RESTORE

Renewable Energy based seasonal Storage
Technology in Order to Raise Economic and
environmental sustainability of DHC

D1.1 - Report on Requirements and Specifications of the Overall Concept (V1)

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Summary

This document aims to provide an extended definition of the RESTORE concept, providing information about the Requirements and Specification of the different innovative components presented in the RESTORE solution (The thermochemical storage system and the thermodynamic cycles).

In addition, the document provides information about the interfaces of the system, considering the different sources and sinks that can be interconnected.

The information provided in this document applies to the RESTORE **overall** concept, thus it provides a general definition, presenting different options, which must be selected, adapted and designed for each use-case in an ad-hoc solution considering the boundary conditions imposed by each specific application. In that context, the document provides the general bases of the concept that will be considered as a guide during the project implementation.

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1. Introduction

This document aims to provide an extended definition of the RESTORE concept, providing additional details of the main innovative components of RESTORE and organizing them into two main subsections: On the one hand, the components associated with the thermochemical energy storage system (TCES). On the other hand, the components associated with the thermodynamic cycles (organic cycles) are connected to the storage system and the energy sources (renewable energy sources, RES or waste heat recovery, WHR) and sinks (District Heating and Cooling). For each of the components, the document provides an extended definition, a template of the data sheet that summarizes the specifications, and a list of requirements that must be considered and fulfilled. The data sheet of specifications are templates which show the main parameters that must be defined for each specific application of the concept, thus the column “value” can be filled for each ad-hoc application such as the virtual use-cases (associated with WP5) or the RESTORE prototype (associated with WP4).

In addition, the document also provides additional information about the interfaces of the RESTORE system, differentiating the “sources” and “sinks” that can be connected to the overall system. “Sources” are those systems that can be connected to the RESTORE solution in order to provide green energy to it (upwards) while “sinks” are those systems that receive the energy stored in RESTORE (downwards).

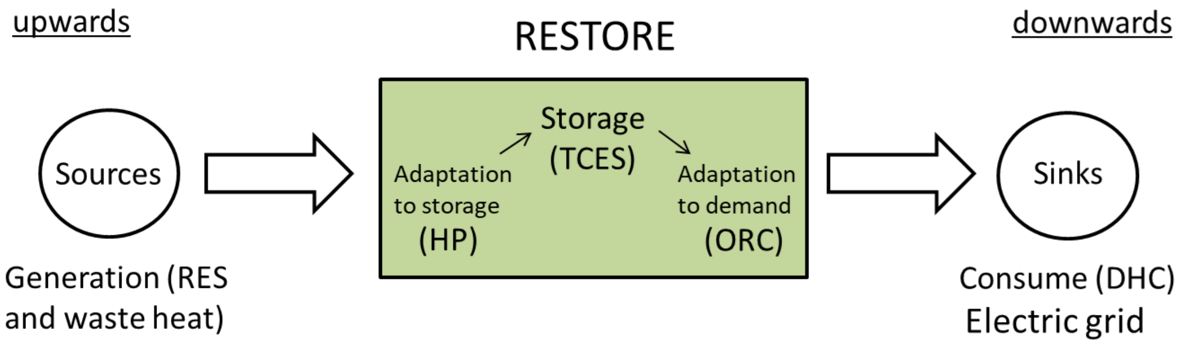


Figure 1.1 – Elements scheme

As explained, the information provided in this document applies to the RESTORE **overall** concept, thus it provides a general definition, presenting different options, which must be selected, adapted, and designed for each use-case in an ad-hoc solution considering the boundary conditions imposed by each specific application. In that context, the document provides the general bases of the concept that will be considered as a guide during the project implementation.

2. Definition of the concept and its requirements and specifications.

This section provides and extended definition of the different innovative components involved in the RESTORE concept. The section is divided into two main subsections, each one associated with the main systems involved in the RESTORE overall solution: The thermochemical energy storage and the thermodynamic cycles. For each system, the main subsystems are identified and defined. Then, the specifications of each subsystem are defined through a datasheet which includes the main and key parameters that must be defined in each specific application of RESTORE. Finally, a list of requirements of each subsystem, defining the necessary conditions and functionalities that must be addressed, is presented.

2.1. The thermochemical energy storage (TCES)

Thermochemical energy storage deals with the energy storage functionality of the RESTORE system. This system is thermally charged through the energy provided by the condenser of the heat pump and can be charged directly by energy sources with a temperature compatible with the thermochemical charge reaction. The heat is provided in the reactor which is filled with the solid thermochemical material (A) suspended in oil. Within the reactor an endothermic reaction takes place, realizing products (commonly water/steam and a thermochemical solid material (B) suspended in oil) that are then cooled to ambient temperature and stored separately. During the discharge, the process is reversed. The products of the charging process are now reactants (solids (B) + water) that are mixed in the reactor, undergoing an exothermic reaction. The heat released is transferred to the evaporator of the Organic Rankine Cycle. The products of the discharging process (thermochemical solid material (A)) are then cooled and stored.

In this system, the following subsystems can be identified:

- The thermochemical reactor(s): where the heat is supplied or released during the thermochemical reaction. The system could consider one or two reactors depending on the boundary conditions.
- The oil transport system: in charge of providing oil for the transportation of the solids.
- The product/reactant system: providing the substances involved in the thermochemical reaction. Two groups can be considered:
    - The water supply system: in charge of providing/receiving the water required/released in the thermochemical reaction. Water could be provided in an open loop or stored.
    - The solids storage: composed of the tanks where the thermochemical material is stored.

Different options can be considered as the ideal solution depends on the operational conditions determined by the boundary conditions imposed for each specific use-case.

Hereunder, the different subsystems are detailed and their specifications and requirements are defined.

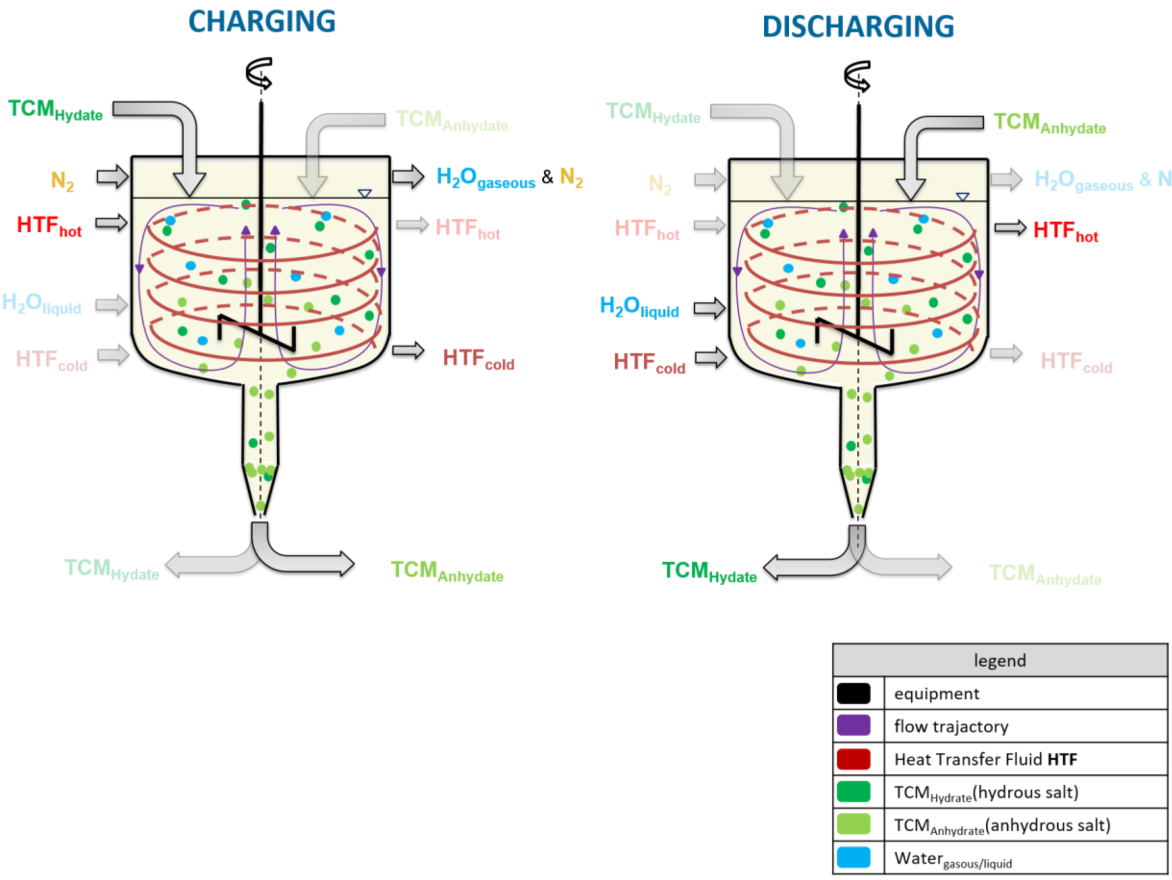
2.1.1. The reactor

The reactor is the subsystem where the thermochemical reaction takes place. It is a stirred tank that works as a suspension reactor where the thermochemical solid material is suspended in a thermal oil. Integrated into the reactor are one or more coils that work as a heat exchanger for transferring heat from or to the thermodynamic cycles. During charging, the suspended solid material (A) receives heat from the coil producing the solid material (B) and water. During the discharge the solid material (B) is recombined with water. This reaction forms the solid (A) and releases heat that is transferred to the coil. The reactor must guarantee a continuous operation which means that the flow of reactants that reach the reactor and the product that leaves it as well as the heat transferred must be uninterrupted during the operation. The tank also includes a mechanical stirrer which helps to produce homogenous conditions within the reactor, thus facilitating the reaction.

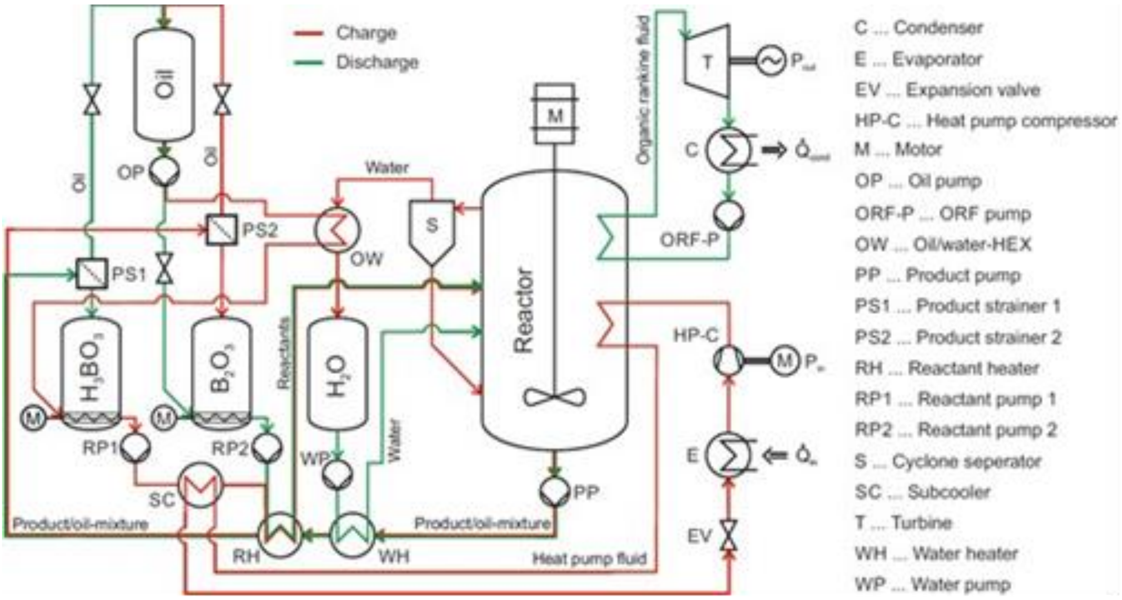
The operating temperature inside the reactor depends mainly on the thermochemical reaction finally chosen but also on other operational parameters such as the working pressure inside the tank. Depending on the boundary conditions the thermochemical energy storage system can use a single reactor with dual purpose or two different reactors (of a single purpose each).

2.1.1.1. Dual-purpose reactor

This solution is based on the use of a unique reactor that can work in both charging and discharging modes. The reactor can include one or several coil(s) inside the tank. This unique heat exchanger can work as a condenser of the heat pump during the charging process or as an evaporator of the Organic Rankine Cycle during the discharge. The reactor must be adapted to receive thermochemical solid material (A) and release water and material (B) during the charging process and be able to mix water and thermochemical solid material (B) for producing material (A) during the discharge. The figure below shows a schematic of the concept:



In addition, as an example of a unique reactor solution, the figure below shows a case specified for the H_3BO_3. The red colored lines describe the charging process meanwhile the green ones described the discharging process.



