D2.2

KPIs definition

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Technical References

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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

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Executive Summary

The goal of WEDISTRICT project is to demonstrate the integration of multiple source of renewable energies in order to achieve 100% renewable district heating and cooling. To achieve this objective, the project upgrades nine renewable solutions for generation, storage, and waste heat recovery for integration in four real district heating and cooling systems. The. The project is performed under a holistic context, considering smart management by information and communication technologies integration, sustainable business models, and engagements of citizens.

The progress towards the WEDISTRICT objective needs a clear definition of the project framework. This includes different levels of analysis, from the performance and improvement of technologies, to the evaluation of the integration into different district heating and cooling. Hence, many technical parameters will be used and monitored in the project, from low level technology specific data to overarching system parameters. For strong communication and assessment, it is important to identify the key performance indicators that clearly monitor the progress towards project goals.

The D2.2 includes the description of the project evaluation framework, identifying the relevant stakeholders, the objectives, and the system boundaries. According to this, the most relevant parameters are identified into key performance indicator at system and technology levels. The document contains the description and the calculation methodology for all the key performance indicators.

This document is related to task 2.2 in which all consortium partners collaborated under the coordination of IREC. It is meant to be the basis for the demo-sites and demo-followers followers performance evaluation, as well as provide the reference indicators for the WEDISTRICT tool.

Disclaimer

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Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Table of Figures

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Nomenclature

WEDISTRICT technologies abbreviations

Ach	Absorption chiller
AD	Advanced digitalization
BB	Biomass boiler
DaC+FC+WHR	Fuel cell powered data centre with waste heat recovery
FTC	Fresnel collectors
PTC	Parabolic through collectors
LCC	Low concentration flat plate collectors
MSTES	Molten salts thermal energy storage
RACU	Renewable air cooling unit
WTES	Water thermal energy storage

WEDISTRICT system KPI

CAPEX	Capital expenditures [€/kW]
f_{nr}	Non-renewable primary energy factor [-]
k_{CO2}	Equivalent CO_2 emission coefficient [g/kWh]
k_{xx}	Pollutant emission coefficients (“xx” being SO_x, NO_x, $PM_{2,5}$) [g/kWh]
LCOE	Levelized cost of energy [€/kWh]
$OPEX_f$	Fixed operational expenditures [€/kW]
$OPEX_v$	Variable operational expenditures [€/kWh]
RER	Renewable energy ratio [-]
sc	Environmental social cost [€/kWh]

WEDISTRICT technology KPI

c	Equipment cost [€]
c_{dec}	Equipment decommissioning cost [€]
COP	Coefficient of performance [-]
ΔT_{TES}	Maximum temperatures inside the tank [ºC]
ED	Energy density [kWh/m^3]
ERF_{Dac}	Energy reuse factor [-]
ESC	Energy storage capacity [kWh]
ev	Emission values [mg/Nm^3]
εTES	Storage energy efficiency [-]
f_{xx}	Emission factor (“xx” being CO_2, $PM_{2,5}$, NO_x, SO_x) [g/kWh]
η_{LHV}	Total boiler efficiency [-]
$K_{DaC.CO2}$	Data centre CO2 emissions [kg]
$LCOE_{DaC}$	Levelised cost of energy of data centres [€/kWh]
LF	Technical lifetime[years]
o_F	Fixed operation and maintenance cost [€/kW]
o_V	Variable operation and maintenance cost [€/kWh]
P_c / P_h	Nominal capacity (cooling / heating) [kW]
p_{col}	Collector output [kW/m^2]
PE_{DaC}	Data centre primary energy use [kWh]
r_{aux}	Auxiliary energy ratio [-]
r_{DH}	District heat to cooling ratio [-]
r_{HtC}	Consumed heat to cooling ratio [-]
RER_{DaC}	Renewable energy ratio [-].
rv	Residual value [€]
s	Space requirement [m^2/kW]
T	Temperature (supply, return, source, storage (min-max), …) [ºC]

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TRL	Technology readiness level
TCO_{DaC}	Total cost of ownership [€]
w_c	Water consumption [kg/kWh]
WUE	Water usage effectiveness [kg/kWh]

