	0
RES Share (%)	88.6%	0	65.4%	0	92.9%	0
FFS (%)	100.0%	0	100.0%	0	100.0%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	0.0	409.7	0.0	409.7	0.0	409.7
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	96.0	409.7	385.0	409.7	63.6	409.7
CAPEX (M€/MW$_t$)	1.86	0.1	7.78	0.1	7.78	0.1
LCOH (€/MWh$_t$) - 20yrs.	140	53	164	53	162	53

(*) including Green certified electricity supply

LGERES = Low Grade Energy RESource

BAU = Business As Usual (Reference)

Strength	**Weakness**
- Good saving indicators - Consolidated technology - It doesn't need a thermal storage system, unless different intermittent sources are used (solar, waste)	It needs an external electric source for the compressors. - Complex upgrading technology (detailed engineering design is needed)

Main Recommendations
- Recommended for use with very low temperature sources (10°C)

DETAILED ANALYSIS N.10 (TECH. SOL. N. 24) –DH INTEGRATION WITH SEWAGE WASTE HEAT + VC-HP

SYSTEM + STEAM COMPRESSION HEAT PUMP (MVR CLOSED CYCLE)

Case 10

Basic reference Technology	Main exploited LGERES	Upgrading Technology
☒ Boiler ☐ CHP . ☒ New Insertion DH temperatures ☐ Delivery 120°C ☒ Return: 60°C ☐ None	☐ Solar ☐ Geoth. ☒ Waste ☐ Biomass ☐ Other	☐ TES + ☒ VC-HP ☒ MVR ☐ ABS-HP ☐ Other ☐ None

Intervention strategy (location):   ☒ central heat station   ☒ Delocalized along the DH network

Overall System Description

Preexisting Plant Concept – fossil fuel boiler to be eliminated (simplified)	New concept : DH integration with **sewage waste heat + Heat Pump + steam heat pump** (MVR closed cycle) integration

This data sheet summarizes results coming from the integration of traditional coal fuelled burner with a sewage LGERES at low temperature (down to 15÷20°C).

The considered integration is based on an in-tube heat exchanger for sewage water exploitation (typically in local district or building solutions) coupled to VC-HP system, (the sewage water is usually a higher temperature of environment, say 20°C on average, and the VC-HP can reach temperatures of about 70°C). Once the local temperature is the same of the return line of the DH network, a topping steam VC-HP (MVR closed cycle), up to 120°C can be added, be it in the central station or locally. The availability of sewage waste heat is supposed to be 15% of the DH heating power.

Despite the availability of "free" heat power from the sewage heat exchanger, the upgrading process is energy-intensive and, for each MWth supplied to the user, an electric power from 0.3 to 0.4 MWe are needed by the devices' compressors.

Some plant retrofit is necessary to maximize performance. The use of a large TES is necessary, due to the discontinuous availability of energy from waste sewage water.

Since electric power is needed the Fossil fuel saving ranges from 20% to 30%. The Renewable share could be higher if the electricity used to operate the compressors was "green".

This technical solution here applied is typically implemented in decentralized substation operating as a DH subnetwork.

Main Parameters

LGERES technology: ground heat pump (VC_HP) + steam compression heat pump (MVR close dcycle)

TRL: 10 – Well established and available technology, but detailed engineering design is needed

Operating temperature of the LGERES with integration: the first stage geothermal heat pump reaches 50÷60°C, the other MVR closed cycle can reach 100÷120°C°.

DH Data

DH User Demand (MW)	T_{lgeres} (°C)	Q_{lgeres} (MW)	RECs %	Local Fuel	Operating Hours (h/y)	TES capacity (MWh)
10.0	20	1.5	0%	coal	4380	61

	Lithuania		Poland		Slovakia	
KPIs	**LGERES**	**BAU**	**LGERES**	**BAU**	**LGERES**	**BAU**
El_{RES_in} (*) (GWh/y)	3.49	0	1.24	0	3.90	0
El_{NRES_in} (*) (GWh/y)	1.10	0	3.35	0	0.69	0
RES Share (%)	22.0%	0	17.1%	0	22.9%	0
FFS (%)	24.5%	0	24.5%	0	24.5%	0
CI_{loc} (tCO$_2$/GWh$_{th}$)	309.5	409.7	309.5	409.7	309.5	409.7
CI_{glob} (*) (tCO$_2$/GWh$_{th}$)	329.9	409.7	391.2	409.7	323.0	409.7
CAPEX (M€/MW$_t$)	0.43	0.1	0.43	0.1	0.43	0.1
LCOH (€/MWh$_t$) - 20yrs.	74	53	79	53	79	53