The use of a unique reactor allows for reducing equipment and cost associated with the storage system but the needed flexibility of this solution is challenging and more limited. The feasibility of this solution strongly depends on the boundary conditions imposed by each specific application.

Specifications and Requirements

The specifications for the unique reactor subsystem are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Dual purpose reactor datasheet		
Parameter	**Value**	**Unit**
Tank		
Type		
Material	Steel?	
Tank diameter		m
Tank height		m
Capacity		m^3
Design pressure		barg
Design temperature		°C
Corrosion allowance		mm
Heat exchanger coil		
Heat transferred at operating conditions in charge		kW_{th}
Heat transferred at operating conditions in discharge		kW_{th}
Mean temperature difference		K
Minimum free space between surfaces		mm
Fouling factor (in and out)		
Thermochemical reaction parameters		
Thermochemical reaction	Charge: Discharge:	
Thermochemical solid material		
Operating pressure in charge		barg
Operating pressure in discharge		barg
Concentration of solids suspended in oil during charge		%wt
Concentration of solids suspended in oil during charge		%wt
Temperature of operation in charge		°C
Temperature of operation in discharge		°C
Stirrer type		
Stirring nominal speed		rpm

The unique tank solutions must fulfil the following requirements:

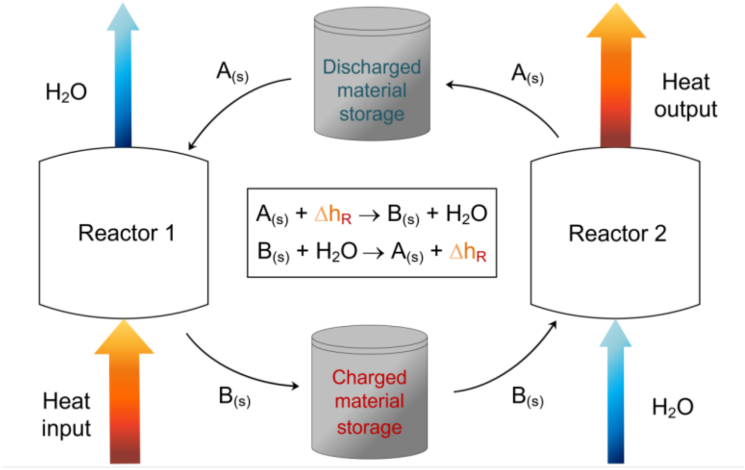
- Continuous operation is mandatory
- Possibility of operating at partial loads.
- Tanks materials compatible with the chosen oil and reaction products/reactants
- Temperatures of operations compatible with the thermodynamic cycle:
    - Heat pump - Charging temperatures < 150°C
    - Organic Rankine cycle – Discharging temperatures around 130 °C
- Security Issues:
    - Low toxicity of materials in the reaction
    - Non-flammability or similar issues.
    - Not exceeding pressures

Other relevant characteristics:

- Compactness is of special interest in small district applications.

2.1.1.2. Double reactor

This solution considers two different reactors, one designed for the charging process and the other for the discharge process. This solution allows an optimization of each reactor considering their unique operational conditions (reactors do not have to alternate their operation between charging and discharging). In that case, must include a heat exchanger that is connected to the thermodynamic cycles. The flexibility of this solution is higher. However, the associated cost also increases. In this case, the condenser of the heat pump and evaporator of the ORC are different heat exchangers, the first one is integrated into the charging reactor while the other one is integrated into the discharging reactor.



Specifications and Requirements

The specifications for the charging reactor subsystem are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Charging reactor datasheet		
Parameter	**Value**	**Unit**
Tank		
Type		
Material	Steel?	
Tank diameter		m
Tank height		m
Capacity		m^3
Design pressure		barg
Design temperature		°C
Corrosion allowance		mm
Heat exchanger coil		
Heat transferred at operating conditions		kW_{th}
Mean temperature difference		K
Minimum free space between surfaces		mm
Fouling factor (in and out)		
Thermochemical reaction parameters		
Thermochemical reaction		
Thermochemical solid material (A) and (B)		
Operating pressure		bar
The concentration of solids suspended in oil		%wt
Temperature of operation		°C
Stirrer type		
Stirring nominal speed		rpm

The specifications for the discharging reactor subsystem are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Discharging reactor datasheet		
Parameter	**Value**	**Unit**

Tank		
Type		
Material	Steel?	
Tank diameter		m
Tank height		m
Capacity		m^3
Design pressure		barg
Design temperature		°C
Corrosion allowance		mm
Heat exchanger coil		
Heat transferred at operating conditions		kW_{th}
Mean temperature difference		K
Minimum free space between surfaces		mm
Fouling factor (in and out)		
Thermochemical reaction parameters		
Thermochemical reaction		
Thermochemical solid material (A) and (B)		
Operating pressure		bar
The concentration of solids suspended in oil		%wt
Temperature of operation		°C
Stirrer type		
Stirring nominal speed		rpm

For both, the charging and the discharging reactor, the list of requirements of this solution is similar to the unique reactor subsystem:

- Continuous operation is mandatory
- Possibility of operating at partial loads.
- Temperatures of operations compatible with the thermodynamic cycle:
  - Heat pump - Charging temperatures < 150°C
  - Organic Rankine cycle – Discharging temperatures around 130 °C
- Security Issues:
  - Low toxicity of materials in the reaction
  - Non-flammability or similar issues.
  - Not exceeding pressures

Other relevant characteristics:

- Compactness is of special interest in small district applications. Although the compactness of this solution is higher than the unique reactor subsystem.

2.1.2. The product/reactant system

The objective of this subsystem is to guarantee the availability and supply of the substances that participate in the thermochemical reactor. For most reactions, these substances are the thermochemical solid material (A), the thermochemical solid material (B) and water. Thus this subsystem can be subdivided into blocks. On the one hand the part in charge of supplying water and on the other hand the part in charge of the solid materials.

2.1.2.1. The solids storage

The solids material that participates in the thermochemical reaction is provided during the construction of the whole system. The amount of material is directly related to the capacity for storing energy of the overall system. In seasonal storage, enough material must be supplied to guarantee one year of operation (the same material is reused in the following years of the plant). Two storage units are required, one for the thermochemical material (A) that is filled during the charge of the system and empty in the discharge, and the other. The number of tanks that are involved in each storage unit depends on the final amount of material that must be stored, for very large plants more than one tank could be required. The solids must be as much as possible separated from the oil, in order to minimize the size of the tanks and thus its costs.

Solids Storage units datasheet		
Parameter	**Value**	**Unit**
Thermochemical solids material (A) Storage Unit		
Number of tanks		
Material of the tanks		
Tank capacity		m^3
Stored mass		kg
Design pressure		barg
Design temperature		°C
Operating pressure		barg
Operating temperature		°C
Corrosion allowance		mm
Thermochemical solids material (B) Storage Unit		
Number of tanks		
Material of the tanks		
Tank capacity		m^3
Stored mass		kg
Design pressure		barg

Design temperature		°C
Operating pressure		barg
Operating temperature		°C
Corrosion allowance		mm

The list of requirements of both storage units is similar and are the following:

- Minimization of oil in the tanks
- Separation of oil and solids before the inlet of the tank
- Capacity to receive oil for empty the tanks from solids in the discharge of the tank
- Security Issues:
    - Security issues commonly applied to the operation and potential storage of thermal oil (e.g. potential flammability or other issues).

2.1.2.2. The water supply system

Most thermochemical reactions considered in the project present water as a substance required for the thermochemical reaction. During the charge process water is released meanwhile in the discharge water is required. The quality of water provided to the system is highly relevant due to it must be adequate for the thermochemical reaction. Two solutions could be differentiated for the water supply system: On the one hand, the open loop configuration, where the water after treatment is received for the discharge reaction and the water produced in the discharge is delivered to water demand. On the other one, the close loop configuration where the water is stored in tanks, that delivered or receive water from the reactor depending on the process (charging or discharging).

2.1.2.2.1. Close loop

The close loop configuration implies the use of water storage units in order to guarantee the supply of water at any time. The CAPEX of this system is tentatively higher due to the use of tanks for storing water. However, it presents some advantages like independency of potential water scarcities or does not require water treatment (the water supplied at the beginning must fulfill the requirements associated with the quality of water). The tanks must be sized in order to guarantee the required operational hours of storage defined for the whole thermochemical energy storage system (in line with the solids storage).

Specifications and Requirements

The specifications for the close-loop water supply system are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Close loop water supply subsystem datasheet		
Parameter	**Value**	**Unit**

Tank		
Number of tanks		
Material of the tanks		
Tank capacity		m^3
Stored mass		kg
Design pressure		barg
Design temperature		°C
Operating pressure		barg
Operating temperature		°C
Corrosion allowance		mm
Pump		
Number of pumps		
Type		
Material		
Nominal/Max flow rate		M3/h
Total differential head		m
Water specifications		
Dissolved Oxygen	Range:	Mg/L
Conductivity (EC)		µS/cm
TDS		ppm
Salinity		mg/L
pH		pH

The requirements to be fulfilled are the following:

- The tanks’ material must be stainless and compatible with water.
- The experimental activities carried out in WP2 have demonstrated that tap water is suitable for the reactions meanwhile salt water is not suitable. Thus, the following requirements associated with the quality of water (required for tap water) can be also demanded in the TCES:
    - Dissolved Oxygen < 8 mg/L
    - Conductivity (EC) < 800 µS/cm
    - TDS < 500 ppm
    - Salinity < 900 mg/L
    - pH in the range of: 6.5 - 8

2.1.2.2.2. Open loop

A continuous flow of treated water is provided to the reactor during the discharge process. During the charge, the released water could be provided for any demand. This solution is tentatively cheaper than the close loop and more adequate in regions that do not present water scarcity during winter (when the system is charged). In those regions, the open loop could be an advantage due to the subsystem being charged, thus releasing water, during summer when the water demand and scarcity are commonly higher.

Specifications and Requirements

The specifications are only related to the quality of the water provided.

Open loop water supply subsystem datasheet		
Parameter	**Value**	**Unit**
Pump		
Number of pumps		
Type		
Material		
Nominal/Max flow rate		m^3/h
Total differential head		m
Water specifications		
Dissolved Oxygen	Range:	Mg/L
Conductivity (EC)		µS/cm
Total dissolved solids (TDS)		ppm
Salinity		mg/L
pH		pH

In this subsystem only requirements associated with the quality of water are identified, and are similar to the shown in the close loop system:

- Dissolved Oxygen < 8 mg/L
- Conductivity (EC) < 800 µS/cm
- TDS < 500 ppm
- Salinity < 900 mg/L
- pH in the range of: 6.5 - 8

2.1.3. The transport system

Due to the fact that the main reacting components are solids, oil is used as a carrier substance to enhance transportability. The thermochemical solids material are suspended in the oil which transports them from the storage units to the reactor and vice versa. In addition, the oil has additional functions as improving the mixing and the heat transfer behavior. This subsystem involves the circulating pumps required to move the solids/oil mixture, the piping that connects the different components as well as the required separators for minimizing the amount of oil stored in the solids storage units. Also, an expansion vessel is typically used in closed circuits that work with thermal oil, this vessel could also use as a small tank for guaranteeing the availability of oil at any moment.

Specifications and Requirements

Transport system		
Parameter	**Value**	**Unit**
Thermal oil specifications		
Type of Oil		
Viscosity (high and low temp. of operation)		Pa s
Density (high and low temp. of operation)		Kg/m^3
Atmospheric Boiling Point		ºC
Flash point		°C
Fire point		ºC
Auto-ignition temperature		°C
Pour point		°C
Coefficient of thermal expansion		mm^3/ °C
Separator		
Type of separator		
Solids concentration before the separator		%wt
Solids concentration after the separator		%wt
Expansion Vessel		
Material		
Diameter		m
Height		m
Circulating subsystem		
In charge, mass flow from solids unit storage (A) to the reactor		Kg/h
In charge, mass flow from the reactor to solids unit storage (B)		Kg/h
In discharge, mass flow from solids unit storage (B) to reactor		Kg/h
In discharge, mass flow from the reactor to solids unit storage (A)		Kg/h

In this subsystem only requirements associated with the quality of water are identified:

  - The thermal oil must have a crystallizing point below the minimum operating temperatures expected.
  - The thermal oil must have an auto-ignition temperature above the maximum operating temperatures expected.
  - If the maximum operating temperature is above the flash point, the design must consider the security standards applied in these cases.
  - Circulating pumps must be chosen in order to fulfill the mass flow demanded/provided by the reactor.
  - Minimum size of the expansion vessels according to the amount of oil and the expansion related to its maximum and minimum operating temperatures.