General abbreviations

AI	Artificial intelligence
CHP	Combined heat and power / plant
CRF	Capital recovery factor
CS	Concentration solar
DaC	Data centre
DC	District cooling
DH	District heating
DHC	District heating and cooling
DHW	Domestic hot water
DW	Desiccant wheel
EES	Electrical energy storage
FC	Fuel cell
GHG	Green-house gasses
GWP	Global warming potential
HOP	Heat only plant
HP	Heat pump
HTF	Heat transfer fluid
HVAC	Heating ventilation and air conditioning
IAQ	Indoor air quality
ICT	Information and communication technologies
IoT	Internet of things
ISO	International standardization organization
KPI	Key performance indicator
IEC	Indirect evaporative cooling
IT	Information technologies
IoT	Internet of things
OPEX	Operational expenditures
O&M	Operation and maintenance
PM	Particulate matter
PV	Photovoltaics
RES	Renewable energies
SOFC	Solid oxide fuel cell
SPF	Seasonal performance factor
SRI	Smart readiness indicator
TES	Thermal Energy Storage
TRL	Technology readiness level
WHR	Waste heat recovery

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Latin symbols

Symbol	Description	Units
C	Cost	€
E	Energy (all sources)	kWh
f	Primary energy factor	-
F	Fuel cost	€
I	Investment cost	€
k	Primary emission factor	kg/kWh
M	Operation and maintenance cost	€
n	Year / annuity	Year
o	Normalized operational cost	€/kWh
O	Operational cost	€
P	Nominal capacity or nominal power	kW
Q	Heat	kWh
rv	Normalized residual value	€/kW
RV	Residual value	€
w	Water use factor	m^3/kWh

Greek symbols

Symbol	Description	Units
α	Energy share	-
β	Cost / investment share	-
ε	Storage efficiency	-
ζ	Energy rate	-
η	Energy efficiency	-
τ	Period	year

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Sub-indexes

Sub-index	Description
aux	Auxiliary
c	cooling
comp	Component
con	Conversion
d	Direct
dec	Decommissioning
del	Delivered
dis	Distribution
el	Electricity
exp	Exported
F	Fixed
g	Generation
h	heating
hc	shared for heating and cooling
imp	Imported
L	Latent
loss	Energy losses
mat	Material
nr /nren	Non-renewable
P	Primary energy
pc	Project contingency
pd	Project development
pe	Project engineering
pf	Project financial
r / ren	renewable
s	Storage
S	Sensible
sys	System
t	Total
V	Variable

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1 Introduction

The present document establishes key performance indicators (KPIs) for WEDISTRICT project. KPIs are a key element for assessing the project evolution and success. This is particularly truth for complex systems, which involves different technological innovation in a single ensemble, as it is case for WEDISTRICT pilots, and more generally for different renewable energy technologies integration in district energy systems. The WEDISTRICT project requires the KPIs which can enlighten the energy, economic and social performance of the particular technologies to be developed, improved and/or integrated within the project, as well as to reflect the most significant aspects of a district heating and cooling system overall behaviour.

The KPIs to be used should give a quantitative information, which is calculated in transparent and traceable manner. Following a holistic perspective of the WEDISTRICT project, the choice of appropriate collection of KPIs should allow to evaluate the proposed and demonstrated set of solutions at different stages within the project, from the concept design to the results of the monitoring demo phase.

One of the main principles applied in the KPIs definition presented below is to use the existing recognized references as starting point and to relate to established standards in case they exist. Evidently, for some of the KPIs there is a need to elaborate new or more precise definitions in order to be able to accomplish the project objectives. This is the case for the systems which provide both heating and cooling. During the literature review we have identified a lack of methodologies to calculate differentiated KPIs for, on one hand heating services, and on the other hand cooling services. We consider this division particularly useful for a complete comparison of different DHC system architectures. Thus, we opt to develop KPIs capable of representing both heating and cooling performance in an independent manner. We believe this approach is going to be useful for WEDISTRICT project but also for a wider use application in DHC performance evaluation.

The following sections describe: the overall methodology applied together with the objectives, targeted stakeholders and system boundaries definition, in section 2; common parameters for calculating system KPI in section 3; system KPIs definition and their calculation methodology in section 4; technologies KPIs definition and calculation methodology in section 5; and finally summary and conclusions in section 6.