(*) including Green certified electricity supply
LGERES = Low Grade Energy RESource
BAU = Business As Usual (Reference)

Strength	Weakness
- Good saving indicators - Consolidated technology - It doesn't need a thermal storage system, unless different intermittent sources are used (solar, waste)	It needs an external electric source for the compressors. - Complex upgrading technology (detailed engineering design is needed)

Main Recommendations

- Recommended for use with very low temperature sources (10°C)

CONCLUSION

District Heating systems play an essential role in providing sustainable, centralized heating to urban communities, especially in the context of Europe's transition to a low-carbon economy. As explored in this report, Low-Grade Energy Resources (LGERES) offer a promising pathway for reducing the carbon footprint of DH networks by integrating renewable energy sources such as solar thermal, geothermal, biomass, and industrial waste heat. However, while the potential of these renewable sources is relevant, fully replacing traditional fossil fuels with renewables presents significant technical, financial, and operational challenges.

The transition towards renewable-based DH systems is not a straightforward process, particularly for High-Temperature District Heating (HT-DH) systems, which have traditionally relied on coal and natural gas. Many existing DH networks, especially in countries like Lithuania, Poland, and Slovakia, were designed based on Soviet approaches, making them heavily dependent on fossil fuels and less flexible for immediate integration of renewable sources. Therefore, a hybrid approach that balances the continued use of fossil fuels with increasing integration of renewables is recommended as a practical strategy for these countries in the near term. This staged transition allows for the gradual upgrade of infrastructure while maintaining the reliability and efficiency of heat supply.

Table 10 - Summary of the developed case studies.

#	Considered Cases
1	EXTRACTION CHP: SOLAR CONCENTRATION HIGH TEMPERATURE PARTIAL OR COMPLETE SUBSTITUTION OF THE HIGH-PRESSURE ECONOMIZER
2	EXTRACTION CHP: FLAT PLATE SOLAR PANEL + STEAM VC-HP ON THE DH RETURN LINE AND RETURN/SUPPLY BYPASS
3	BOILER PRE-HEATING OR SUBSTITUTION WITH PARABOLIC SOLAR TROUGH INTEGRATION
4	BOILER INTEGRATION OR SUBSTITUTION WITH HIGH TEMP. PARABOLIC SOLAR TROUGH WITH HIGH TEMPERATURE TES
5	BOILER INTEGRATION OR SUBSTITUTION WITH INDUSTRIAL WASTE HEAT + ABS-HP ON THE DH RETURN LINE
6	BOILER INTEGRATION OR SUBSTITUTION WITH LOW TEMP. WASTE HEAT+ STEAM COMPRESSION HEAT PUMP))
7	BOILER SUBSTITUTION WITH GENERIC MEDIUM TEMPERATURE LGERES AND WATER STEAM HP
8	BOILER SUBSTITUTION WITH AEROBIC DIGESTOR AND WATER STEAM HP
9	BOILER SUBSTITUTION WITH GEOTHERMAL HEAT PUMP + STEAM COMPRESSION HEAT PUMP (MVR CLOSED CYCLE)
10	DH INTEGRATION WITH SEWAGE WASTE HEAT + VC-HP SYSTEM + STEAM COMPRESSION HEAT PUMP (MVR CLOSED CYCLE)

It emerged the need to differentiate between types of interventions for the transition from fossil fuels to renewable energy sources in DH systems. Two main approaches are outlined: integrating renewable sources into existing fossil-fuel-based systems or completely replacing them with renewable alternatives. The latter option may require enabling technologies to meet temperature requirements, particularly when integrating with High Temperature District Heating.

A key part of this transition involves upgrading technologies like heat pumps, mechanical vapour recompression (MVR), and thermal energy storage (TES), which are critical for converting low-temperature renewable sources into the higher temperatures needed for DH networks. The report provides a thorough

analysis of 24 technologies and strategies for integrating LGERES into existing DH systems, of which 10 cases were explored in more detail as summarized in Table 10.

Table 11 – Summary of the preliminary estimations of RES share and LCOH achievable with each of the proposed LGERES solutions.