2.2. The organic cycles (HP and ORC)

The other innovative main systems involved in the RESTORE solution are the thermodynamic cycles based on organic fluids. Two main cycles can be identified. On the one hand, the Heat Pump cycle, which works during the system charge, exploits the medium temperature heat and electricity provided by RES and waste heat recovery to provide higher temperature heat required by the TCES. On the other hand, the Organic Rankine Cycle, which works during the system discharge, exploits the heat provided by the TCES thus generating electricity and providing heat to the temperature required by the District Heating.

In addition, the RESTORE project differentiates two solutions depending on the scale of the system: Small-Scale Machines based on volumetric machines and Large-Scale Machines based on turbomachinery, and being representative of systems able to provide heat for supporting decentralized and centralized DHC networks respectively.

Depending on the boundary conditions imposed by each use case, the solution could be:

a) Full reversibility: also named within the project as reversible Organic Rankine Cycle (rORC). In this solution both organic cycles are integrated into a one-system reversible machine sharing almost all the components (except valves and circulating pumps). This unique machine operates as Heat Pump during the charge and as Organic Rankine Cycle during the discharge. This solution is only suitable for solutions based on volumetric machines (small scale).

b) Medium reversibility: both organic cycles adopt the same working fluid and share most components but not all of them. In this case, the compressor and the expander are different machines while the same heat exchangers can be used in both modes. This solution is suitable for both small and large-scale applications unless very different operating pressures in charging and discharging modes at both the high temperature and low temperature heat exchangers would not imply the use of different components.

c) Split systems: the organic cycles do not share any of their components and two different working fluids can be used. This solution is suitable for both small and large-scale applications and it is more adequate for the two reactors TCES.

Regarding the working fluid(s) the following general requirements are identified:

- The organic fluids used must be friendly with the ozone layer (according to the Regulation 2037/2000 European Parliament and similar regulations) having zero Ozone Depletion Potential (ODP)
- The organic fluids must have low or non-toxicity. If the use of a toxic fluid cannot be avoided, security standards must be applied for all the components.
- If the organic fluid is flammable under the conditions defined for the cycle, the associated security standards must be applied for all the components.
- Materials of all components must be fully compatible with the organic fluid chosen.

2.2.1. Fully reversible organic cycles (rORC)

As introduced above, in this solution there is a unique machine that can be operated for charge (heat pump mode) and discharge (Organic Rankine Cycle, ORC mode). This solution is only addressable using volumetric machines, thus only available for small-scale facilities.

The following components can be easily differenced in the rORC:

- High temperature heat exchanger: working as Condenser on Heat Pump mode and Evaporator on ORC mode.
- Low temperature heat exchanger: working as Evaporator on Heat Pump mode and Evaporator on ORC mode.
- Volumetric machine: working as both compressor and expander.
- Pumps and expansion valves: Connected in parallel. Valves are used for the Heat Pump mode while Pumps are used in the ORC mode.

In addition, a Regenerator(s) could be also integrated into the cycle in order to improve the efficiency of the system or to avoid two phase flow in compression although although it leads to an increase in the cost. This must be evaluated in each use case.

The following general specifications can be defined for the rORC:

rORC General Specifications		
Parameter	**Value**	**Unit**
Organic fluid		
COP (Heat pump mode)		
Electrical efficiency (ORC mode)		%
Nominal organic fluid mass flow in charge mode		kg/h
Nominal organic fluid mass flow in discharge mode		kg/h

In addition, specific template datasheets and requirements of the different main components involved in the rORC are shown in the following sections.

2.2.1.1. The High pressure heat exchanger

The high pressure heat exchanger is in charge of transferring/receiving heat to/from the thermochemical reactor. It works as a condenser when the machine is operated in Heat pump mode and as an evaporator when the machine works as ORC. It is commonly integrated inside the thermochemical reactor as a coil heat exchanger. The double reactor solution is not required in this solution, since the same coiled heat exchanger can work as a condenser (plus vapor desuperheating) in the heat pump charging reactor and as an evaporator (plus liquid preheating) in the ORC discharging the reactor.

The specifications for the high pressure heat exchanger are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

High pressure heat exchanger		
Parameter	**Value**	**Unit**
Heat Pump mode		
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature (If superheating)		°C
Organic fluid outlet temperature (If subcooling)		°C
Heat transfer coefficient at nominal conditions		$W/m^2\ K$
Heat transferred at operating conditions		kW_{th}
ORC mode		
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature		°C
Organic fluid outlet temperature		°C
Heat transfer coefficient at nominal conditions		$W/m^2\ K$
Heat transferred at operating conditions		kW_{th}
Constructive parameters		
Heat exchanger type	Coil inside reactor	
Heat transfer area		m^2
Diameter of tubes		cm
Tubes thickness		cm
Drum capacity		m^3

The list of requirements of the high pressure heat exchanger is the following:

- The definition of the heat exchanger must be compatible with the thermochemical reactor specifications.
- The heat exchanger must include a drum/phase separator in order to guarantee single phase fluid at the outlet avoiding vapor fraction at throttling valve inlet (Heat Pump mode) and liquid fraction at turbine inlet (ORC mode).

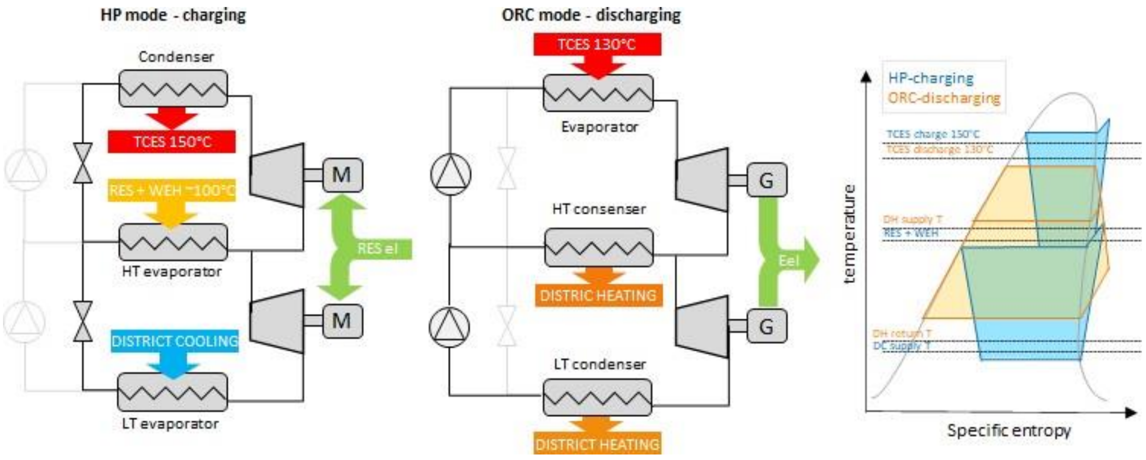
2.2.1.2. The low pressure heat exchanger

The low pressure heat exchanger works as an evaporator in the Heat Pump mode, harnessing the medium-temperature heat provided by the RES or the waste heat recovery. During the discharge, it operates in ORC mode providing heat to the district heating.

The specifications for the low temperature heat exchanger are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Low pressure heat exchanger		
Parameter	**Value**	**Unit**
Heat Pump mode		
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature		°C
Organic fluid outlet temperature		°C
Heat transfer coefficient at nominal conditions		$W/m^2\ K$
Heat transferred at nominal conditions		kW_{th}
ORC mode		
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature		°C
Organic fluid outlet temperature		°C
Heat transfer coefficient at nominal conditions		$W/m^2\ K$
Heat transferred at nominal conditions		kW_{th}
Constructive parameters		
Heat exchanger typology	Plate Hx	
Heat transfer area		m^2
Diameter of tubes		cm
Tubes thickness		cm

In some cases, a double low pressure heat exchanger could be included, depending on the requirements of the specific case. This double configuration allows a double evaporator in the Heat Pump mode, each evaporator will work at a different temperature level providing thus increasing the capacity of integrating different heat sources (for instance, integrating RES and WHR sources that provide heat at different temperature levels, or involving an evaporator for providing cooling services for District Cooling). In the same way, during the discharge, the system can provide heat at two temperature levels with a better matching with the District Heating water. This possibility will be investigated only for use cases that may include district cooling in summer months.



The list of requirements of the low pressure heat exchanger is the following:

- The heat exchanger must be able to receive heat at the temperate provided by the RES and WHR.
- The heat exchanger must be able to deliver heat at the temperature required by the District Heating.

2.2.1.3. The Recuperator

Recuperator is required in order ensure a compression process in vapor phase avoiding liquid droplet formation that may reduce machine efficiency. As additional benefit it allows to reduce the throttling valve inlet enthalpy thus increasing the liquid fraction at evaporator inlet and the COP of the Heat pump. Finally in discharging mode it allows for a preheating of the working fluid before entering in the reactor, increasing the fluid mass flow rate and the cycle performance.

The specifications for the low temperature heat exchanger are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Recuperator		
Parameter	**Value**	**Unit**
Heat Pump mode		
Pressure inside tubes at nominal conditions		bar
Pressure outside tubes at nominal conditions		bar
Liquid phase inlet temperature		°C
Liquid phase outlet temperature		°C
Vapor phase inlet temperature		°C
Vapor phase outlet temperature		°C
Heat transfer coefficient at nominal conditions		W/m² K
Heat transferred at nominal conditions		kW_{th}

ORC mode		
Pressure inside tubes at nominal conditions		bar
Pressure outside tubes at nominal conditions		bar
Liquid phase inlet temperature		°C
Liquid phase outlet temperature		°C
Vapor phase inlet temperature		°C
Vapor phase outlet temperature		°C
Heat transfer coefficient at nominal conditions		W/m² K
Heat transferred at nominal conditions		kW_{th}
Constructive parameters		
Heat exchanger typology		
Heat transfer area internal		m²
Heat transfer area external		m²
Diameter of tubes		cm
Tubes thickness		cm

2.2.1.4. The Volumetric reversible machine

The volumetric reversible machine works as a compressor in the Heat Pump mode and as an expander in the ORC mode. An electric device able to work as a motor in the charge or a generator in the discharge must be connected to the volumetric machine. Scroll and screw compressors/expanders are versatile machines that can be used in reversible mode. Both are the most promising technologies for the volumetric reversible machine.

The specifications for the volumetric machine are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Volumetric reversible machine		
Parameter	**Value**	**Unit**
Heat Pump mode		
Inlet pressure		bar
Outlet pressure		bar
Inlet Temperature		°C
Outlet Temperature		°C
Mass flow		Kg/h
Oil charge		ml

Volume ratio		-
ORC mode		
Inlet pressure		bar
Outlet pressure		bar
Inlet Temperature		°C
Outlet Temperature		°C
Mass flow		Kg/h
Volume ratio		-
Electric connection		
Power consumption in motor mode		kW
Power generation in expander mode		kW
Voltage range		V
Frequency		Hz
Phases	1 or 3 Phase(s)	

The list of requirements of the volumetric machine is the following:

- The electric motor coupled to the system must be reversible, which means it must be able to work also in generator mode for discharge.
- The volumetric machine must be able to operate at the required pressures in compressor mode as well as in the expander mode possibly adapting its geometry to the actual cycle pressure ratio.
- Lubricating oil is required in the compressor mode in order to avoid damaging the machine (e.g. seizure)

2.2.1.5. Pumps and expansion valves

Both are connected in parallel, a three-way valve deviates the flow through the valves or the pump depending on the operating mode. The organic fluid circulates through the valve side in the Heat Pump mode, adapting the conditions to the demand of the evaporator. In ORC mode the fluid circulates through the pump, which is in charge of increasing the pressure to the one demanded in the evaporator.

The specifications for the expansion valves and the pumps are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Valves and pumps		
Parameter	**Value**	**Unit**
Valves		
Inlet pressure		bar

Outlet pressure		bar
Pumps		
Inlet pressure		bar
Outlet pressure		bar
Mass flow		Kg/h
Pumps electric connection		
Power		kW
Voltage range		V
Frequency		Hz
Phases	1 or 3 Phase(s)	

2.2.2. Mid-reversible organic cycles

In this case, the HP and ORC organic cycles use the same working fluid and share the low pressure and high pressure heat exchanger. However, the compressor and the expander are different machines. During the charge, the organic fluid circulates through the compressor increasing its pressure and temperature. During the discharge the organic fluid circulates through the expander, decreasing its pressure and temperature and generating electricity. This solution is suitable for both small and large-scale applications. In the case of large scale, due to the higher size of the systems and thus high organic fluid mass flow, the turbomachines are more suitable for working as compressors and expanders. In the case of small scale, volumetric machines are more adequate for the compressor and the expander.

In this case, the datasheets and requirements of the following subsystems are similar to the shown in the previous section: High pressure heat exchanger, low pressure heat exchanger, pumps and expansion valves. However, the compressor and the expander are not the same machines thus they have their own datasheet. Thus, this section will only show the subsection of the compressor and the expander, being the template of the datasheets and the list of requirements of the other components exactly similar to the shown in the previous section.

The following general specifications can be defined for the Mid-reversible organic cycles:

Mid-reversible cycles. General Specifications		
Parameter	**Value**	**Unit**
Organic fluid		
COP (Heat pump mode)		
Electrical efficiency (ORC mode)		%
Nominal organic fluid mass flow in charge mode		kg/h
Nominal organic fluid mass flow in discharge mode		kg/h

2.2.2.1. Compressor

Only works when the system is operated in Heat Pump mode. A three-way valve is switched to deviate the organic mass flow through the compressor which is moved by an electric motor in order to increase the pressure up to the one required by the high temperature heat exchanger (directly related to the temperature demanded by the thermochemical reactor). The type of compressor could be based on volumetric machines or turbomachinery, the most convenient would depend on the size of the whole system, specifically, the organic mass flow that circulates through the compressor directly related to the amount of heat demanded in the reactor in charge mode.

The specifications for compressors are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Compressor		
Parameter	**Value**	**Unit**
Type of compressor	*Scroll, screw, axial, radial…*	
Inlet pressure		bar
Outlet pressure		bar
Inlet Temperature		°C
Outlet Temperature		°C
Specific volume at the suction		m³/kg
Mass flow		kg/h
Oil charge		ml
Volume ratio		-
Electric connection		
Power consumption		kW
Voltage range		V
Frequency		Hz
Phases	1 or 3 Phase(s)	

The list of requirements of the compressor is the following:

- The compressor must be able to increase the pressure to the one demanded by the high temperature heat exchanger while operating at the suction pressure imposed by the low temperature heat exchanger.
- Lubricating oil is required in the compressor mode in order to avoid damaging the machine (e.g. seizure)

2.2.2.2. Expander

Only works when the system is operated in ORC mode. A three-way valve is switched to deviate the organic mass flow through the expander which moves an electric generator in order to produce electricity while the pressure is decreased up to the pressure demanded in the low-temperature heat exchanger (directly related to the temperature demanded by the District Heating). As the compressor, the type of expander could be based on volumetric machines or turbomachinery, the most convenient would depend on the size of the whole system, specifically, the organic mass flow that circulates through the expander.

The specifications for expanders are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Expander		
Parameter	**Value**	**Unit**
Type of expander	*Scroll, screw, axial, radial…*	
Inlet pressure		bar
Outlet pressure		bar
Inlet Temperature		°C
Outlet Temperature		°C
Mass flow		Kg/h
Volume ratio		-
Electric connection		
Power generation		kW
Voltage range		V
Frequency		Hz
Phases	1 or 3 Phase(s)	

The list of requirements of the compressor is the following:

- The expander must be able to expand the fluid from the value set by high temperature heat exchanger up to the level required by the low temperature heat exchanger (directly related to the temperature demanded in the District Heating).

2.2.3. Split systems.

In that case, the two cycles can adopt a different working fluid and do not share any of their components, being the Heat Pump totally independent of the Organic Rankine Cycle. It allows the decoupling of the charge and discharge processes adapting them to particular issues imposed by the use-case. This solution is suitable for both small and large-scale applications, although the use of different machines decreases the compactness of the whole system which is relevant for small-scale applications. This solution is more adequate for the two-reactor thermochemical system, allowing the designing and optimization of the charge and the discharge reactor independently.

This section is divided into the mentioned two main subsystems: the Heat Pump and the ORC, each one containing its associated components.

2.2.3.1. The Heat Pump

Working during the charging process, the Heat Pump adapts the medium temperature heat provided by the RES or the WHR to the conditions required by the Condenser. To run the compressor, it is required an electric motor whose power consumption can by provided by electric RES.

The following main components can be identified in the heat pump: the condenser, the evaporator, the compressor and the expansion valve. The compressor and recuperator sections are not shown due to the template of the datasheet of these components and the requirements similar to section 2.2.2.1 and 2.2.1.3 respectively.

The general specifications of the heat pump are:

Heat Pump General Specifications		
Parameter	**Value**	**Unit**
Organic fluid		
COP		
Nominal organic fluid mass flow		kg/h

In addition, specific datasheets and requirements of the different main components involved in the heat pump are shown in the following sections.

2.2.3.1.1. Heat pump condenser

Where the organic fluid condenses at high pressure, providing heat to the thermochemical reactor. It is commonly integrated inside the thermochemical reactor as a coil heat exchanger. It must include a drum in order to guarantee the phase change of the organic fluid within the coil.

The specifications for the Heat Pump condenser are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Heat pump condenser		
Parameter	**Value**	**Unit**
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature (If superheating)		°C
Organic fluid outlet temperature (If subcooling)		°C

Heat transfer coefficient at nominal conditions		W/m^2 K
Heat transferred at operating conditions		kW$_{th}$
Constructive parameters		
Heat exchanger type	Coil inside reactor	
Heat transfer area		m^2
Diameter of tubes		cm
Tubes thickness		cm
Drum capacity		m^3

The list of requirements of the ORC condenser is the following:

- The definition of the heat exchanger must be totally compatible with the thermochemical reactor specifications.
- The heat exchanger must include a drum in order to guarantee phase change in the reactor.

2.2.3.1.2. Heat pump evaporator

Where the organic fluid is evaporated at low pressure, using the heat provided by the RES and WHR. A double evaporator configuration could be possible for those cases where the heat pump must harness heat from two different temperature levels. In the case of using a double evaporator, the template datasheet associated with the 2nd evaporator is similar to the previous one.

Heat pump evaporator		
Parameter	**Value**	**Unit**
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature		°C
Organic fluid outlet temperature		°C
Heat transfer coefficient at nominal conditions		W/m^2 K
Heat transferred at nominal conditions		kW$_{th}$
Constructive parameters		
Heat exchanger typology	Plate Hx	
Heat transfer area		m^2
Diameter of tubes		cm
Tubes thickness		cm

The list of requirements of the Heat pump evaporator is the following:

- The heat exchanger must be able to receive heat at the temperate provided by the RES and WHR.

2.2.3.1.3. Expansion valve

The expansion valve adapts the organic flow from the condenser to the conditions demanded by the evaporator (directly related to the conditions of the heat supply). The specifications of the expansion valve are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Expansion valves		
Parameter	**Value**	**Unit**
Valve type		
Inlet pressure		bar
Outlet pressure		bar

2.2.3.2. Organic Rankine Cycle

Working during the discharge process, the ORC adapts the heat provided by the thermochemical reactor to the conditions required by the District Heating. Its expander moves a generator which produces electricity that can be used by the District. The following main components can be identified in the ORC: the evaporator, the condenser, the expander and the circulating pumps. The expander and recuperator sections are not shown due to the template of the datasheet of these components and the requirements similar to section 2.2.2.2 and 2.2.1.3 respectively.

The general specifications of the ORC are:

ORC General Specifications		
Parameter	**Value**	**Unit**
Organic fluid		
Electric efficiency		
Nominal organic fluid mass flow		kg/h

In addition, specific datasheets and requirements of the different main components involved in the ORC are shown in the following sections.

2.2.3.2.1. ORC evaporator

Where the organic fluid is evaporated at high pressure, using the heat provided by the discharge of the thermochemical reactor. It is commonly integrated inside the thermochemical reactor as a coil heat exchanger. It must include a drum in order to guarantee the phase change of the organic fluid within the coil.

The specifications for the ORC evaporator are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

ORC evaporator		
Parameter	**Value**	**Unit**
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature		°C
Organic fluid outlet temperature		°C
Heat transfer coefficient at nominal conditions		$W/m^2 K$
Heat transferred at operating conditions		kW_{th}
Constructive parameters		
Heat exchanger type	Coil inside reactor	
Heat transfer area		m^2
Diameter of tubes		cm
Tubes thickness		cm
Drum capacity		m^3

The list of requirements of the ORC evaporator is the following:

- The definition of the heat exchanger must be totally compatible with the thermochemical reactor specifications.
- The heat exchanger must include a drum in order to guarantee to provide organic fluid vapor to the expander.

2.2.3.2.2. ORC condenser

Where the organic fluid is condensed at low pressure, providing heat to the District Heating. A double evaporator configuration could be possible if the heat is demanded at two different temperature levels. The specifications for the ORC condenser are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

ORC condenser		
Parameter	**Value**	**Unit**
Pressure inside tubes at nominal conditions		bar
Phase change temperature at nominal conditions		°C
Organic fluid inlet temperature		°C
Organic fluid outlet temperature		°C

Heat transfer coefficient at nominal conditions		W/m² K
Heat transferred at nominal conditions		kW_{th}
Constructive parameters		
Heat exchanger typology	Plate Hx	
Heat transfer area		m²
Diameter of tubes		cm
Tubes thickness		cm

The list of requirements of the ORC condenser is the following:

- The heat exchanger must be able to deliver heat at the temperature required by the District Heating.

2.2.3.2.3. Pump

The pump is in charge of increasing the pressure to the value required by the evaporator of the ORC system (directly related to the conditions of the discharge of the thermochemical reactor). The specifications of the pump are stated in the following template datasheet which summarizes the main parameters. The value of these parameters must be defined in an ad-hoc solution.

Circulating pump		
Inlet pressure		bar
Outlet pressure		bar
Mass flow		kg/h
Pumps electric connection		
Power		kW
Voltage range		V
Frequency		Hz
Phases	1 or 3 Phase(s)	

3. RESTORE interfaces

The RESTORE concept can be applied to a large variety of use-case in order to integrate green energy sources, such as renewable energy sources but also waste excess heat recovered from industrial proccesses, in the district heating and cooling networks. Two type of connections are distingused:

Connection to other systems that provide clean energy (sources).

Connection to other systems that receive energy from the RESTORE system (sinks).

3.1. Sources

The energy sources provide energy to the RESTORE system during its charge. A wide variety of potential sources that can be integrated in the RESTORE concept are studied. The sources can be classified in heat and electricity sources. In addition, the heat sources can be classified considering its operation temperature levels. High-temperature sources (with heat supply temperatures above 10 K higher than the thermochemical reaction temp.) can be directly exploited by the thermochemical energy storage (TCES). However, lower temperature sources, such as, waste heat, non-concentrating solar thermal energy or low-enthalpy geothermal, are integrated in the heat pump organic cycle. The electricity sources, provides the required supply demanded by the heat pump during the charge.

3.1.1. Heat sources

The heat sources provide the thermal energy required by the TCES during the charge process. Several renewable technologies are compatible with the RESTORE system but also the waste heat. In this section, a review of the different potential heat sources compatible with the RESTORE solution is stated and discussed.

3.1.2. Solar Thermal Energy

The renewable technologies that harness the sun radiation in order to provide thermal energy are very suitable for the RESTORE concept. Globally, 260 large-scale solar-based DH systems were in operation in 2020 and it is estimated that it will represent between up to 15% of the installed capacity of all solar thermal systems [1]. **These kind of plants can be centralized or distributed and RESTORE project will assess both of them.** However, authors have carried out a techno-economic evaluation in order to compare these two types of solutions and results showed that **centralized systems present significantly lower cost than distributed solar system**, specifically this cost reduction was found to be higher for low-temperature networks [2]. In the case of RESTORE, centralized plant are more suitable, due to solar generation is closer to the RESTORE system, thus minimizing the thermal losses, especially important if the solar technology provides heat at high temperature.

Typically, these solar thermal plants circulate a heat transfer fluid, which is heated up in the solar thermal collectors on an open field installation or less often on large scale roof installations. Heat exchangers are typically used to decouple the district heating grid from the solar field. A storage tank or buffer tank is utilised to store peak heat generation on hot and sunny summer days for heat supply during the night hours or periods with higher demand or lower solar heat supply. Alternatively seasonal heat storages can be utilized, as intended by RESTORE.