Case #	Indicator	Lithuania		Poland		Slovakia	
		LGERES	BAU	LGERES	BAU	LGERES	BAU
1	RES Share (%)	19.7%	0	19.7%	0	19.7%	0
	LCOH (€/MWh$_t$)	60	51	63	54	78	71
2	RES Share (%)	42.2%	0	35.9%	0	43.4%	0
	LCOH (€/MWh$_t$)	70	51	80	54	87	71
3	RES Share (%)	48.0%	0	48.0%	0	48.0%	0
	LCOH (€/MWh$_t$)	51	53	54	59	68	81
4	RES Share (%)	48.0%	0	48.0%	0	48.0%	0
	LCOH (€/MWh$_t$)	51	53	51	53	51	53
5	RES Share (%)	64.2%	0	64.2%	0	64.2%	0
	LCOH (€/MWh$_t$)	43	53	47	59	60	81
6	RES Share (%)	44.0%	0	39.1%	0	44.8%	0
	LCOH (€/MWh$_t$)	62	53	71	59	84	81
7	RES Share (%)	93.8%	0	81.0%	0	96.1%	0
	LCOH (€/MWh$_t$)	83	53	96	59	95	81
8	RES Share (%)	93.8%	0	81.0%	0	96.1%	0
	LCOH (€/MWh$_t$)	80	53	91	53	92	53
9	RES Share (%)	88.6%	0	65.4%	0	92.9%	0
	LCOH (€/MWh$_t$)	140	53	164	53	162	53
10	RES Share (%)	22.0%	0	17.1%	0	22.9%	0
	LCOH (€/MWh$_t$)	74	53	79	53	79	53

These cases highlight various integration approaches, from combining solar or geothermal heat with Combined Heat and Power (CHP) systems to utilizing waste heat recovery for boosting system efficiency. Table 11 summarizes two key performance indicators, namely the RES share and the Levelized Cost of Heat.

From a financial perspective, the Levelized Cost of Heat (LCOH) is a crucial metric in evaluating the feasibility of these solutions. While renewable sources like waste heat provide the most cost-effective options, other technologies such as geothermal and certain CHP retrofits can lead to significant cost increases, sometimes as high as 300%. Despite these cost challenges, the LCOH of renewable energy solutions remains competitive within the broader European energy market, especially when considering long-term benefits such as reduced greenhouse gas (GHG) emissions and fossil fuel dependency. In addition, further economic assessment based on externalities saving could be considered to develop a more comprehensive analysis.

The findings of this report also stress the importance of aligning technological upgrades with the specific needs of the DH systems in each country. For instance, strategies that work well in one context may be less efficient or cost-effective in another, due to local climate conditions, energy market structures, and infrastructure readiness. Therefore, tailored solutions that consider both energy performance and financial feasibility are essential. To provide detailed indications, specific DH sites should be analysed, and different technologies/strategies analysed.

In conclusion, the integration of LGERES into DH systems presents a promising pathway to achieving sustainable energy goals. However, this transition requires a multifaceted approach that combines technological innovation, strategic planning, and financial investment. While significant progress has been made, the full decarbonization of DH networks will depend on continued advancements in heat upgrading technologies and a phased, region-specific approach to replacing fossil fuels with renewable energy. By adopting a flexible and gradual transition plan, Europe can effectively move towards more eco-friendly and cost-efficient DH systems, helping to mitigate climate change while maintaining the resilience and reliability of energy supply.

References

Alva, G., Lin, Y. & Fang, G., 2018. An overview of thermal energy storage systems. *Energy,* 144(February), pp. 341-378. DOI: 10.1016/j.energy.2017.12.037.

Atienza-Márquez, A., Brun, J. C. & Coronas, A., 2020. Recovery and Transport of IndustrialWaste Heat for Their Use in Urban District Heating and Cooling Networks Using Absorption Systems. *Applied Science,* 10(291), pp. 1-20. DOI: 10.3390/app10010291.

Camia, A. et al., 2020. *The use of woody biomass for energy production in the EU, EUR 30548 EN,* Luxembourg: Pubblication Office of the European Union.

Cudok, F. et al., 2021. Absorption heat transformer - state-of-the-art of industrial applications. *Renewable and Sustainable Energy Reviews,* 141(110757), pp. 1-18. DOI: 10.1016/j.rser.2021.110757.

ENERDATA, 2023. *carbon price forecast under the EU ETS.* [Online]
Available at: https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html
[Accessed 28 July 2024].

EU_Parliament, 2009. Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union,* pp. 16-62.

EU_Parliament, 2018. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union,* Volume L 328, pp. 82-205.

European Commission, DG JRC,, 2017. *Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU,* s.l.: Joint Research Centre.

Gil, A. et al., 2010. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. *Renewable and Sustainable Energy Reviews,* 14(1), pp. 31-55. DOI: 10.1016/j.rser.2009.07.035.