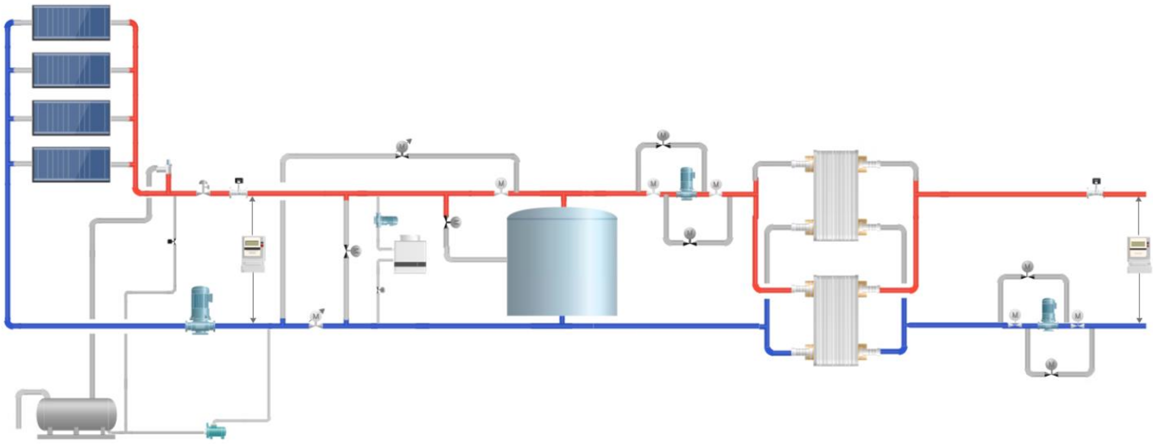


Figure 1. Schematic depiction of a solar thermal system with storage tank and heat exchangers to the district heating grid.

Several technologies are found for the production of thermal energy, this section differentiates between technologies using solar concentration and non-concentration.

The **operation temperature of non-concentrating solar thermal collectors in DH networks is typically between 40 °C and 95 °C so in the case of RESTORE they must be integrated in the heat pump cycle in order to provide suitable heat for the TCES**. Considering that their efficiency decrease as temperature levels increase, its application in low-temperature DH networks (4G or 5G) becomes highly recommended. It has been analysed that the efficiency of a commercial flat plate can reach up to 70 % when operating temperature is about 40 °C, which corresponds to a 50-30 °C DH network. Nevertheless, when average fluid temperature increases to 70 °C - which corresponds to a 90-50 °C DH network – efficiency decreases to 60 % [3].

Flat plate collectors as well as other non-concentrating collectors are typically classified by the voluntary third-party certification mark Solar Keymark, which is internationally recognized. Solar thermal products are classified and listed in the Solar Keymark data base, allowing to compare flat plate collectors for different locations (Athens, Davos, Stockholm, Würzburg) and mean temperatures between in- and outlet of the solar thermal field. The results for the annual heat output per gross collector area of common non-concentrating solar collectors for district heating purposes is shown in the following figure below. As mentioned before, it can be seen that an increase in temperature decreases the efficiency of the collectors.

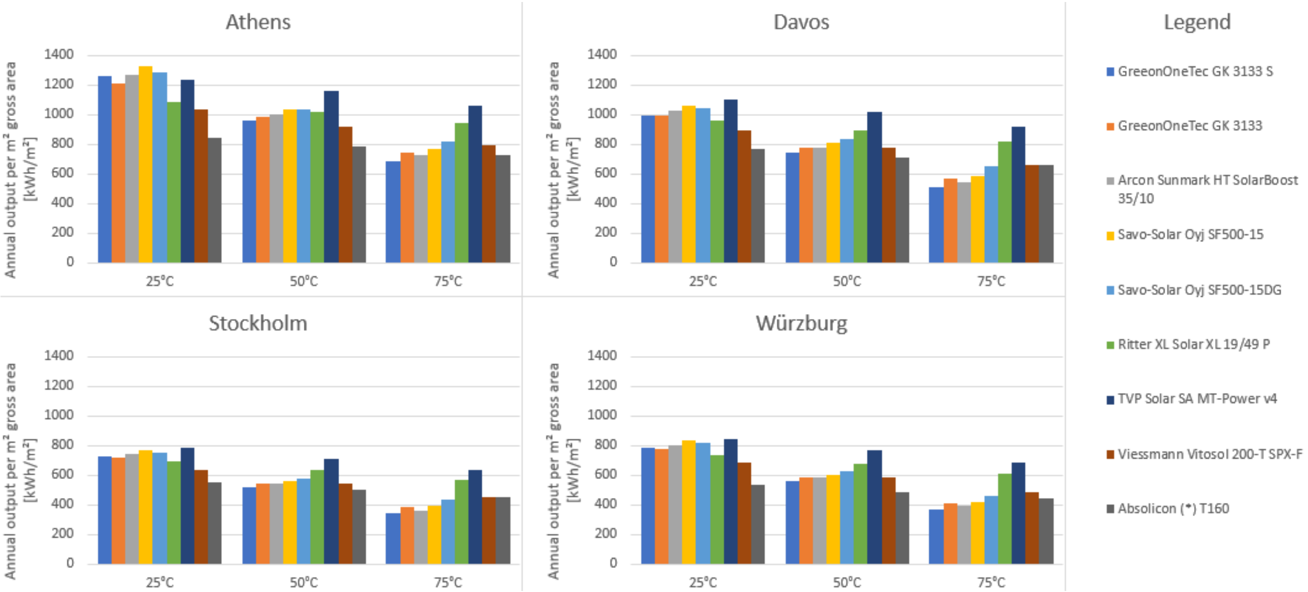


Figure 2. Annual heat output per m² gross collector area in kWh/m² for the selected location and temperatures according to Solar Keymark results.

A visualisation of the performance of common non-concentrating solar collector technologies (flat plate, vacuum-isolated flat plate and vacuum isolated tube) and suppliers for district heating purposes over the temperature difference is depicted in the following figure. Again, it can be seen that an increase in temperature decreases the efficiency of the collectors.

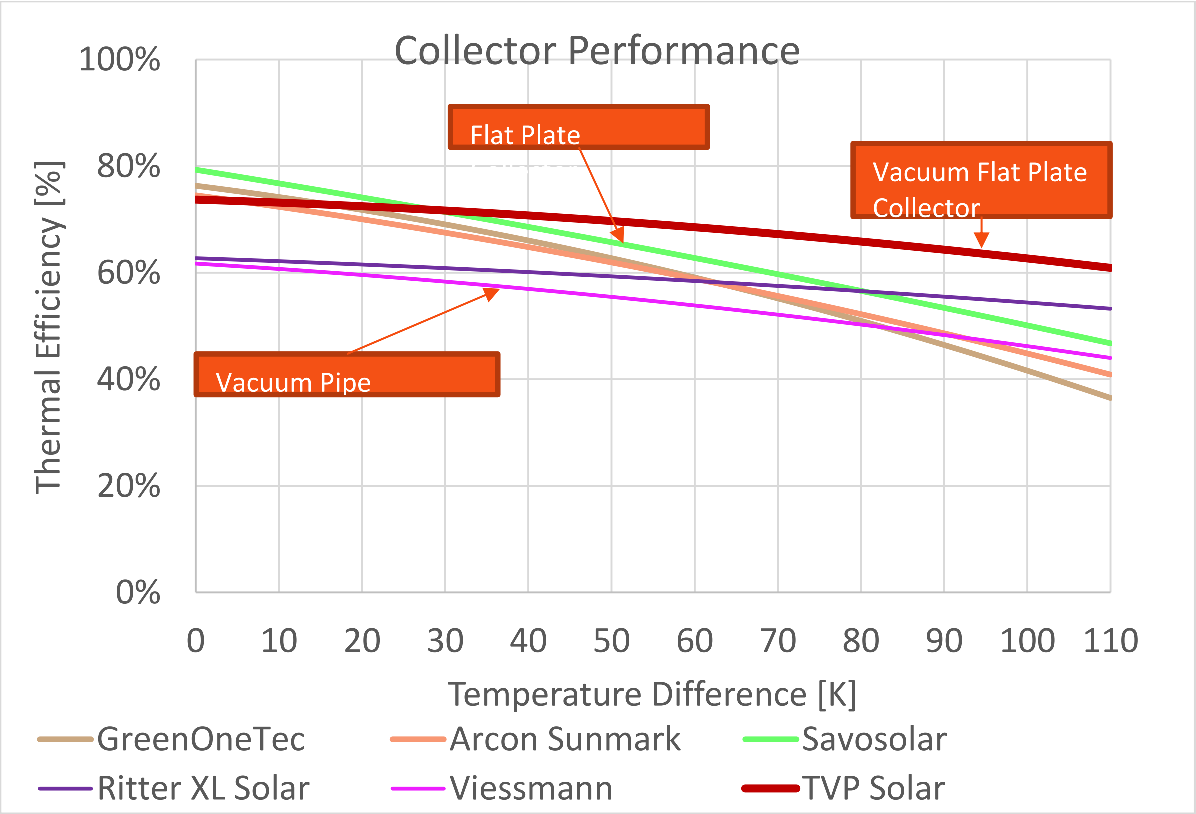


Figure 3. Collector performance of different technologies and suppliers depending on the temperature difference.

Although typically commercial non-concentrating solar thermal collectors are able to provide hot water up to 100 °C, it is highly recommended to avoid higher operating temperatures than 80-90 °C. For providing heat at higher temperature, a potential solution is combine **non-concentrating solar thermal collectors with parabolic trough collectors in series**, which can even reduce LCOH by about 5-9 % [4], although it also increases the system complexity.

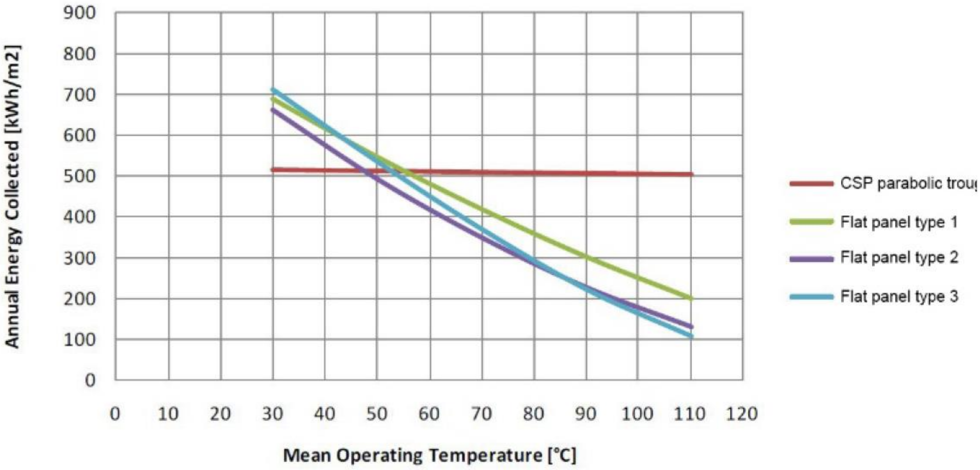


Figure 4. Parabolic trough collector performance vs. flat plate collectors in low heating temperatures [5].

In regard to concentration solar technologies, it is mainly composed of parabolic trough collectors, linear Fresnel reflector systems and tower systems. As it has been mentioned above, this technology brings about an increment in operating temperatures. Thus, the main consequence is that **concentrated solar power can be directly exploited by RESTORE in the TCES**. Another point is that typically this energy sources are centralized, so **an excellent insulation in the connection network, as well as minimize its length, is compulsory in order to avoid excessive heat losses due to high temperatures**. Parabolic trough and Fresnel in industrial processes usually provide heat between 100-·300 °C which is totally compatible with direct integration in the TCES. Tower systems are more competitive for generating heat at higher temperatures, although it could be harnessed by the thermochemical reactor, it is not required by the system, so linear focus technologies (Fresnel and Parabolic trough) are more suitable for the RESTORE concept.

Another important issue to consider in the solar thermal technology is that finding and providing enough space for solar collectors is not always easy when integrating the system into an urban environment. It is reported that **big buildings in the commercial or residential sector could offer enough roof space** to integrate large-scale collectors in urban environments. However, it is necessary to point out that PV technology requires its own space as well. Another solution might include the network extensions to access land in **low density urban periphery [6].**

As summary of the combination of the solar technologies in the RESTORE concept, non-concentrating technologies hardly reach temperature above 100 °C, thus they must be integrated in the low pressure heat exchanger in the heat pump mode while concentrating technologies are suitable to provide heat at higher temperatures thus being able to provide heat directly to the TCES.

In the context of the project, a specific case considering solar energy, specifically, Parabolic trough collectors, will be analysed (Use-Case I), where these collectors are also combined with biomass.

3.1.3. Geothermal Energy

The geothermal energy is another renewable source quite suitable for its integration with the RESTORE system. Geothermal technology is the most mature renewable energy used in the context of DH systems so it presents less challenges and barriers than other renewable energies. In Europe there are already 240 districts heating systems integrated with geothermal energy ranging from small systems (0.5-2-0 MW_{th}) to large ones with a capacity over 50 MW_{th}[1]. However, the assessment of the geothermal resources can be a significant upfront cost with high risks and disclosure of information on geological condition varies between countries.

Geothermal sources can be classified depending on its temperature into high enthalpy (> 180 °C) resources, medium (100-180 °C) and low enthalpy (<100 °C) resources that are used to produce heat [10]. According to the barriers associated to its size, the limited extension and low spatial spread of demand in smaller cities facilitates the addition of geothermal plants, while the diversity of large networks facilitates the identification of suitable locations within the existing infrastructure; i.e. integration of a well at a central location next to an existing CHP plant [6].

In addition, these geothermal systems can be further categorized as open-, close- or fully close-loop. Open-loops utilize directly the water from wells to circulate it through radiators, close-loops make use of an intermediary above-the-ground heat exchanger that transfers heat from the geothermal water to heated water through the system and fully close-loops use boreholes with closed pipes typically in U-shape configuration. Although open-loops can provide higher temperatures and capacities, RESTORE solutions – as far as possible - will focus on fully close-loops given that it reduces the environmental impact and helps to maintain and manage the reservoir. Pipes and radiative heat exchangers must be correctly dimensioned since lower water temperature in the network return line allows a greater fraction of the heat content to be extracted from the geothermal hot water.

According to the literature, a single connection/geothermal collector provides more revenue than that for several, smaller energy consumers. Thus, district heating enhances the application of this renewable energy.

High-temperature geothermal systems could be directly integrated with TCES. Mid-temperature can be integrated directly in TCES in case the heat provided is above 10°C higher than the temperature of the charging reaction or in the heat pump in case of providing a lower temperature. The very shallow geothermal systems with low-temperatures could be integrated with the heat pump thermodynamic cycle.

In the context of the project, a specific case considering geothermal energy will be analysed, (Use-Case V), where heat can be used as a direct supply to district heating and hot temperatures are in the range of 120-140 °C suitable for the RESTORE exploitation.

3.1.4. Biomass Energy

The RES based on biomass is also suitable for RESTORE. As in the case of geothermal energy, the possibility of continuous operation (lack of intermittencies) makes biomass an attractive renewable energy source, although **it is typically used to cover base load/the bulk of heat due to the low flexibility of biomass boilers**. Nowadays, it is the dominating RES in DH systems given that Combined Heat and Power (CHP) systems are the most efficient way for energy production using biomass and it has been the simplest sustainable solution to replace the previous fossil-based CHP. However, biomass boilers are commonly combined with gas boilers as a back-up system to ensure high revenue and high reliability and cost of biomass differs greatly between countries and local regions. This has profound impacts on the viability of the proposed solution. To include the RESTORE solution allows storing the excess of energy during reduced demand periods and provide it replacing the gas based back-up system and thus making feasible a DH based 100% on RES.

There is a wide range of biomass CHP plants with different technology used to convert the energy and the components used in the process. It can be classified into anaerobic digestion, direct combustion (boilers) or gasification. The main point is that **existing biomass power plants have already a heat-to-power unit able to generate electricity. Hence, with regard to the integration of RESTORE concept, it would be uncomplicated to take advantage of this electricity and heat at different temperatures provided by the system at the same time.**

Heat recovery systems are located at the exhaust of the engine (i.e. steam turbine, gas turbine, internal combustion engine…) and they are typically **Heat Recovery Steam Generators (HRSG), condensers in the steam turbine system or condensers in Organic Rankine cycles.**

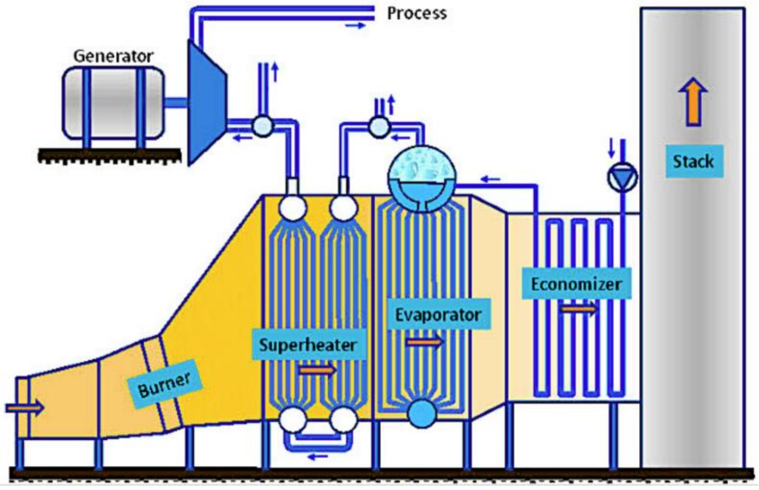


Figure 5. Scheme of heat recovery steam generator (HRSG) with steam drum and duct burner [12].

In first place, **RESTORE solution could make use of the steam from HRSG and transfer heat directly to TCES reactor**. It depends on the specific plant, but this steam can be at temperatures in the range of **250-400 °C** that could conveniently fit with the chemical reaction. Secondly, the **steam outlet of the turbine** can be in the range of **150-250 °C**, so it could be directly integrated with RESTORE high-temperature level as well [13]. Finally, small-scale or distributed biomass plants include Organic Rankine Cycles. In this cases, operating temperatures are lower but enough to supply hot water to district heating networks (i.e. at **85 °C** [14]) or store energy in TCES through RESTORE heat pump evaporators.

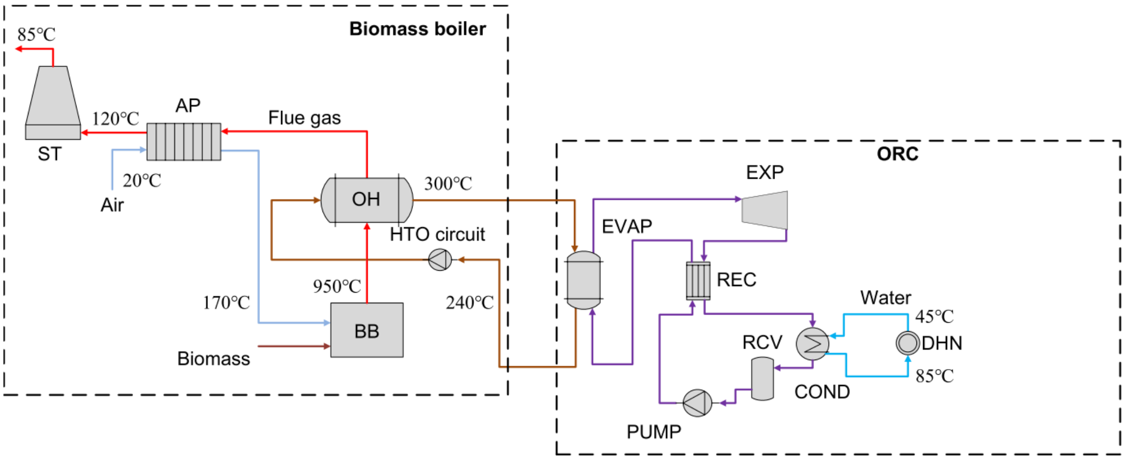


Figure 6. Example of the layout of a biomass CHP plant integrated with ORC. District heating connected to ORC condenser. Plant without energy storage [14].

3.1.5. Waste Heat

At this phase, the project will be focus on industrial waste heat, although it could also be suitable for other forms of urban waste/surplus heat such as the waste heat produced by data-centers and other urban buildings or facilities (e.g. metro).

Industrial waste heat is the energy that is generated in industrial processes and that cannot be exploited to any practical use within the industrial process, so it is lost, wasted and dumped into the environment [7]. Waste heat sources can be classified according to its industrial processes, temperature ranges or intermittency and each case will bring about different boundary conditions. For instance, **waste heat from industrial processes can be supplied to DH networks either using heat pumps or via direct heat exchange (WHR – waste heat recovery).**

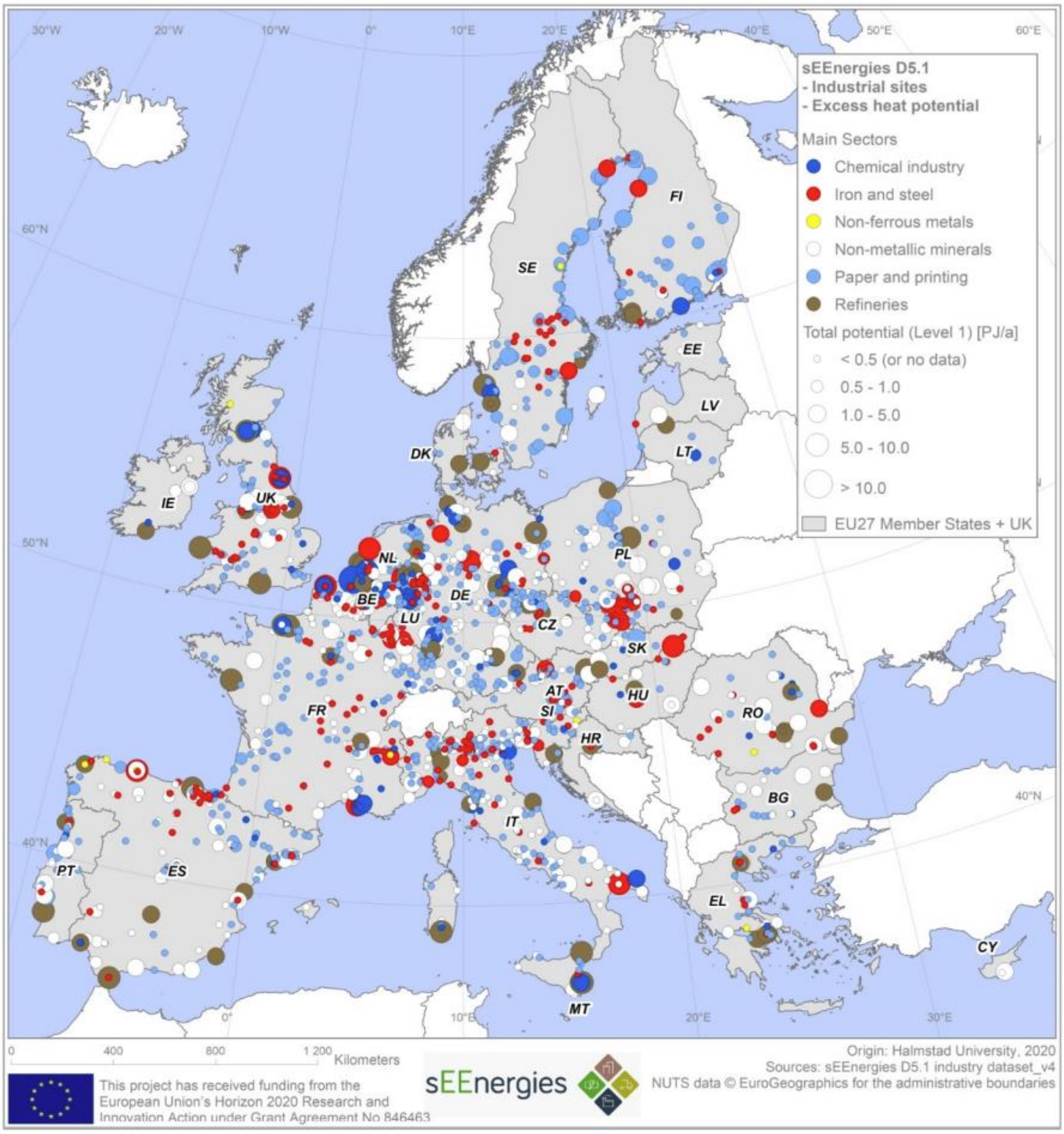


Figure 7. EU29 map of relevant georeferenced industrial sites by Main Sectors with Level 1 (exhaust gas cooled to ambient temperatures - 25 °C) excess heat potential at current rate of internal heat recovery [8].