Int_Energy_Agency, 2024. *IEA DHC - District heating network generation definitions,* s.l.: IEA DHC, 1-3..

Koch, K., Alt, B. & Gaderer, M., 2020. Dynamic Modeling of a Decarbonized District Heating System with CHP Plants in Electricity-Based Mode of Operation. *Energies,* 13(4134), pp. 1-14. DOI: 10.3390/en13164134.

Lund, H. et al., 2014. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy,* 68(April), pp. 1-11. DOI: 10.1016/j.energy.2014.02.089.

Lund, R. & Persson, U., 2016. Mapping of potential heat sources for heat pumps for district heating in Denmark. *Energy,* 110(September, Supplement C), pp. 129-138. DOI: 10.1016/j.energy.2015.12.127.

Ommen, T., Thorsen, J. E., Markussen, W. B. & Elmegaard, B., 2017. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps. *Energy,* 137(October), p. 544–555. DOI: 10.1016/j.energy.2017.05.165.

Østergaard, P. & Andersen, A., 2016. Booster heat pumps and central heat pumps in district heating. *Applied Energy,* 184(December), p. 1374–1388. DOI: 10.1016/j.apenergy.2016.02.144.

Persson, U. & Münster, M., 2016. Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review. *Energy,* 110(September, Supplement C), p. 116–128. DOI: 10.1016/j.energy.2015.12.074.

Ramboll, 2020. *WEdistric - D2.3 District Heating and Cooling Stock at EU level,* s.l.: EU Commission - EU Horizo 2020 n. 857801.

Rasmussen, J. F., 2024. *The role of district heating in the energy system,* s.l.: Danish District Heating Association.

Scarpa, F., Tagliafico, L. A. & Bianco, V., 2013. Inverse cycles modeling without refrigerant property specification. *International Journal of Refrigeration,* 6(36), pp. 1716-1729. DOI: 10.1016/j.ijrefrig.2013.04.003.

Scarpa, F., Tagliafico, L. & Bianco, V., 2013. A novel steady-state approach for the analysis of gas-burner supplemented direct expansion solar assisted heat pumps. *Solar Energy,* Issue 96, pp. 227-238. DOI: 10.1016/j.solener.2013.07.016.

Sipra, A. T., Gao, N. & Sarwar, H., 2018. Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts. *Fuel Processing Technology,* 175(June), pp. 131-147. DOI: 10.1016/j.fuproc.2018.02.012.

Sokolovs, A. et al., 2015. Heat Recovery Technologies from Aerobic Bio-degradation: From Theoretical Finding to Modeling Results. *Procedia Computer Science,* Volume 77, pp. 141-150. DOI: 10.1016/j.procs.2015.12.371.

Tagliafico, L., Scarpa, F. & Valsuani, F., 2014. Direct expansion solar assisted heat pumps - A clean steady state approach for overall performance analysis. *Applied Thermal Engineering,* 66(1-2), pp. 216-226. DOI: 10.1016/j.applthermaleng.2014.02.016.

Toppi T, Aprile, M., Abrami, G. & Motta, M., 2021. *Compressor-assisted heat transformer for waste-heat powered district.* ISHPC 2021, Berlin, August 22nd to 25th, s.n.

Werner, S., 2006. *Possibilities with more district heating in Europe, WP4 report from the IEE Ecoheatcool project,* Brussels: s.n.

Wu, J. & Han, Y., 2023. Integration strategy optimization of solar-aided combined heat and power (CHP) system. *Energy,* 263(125875), pp. 1-17. DOI: 10.1016/j.energy.2022.125875.

Zeh, R. et al., 2021. Large-Scale Geothermal Collector Systems for 5th Generation District Heating and Cooling Networks. *Sustainability,* 13(6035), pp. 1-18. DOI: 10.3390/su13116035.

Zeng, Z. et al., 2021. Parametric analysis and system optimization of a novel steam production system by synthetic cascade utilization of industrial waste heat. *Energy Reports,* Volume 7, p. 5909–5921. DOI: 10.1016/j.egyr.2021.08.178.

Zhao, S., Wang, W. & Ge, Z., 2019. Energy and Exergy Evaluations of a Combined Heat and Power System with a High Back-Pressure Turbine under Full Operating Conditions. *Energies,* 13(4484), pp. 1-18. DOI: 10.3390/en13174484.

Zhu, T. et al., 2023. Integration of booster heat pumps in ultra-low temperature district heating network: Prototype demonstration and refrigerant charge investigation. *Energy and Buildings,* 298(113516), pp. 1-14. DOI: 10.1016/j.enbuild.2023.113516.