The main barrier of waste heat as a source is that 50 % of industrial energy is at low-temperature range – between 30-100 °C – with **a major portion in the range of 30-40°C.** Then its application is typically restricted to supply 4G or 5G DH networks - supply/return of about 50/20 °C – with heating systems using low-temperature radiative heat exchangers like radiant floors so return temperature can be minimized and most of the waste energy recovered. Additionally, another particular requirement to design a cost-effective system is that **waste heat source/industrial factory needs to be close to DH network in order to reduce heat losses and initial investment on pipelines** [9]. Consequently, some authors have concluded that waste heat cannot lead the sustainable heat generation of all DH systems on global level, but it can be absolutely crucial in some specific industrial regions. High-temperature waste heat is commonly available far from the city centre, in which case distance can be a limit; low-temperature waste heat may be more diffused within the urban environment, but usually requires the use of heat pumps. In these cases, the low-temperature can be harnessed in the RESTORE heat pump. Due to the low temperature (30-40°C) the heat pump could integrated a double-evaporator configuration, it allows increasing the Coefficient of Performance of the heat pump and thus the amount of heat that can be harnessed by it. The first level can exploit the low temperature waste heat, meanwhile the second can be integrated with a RES which provides heat in the medium temperature range (70-140°C). In this cases, in order to couple the industrial waste heat and the RES production, **short-term buffers – water storage - for low-temperature hub shall be included as well.**

Other processes can provide waste heat at higher temperature levels. In case of medium temperature level (70-140°C), the heat can be exploited in a heat pump with only one evaporator. In case of higher temperatures it could be directly integrated in the TCES reactor.

Another challenge is that industrial production follows its own schedule and cannot be considered a dispatchable heat source for DH. Although RESTORE TCES mitigate this issue, it is necessary to point out that **in case of intermittent heat source, heat exchangers will be exposed to both low-temperature and high-temperature. Thus, it is required to ensure that its material does not fatigue because of the thermal cycling** [1].

Another non-technical obstacle to consider is that from financial and contractual standpoints, the main hurdle with industrial heat recovery is to ensure that the industrial plant will stay in operation long enough to pay off the investment cost of installation of heat exchangers and thermal grids [10].

Waste heat source is contemplated in three of the RESTORE virtual-cases. In all of them the possibility of combining them with other RES will be analysed.

With regard to RESTORE Use-Case II, the proposed solution will be integrated with a cement factory in Austria. In this case, waste heat can be obtained from different sources: the air that cools the clinker after the cement kiln, the gas from cyclone tower or even the extraction steam from a steam turbine. Nowadays, in most of the cement plants there is a conditioning tower that cools the gas before the bag filter in order to avoid exhausting high-temperature gas. Thus, one option to be studied in this use-case is to install a heat exchanger instead and recover that energy. **This gas is typically at 300-400 °C so it will be integrated with RESTORE high temperature level directly or through an extra loop with an intermediate heat transfer fluid.** An important point for this application is that the gas from the cement manufacturing process contains a huge amount of particles (80-100 grams of dust per Nm³) so layers of dust on the heat exchanger bundles decrease the thermal exchange. Therefore, **periodic –dry or wet – cleaning of heat exchanger and coatings applied on the pipes surface can reduce fouling, wear and corrosion.**

With respect to RESTORE Use-case III, a plant of the pulp and paper industry is connected to district heating (DH) and RES. There is a new recovery boiler, the mill is 100% energy self-sufficient with over 94% of its energy coming from renewable resources. Waste heat in the form of steam at 5 bar is used to heat up the district heating water through a heat exchanger station. **This heat exchanger station is the key component because conventional metal air preheaters are not suitable for deep cooling of flue gas**

because the acids in the flue gas will condense. Therefore, some commercial solutions propose the combination of a metal and polymer air preheater system able to preheat air from 25 to 179 °C and bring about a 6 % efficiency improvement. In a paper and pulp plant, a number of thermal processes are in operation, such as steam boilers, CHP installations, Dryers, regenerative thermal oxidizers (RTO's) and incinerators. However, in summer due to the reduced heat demand of the district, the energy is not fully harnessed. Thus, RESTORE Use-case III will assess this sector and overall manufacturing process in order to present different alternatives for waste heat recovery and how RES can be integrated in a real plant in Slovakia.

In relation to RESTORE Use-Case IV, the proposed solution will be integrated with a steel-working industry plant in Italy. The plant is composed by 2 electric arc furnace (EAF) units and 3 rolling mills. Waste heat recovery system is based on a large HP able to recover heat in the range of 30-40 °C from the cooling system of the furnaces and upgrade it up to 90 °C to supply the district heating. **According to the literature, steel industry has the highest potential for high-temperature waste heat utilization** including blast furnaces (BF) and electric arc furnaces (EAF), this second one presents much lower potential for waste heat recovery although the basic oxygen process fits the requirements. However, making top gas recovery with BF is difficult and uneconomical unless there is a large quantity of exhaust gas or in case of installation in a new system. In relation to recuperators, they need to be made of appropriate materials in order to tolerate high temperatures and corrosion [11]. **Thus, the integration of low temperature waste heat and large HP - as implemented in RESTORE Use-CASE IV – stands out as a suitable and efficient solution without much technical challenges, although high temperature heat integration will be also analysed.**

3.1.6. Only electrical base: Photovoltaic Solar Energy and Wind Energy

The RESTORE concept also allows the integration of RES that provide electricity. In this field, the most extended and competitive renewable technologies, i.e., the integration of PV technology and wind energy are the more interesting for providing electricity. These kind of non-dispatchable RES could be implemented by stand-alone systems and supply electricity directly to the heat pumps compressor and auxiliary consumptions. Special interest for the RESTORE concept are the **grid-connected systems**, this ensure high-reliability when the solution also exploits heat provided by other RES. **Both large-scale centralized plants far from the urban areas and small-scale distributed systems** installed on residential areas can be adopted by the RESTORE system, applying the large-scale or the small-scale concept depending on the boundary conditions imposed by each case.

In case of grid connected systems, the most important condition is that the output frequency and voltage must be matched with the grid’s frequency and voltage. And also, **the power quality maintains the grid standard thus is also guarantee the compatibility with the electric motor that runs the compressor heat pump**. In stand-alone systems, this requirement must be also considered, adapting the electric source or the electric motor for ensuring compatibility.

In relation to PV, it must be considered that energy from an array is direct current (DC). Hence, **inverters are required** to transform direct current (DC) into alternating current (AC). With regard to wind energy, alternating current (AC) is directly generated.

The most small-scale **(<100 kW)** widespread wind turbines are those with a **horizontal axis**, although the needs of urban areas have led to the emergence of **vertical solutions** in recent years. Referring to PV technology, it is estimated that **fixed racking systems** will be mounted on residential buildings and **horizontal single axis tracking systems** in suitable areas. Hence, both renewable energy sources ensure the ease of installation and maintenance.

3.2. Sinks

The sinks are defined as the systems that receive energy (thermal and electrical) from the RESTORE solution, thus the unique system considered are the District Heating and Cooling networks. This section is focused on reviewing and discussing the wide range of DHC networks, including its classification, the analysis of DHC state in Europe, main technical and non-technical issues and how to integrate it with the RESTORE concept in order to design the overall system.

3.2.1. DHC networks classification

The historical progression of district heating and cooling networks can be classified into **five generations**, which main characteristics have been summarized in Table 1. Traditional DH (1G, 2G and 3G) systems consist of centralised power stations that feed hot water or steam into pipes to distribute heat in urban areas. High-temperature DH systems still suffer from significant heat losses and high installation costs. Especially in summer, when generally many DH systems operate only to meet the DHW demand, the network thermal losses can reach a value of about 30% of the supplied energy because of the high retention time of water in the network [16]. However, 4G and 5G propose a reduction in the operating temperatures – or even variable set-point temperature according to the outside temperature - and the integration of renewable energy sources to contribute to the decarbonisation of the sector. **Therefore, RESTORE concept will mainly focus on the 4th and 5th generations that are expected to be the most common district heating and cooling networks in the following decades, as well as considering the adaptation of previous older existing DHC networks.**

Table 1. Summary of each District Heating and Cooling generation [16]–[19].

Generation	1st Generation	2nd Generation	3rd Generation	4th Generation	5th Generation
Period	1880-1930	1930-1980	1980-2020	2020-2050	2025-2075
Supply Temp (°C)	120-200	120-160	70-100	35-70	10-35
Pressure (MPa)	≥1.6	1.6	1.0	≤0.5	≤0.5
Heat carrier	Steam	Water	Water	Water	Water
Heat source	Fossil fuel	Fossil fuel	Fossil fuel + Renewable energy	Fossil fuel + Renewable energy	Renewable energy
Circulation systems	Steam pressure	Central pumps	Central pumps	Central and decentralized pumps	Central and decentralized pumps
Substations heat exchanger	No	Tube-and-shell heat exchanger	Without or with plate heat exchangers	Probably mostly with plate heat exchangers Introduction of flat-stations	Plate heat exchangers and flat-stations. Larger size.
Consumer heating system	High-temperature radiators (+90 °C) using steam or water	High-temperature radiators (+90 °C) using DH water directly or indirectly	Medium-temperature radiators (70 °C) using DH water directly or indirectly. Floor heating	Low-temperature radiators (50 °C). Indirect system. Floor heating	Low-temperature radiators (30 °C). Floor heating or radiant ceiling panels
Consumer hot water preparation	DHW tanks heated directly with steam or from a secondary water circuit.	DHW tank heated to 60 °C. Circulation at 55 °C when needed.	Domestic DHW heated to 60 °C. Circulation at 55 °C when needed. Heat exchanger heating DHW to 50 °C	Very efficient local heat exchangers preheat DHW and heat pump with buffer tank increases DHW temperature to 40 °C	An electric heater or a booster HP is used to raise the temperature for DHW preparation. DHW temperature is about 35-40 °C.
Advantages	For industrial setups, only	Reliable operation, high flexibility, and existing infrastructure	Reliable operation, high flexibility, and existing infrastructure	Low heat losses, integration of low-grade renewable heat sources, exergetically efficient	Allow recovering low-temperature excess heat and include RES. High modularity and flexibility. The same pipes can provide simultaneously both heating and cooling services to different buildings.
Disadvantages	High heat losses and exergetically inefficient	Exergetically inefficient, unable to integrate low-grade renewable sources	Limited integration of renewable energy sources and energy storage systems	Emerging technology, substations are more expensive, individual domestic hot water is needed	Emerging technology, electricity costs for HPs, high pumping cost per unit of energy due to small operative temperatures

3.2.2. Analysis of DHC in Europe

More than 50 % of the EU final energy consumption comes from heating and cooling activities, being the largest energy sector. However, **only 13 % of the energy demand for heating and cooling is supplied through DHC networks** with most of the primary energy supplied by fossil fuels (40 % natural gas, 29 % coal and 16 % biomass) [20]. A statistical survey carried out in 2017 on the DHC sector reports that **about 6000 district heating (DH) networks were in operation in Europe, while only 115 district cooling (DC) networks were identified** [21] (some of them are represented in Figure 8). However, RESTORE project will focus on DH, DC and DHC, given that it is expected a huge growth in the cooling service thanks to the implementation of 4th and 5th generations in the following decades.

The integration of district cooling in the existing district heating networks appears also as a crucial leverage for new efficiencies and a higher RES integration. The cooling demand keeps growing, due to climate change and higher air quality standards in efficient buildings. Therefore, **co-production of heating and cooling is more efficient than separate production**, and DC has numerous advantages with respect to alternative individual chillers, such as lower costs in dense areas, lower environmental impact, better flexibility and reduced space use [15].

Nowadays, the huge majority of DHC networks belong to 3th generation or even 2nd generation. In relation to 4th generation, cooling is announced to be implemented in the following years and it has already been successfully operated in several commercial applications or systems. Finally, 5th generation networks are at the early stage of development so only few systems are still operating as pilot projects.

In addition, it is claimed that the district heating and cooling industry across Europe looks rather heterogeneous in terms of technological status, economic approaches and policies related to energy savings and environmental conditions [22]**.** For instance, only 2 to 7 % of heating and cooling in North West Europe is covered by district networks, whereas in North and East Europe the share of DHC can reach more than 50 % [23].

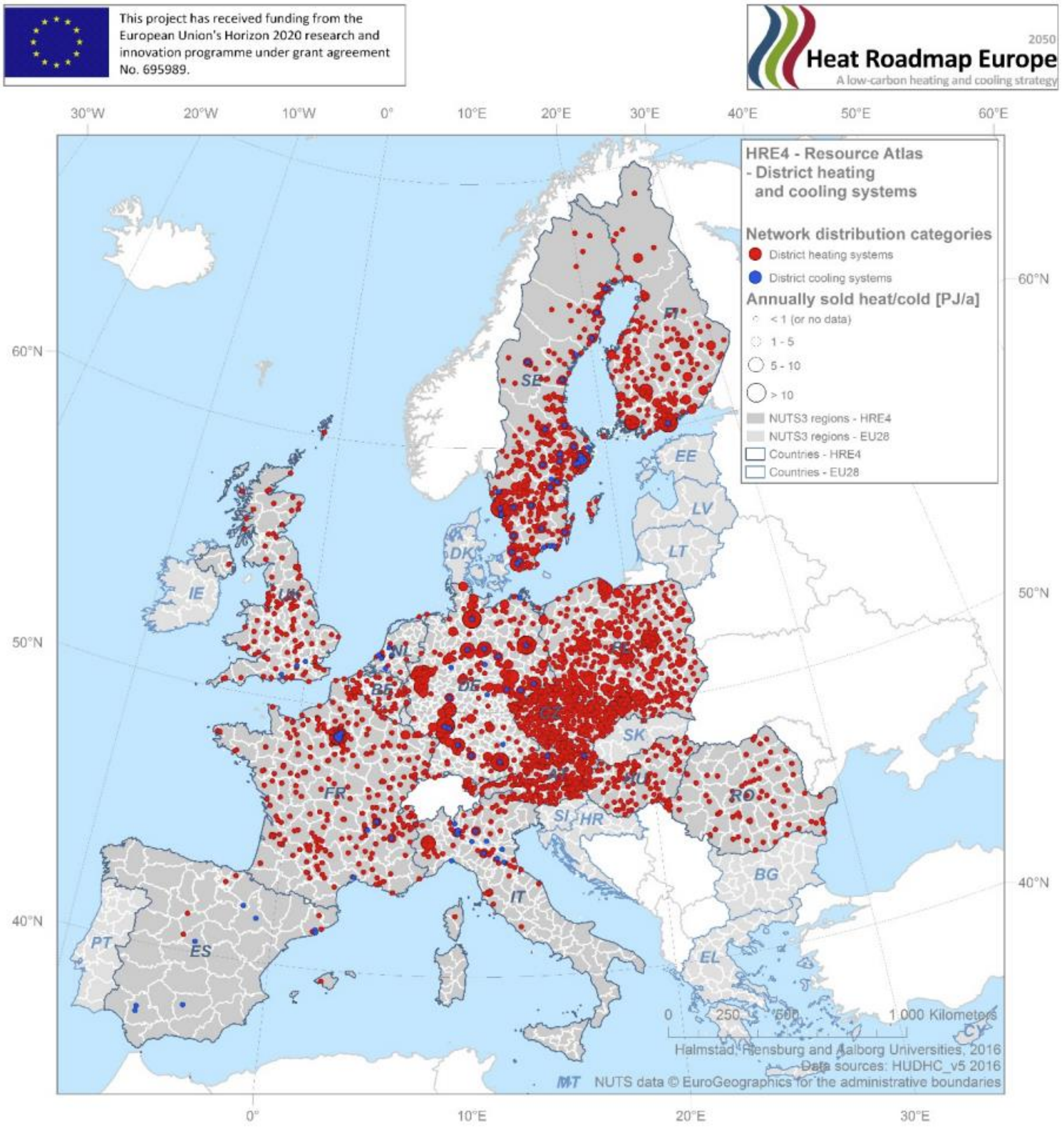


Figure 8. Map of 3207 district heating (3106) and cooling (101) systems in 2737 European cities, by network distribution category and annual volumes of heat and cold sold [24].

3.2.3. States of DHC networks

Depending on its state, district heating and cooling systems can be classified into: saturated, expanding or new. Each has its own unique challenges and opportunities [6].

Firstly, in **saturated networks** the bulk of the heating and cooling demands are met by district energy so network expansion is limited. Hence, RES will be primarily used to replace existing conventional capacity. The main opportunities of using these facilities are outlined below:

This networks extend to the outskirts of the urban agglomeration, providing **suitable space for centralized RES plants** or accessible waste heat from industry.

- The **initial investment is reduced** given that networks connections, power plant conversions or auxiliary infrastructure already exists.

- **Demand profile is already precisely known** so designing the RES integration holds a lower investment risk.

Nevertheless, at the same time the **inflexibility and static nature** of a saturated network could create difficulties in the integration of certain intermittent RES. Additionally, if the network is old enough, it will belong to a previous district generation, presenting high supply/return temperatures and thus low efficiency.

Secondly, **expanding networks** exist in both established and new urban environment and present the following advantages:

- Expanding networks allow designing **optimized parameters**, such as the minimisation of operating temperature. There is a **high degree of flexibility** due to substations that can couple different sections of the network.
- A sufficiently large existing system offers all the advantages of a saturated network and **available storage capacity** that could facilitate the integration of RESTORE solution being used as short-term buffers for both RESTORE low- and mid-temperature hub.
- Novel concepts (4G or 5G) can be integrated with the pre-existing high-temperature DHC networks, for instance by decreasing the temperature of return pipelines. This concept could lead to a **Multi-Level District Heating** where thermal energy is supplied with pipes working at different temperatures [16].

Finally, **new networks** (4G or 5G) present a **complete freedom to choose the operating parameters** of the system and, thus, the final solution can be conveniently optimized. However, the **lack of information on the actual heating/cooling demand** and the lack of previous infrastructure brings about a higher investment risk. Finally, potential customers could lack awareness of the benefits, thus, **RESTORE project aims to develop activities related to social assessment and community-engagement.**

3.2.4. Influence of demand profile

Accurate heating and cooling demand forecasting is a challenge for new districts, and DHC solutions can contribute to reducing the risk of overinvestments in H&C equipment in buildings. Sink must be defined considering a simultaneity factor, meaning that only a certain percentage of the contracted capacity is expected to be used at the same time. In comparison with individual heating and cooling systems – where there is a significant overcapacity installed considered as “dead capital” -, **DHC solutions reduce this dead capital in excess capacity in the long term**, as available capacity from one consumer can be sold to another, providing a new flexibility lever.

It is strategical for an optimal DHC design and operation to have the most accurate consumption estimates while assessing associated uncertainties, as their impact on load and temperature differentials will condition the pipes design. As a certain degree of uncertainty is unavoidable during the early planning phases, **the project should be conceived and monitored in a way that allows a later adjustment to real demand**. Thus, a **flexible/modular approach** will ensure to cope with this demand uncertainty in a cost-effective way and to progressively increase capacity as the district develops while integrating additional leverages of optimisation [15].

Analysing the demand profile, mainly considering its fluctuation (in terms of heat demand in kW) and its temperature level requirements, and assessing the compatibility with the DHC system and connected buildings is crucial to develop a cost-optimal, reliable and flexible DHC network. Indeed, in order to minimize the fluctuation in demand profiles, **it is highly recommended to combine a wide range of public and private buildings in the DHC network.** The main reason is that public buildings (universities, office buildings, institutions) are heated only during working hours, while residential buildings require a constant supply, resulting in an overall relatively flat demand that is easier to forecast in each season.

In addition, each client of a district heating and cooling network usually present different demand profiles, **high-flexibility systems and diverse configurations enable the efficient individual supply of heat to each building**. Even may be synergies between the different profiles, for instance, if there are consumers with high-temperature demands and others with low-temperature demand, direct returns from high-temperature clients could supply low-temperature ones or the **DHC network could be designed with separated circuits**, as it has already been demonstrated in some existing DH systems [25].

Finally, applying a participatory approach is considered a key success factor for the smart grid, where **the final purpose is to commit all DHC users to interact with the global system** (buildings and network) to enable its optimisation. In addition, smart demand side response will play a crucial role in the long-term operation of DHC that – based on **artificial intelligence control system** – will be able to determine in advance the heat, cooling and even electricity consumptions of each client, reducing excesses and optimizing the design and performance of smart grids.

3.2.5. DHC integration with RESTORE

The integration between RESTORE and the district network is carried out through the discharge thermodynamic cycle, particularly RESTORE is connected to the DHC supply through the ORC condenser (in case of rORC, it will be the low pressure heat exchanger). The heat rejected within the condenser has the double effect: first, condense the organic fluid of the cycle and second, heating the water return of the DH network in order to supply hot water to the demand. Additionally, district network can be connected to other components in order to increase the overall efficiency (i.e. **the biomass dryer could be connected in series**, before the heat exchanger/condenser of the ORC, and/or supply the district network at a lower temperature, as a preheater [26]).

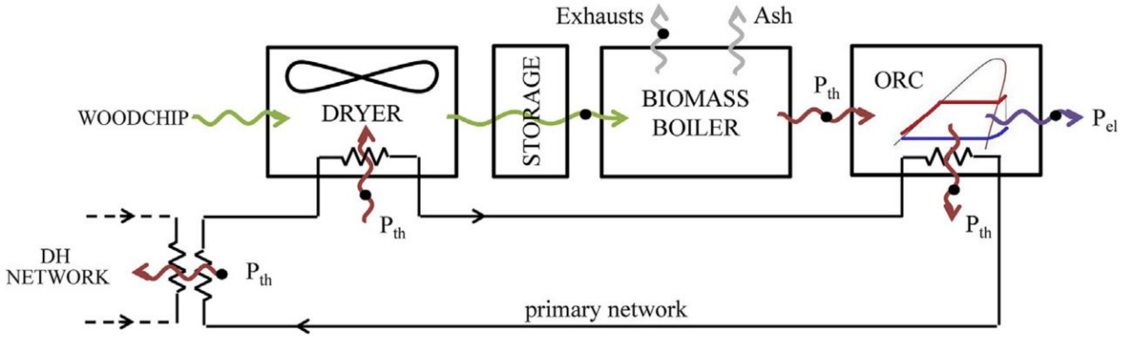


Figure 9. Layout scheme of integration in series of DHC with ORC and other heat source (i.e. biomass dryer) [26].

The way the organic fluid is cooled down plays a very relevant role in the cycle performance, thus, a special attention must be paid to the design of the condenser in order to optimize the overall efficiency of the system. Thus, a **plate heat exchanger is commonly used as condenser** in order to ensure a large surface area for heat transmission and fit with the flow rate and temperature conditions of each application [27], although if the mass flow are quite high due to a very large-scale application, other types of heat exchangers based on tube-shell, can be considered . Additionally, the design or selection of the suitable condenser must contemplate the **requirement of a certain subcooling** in order to ensure that inlet of the ORC pump is completely liquid (i.e. some authors contemplate this subcooling around 5 °C [28]).

In relation to the electrical connection of the ORC, the electricity generated is provided to the grid through the generator. Nowadays it is easy to find electric generators that can be adapted to the requirements imposed by the electrical grid, matching voltage and frequency. For these purpose, these generators usually include brake resistors and electromagnetic compatibility (EMC) filters so the electricity can be correctly supplied. Fulfil the requirements imposed by the grid will do also fulfil the requirements imposed by the auxiliary systems of the district. Thus, the electricity may be consumed by this equipment or provided to the grid.

4. Conclusion

The deliverable presents an extended definition of the RESTORE concept, providing additional details of the main innovative components of RESTORE. The document present the different components grouped in two main subsections: On the one hand, a section that deals with the components associated with the thermochemical energy storage system (TCES). On the other hand, a section that deals with the components associated with the thermodynamic cycles (organic cycles) which are connected to the storage system, the energy sources (renewable energy sources, RES or waste heat recovery, WHR) and sinks (District Heating and Cooling). For each of the components, the document provides an extended definition, a template of the data sheet that summarizes the specifications, and a list of requirements that must be considered and fulfilled. The data sheet of specifications are templates which show the main parameters that must be defined for each specific application of the concept, thus the column “value” can be filled for each ad-hoc application. In future work within the project the template datasheets will be fulfilled for specific applications, specifically for the project virtual use-cases (associated with WP5) and the RESTORE prototype (associated with WP4). This information will be presented in the deliverables associated to the activities that deals with each one (virtual use-cases in WP5 and prototype in WP4)

In addition, the document also provides an overview about the interfaces of the RESTORE system, differentiating the “sources” and “sinks” that can be connected to the overall system. Understanding as “sources” those systems which are connected to the RESTORE solution in order to provide green energy to it (upwards), and as “sinks” those systems that receive the energy stored in RESTORE (downwards).

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