2 Methodology

Following a holistic perspective, this task is focused on the KPIs definition for both technologies and overall system level.
The KPI selection methodology followed in WEDISTRICT project is described in Figure 2-1. It follows a common scheme of identifying the objectives and the involved stakeholders of the project, then setting the scope and boundaries of the analysis. Finally, with this setup, the parameters that measure the performance of the system inside the defined boundaries are listed, in order to finally select the indicators that best measure the progress towards project objectives according to stakeholder perspectives. The following sections details the implementation of this methodology in WEDISTRICT project.

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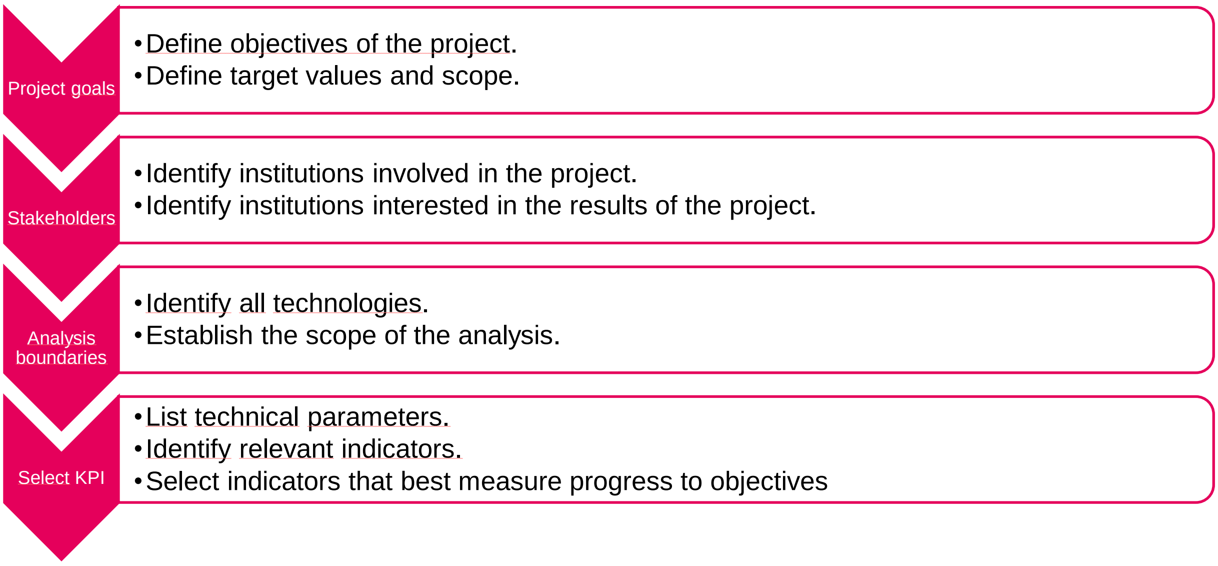

Figure 2-1. KPI selection methodology.

Project goals

As described in the GA agreement, the WEDISTRICT project is focused around a clear central objective. Then, as usual, this is divided into scientific and technical objectives mainly related to the technologies specific challenges as well as to demonstrating their performance, replicability, and profitability on top of its promotion.

As a summary, the main objectives can be summarized as follows:

- *Increase renewables share in DHC between 60 % and 100 % for retrofitting and 100 % for new DHC.*
- *Demonstrate feasibility and cost-effectiveness of renewable DHC.*
- *Develop renewables technologies for DHC up to TRL 6-7 and demonstrate its integration.*

KPIs allow the analysis and monitoring of the overall project in relation to the main objectives, but also in relation to the specific goals for the upgraded integrated technologies..

Stakeholders

The stakeholders define the approach and level of detail required by the KPI. Each has different interest, knowledge, and action capabilities, hence the data they require from the project differs. Consequently, the KPI definition requires correctly identifying the relevant stakeholders at each stage of the project. For the WEDISTRICT case and scope, the KPIs are selected and defined having in mind the following stakeholders:

- *Technology developers*
- *Technology integrators*
- *Utilities and DHC operators.*
- *Local public authorities*
- *Policy makers*

The KPIs for particular product/technology should be useful for technology developers while the system KPIs should serve to technology integrators and utilities, but also to public administration, to check the environmental, economic, and social impacts of the system. In

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coherence with the target TRL and overall project objectives, end users are not directly considered in the evaluation.

System boundaries

WEDISTRICT project is focused on integrating renewable energy sources (RES) for supplying district heating and cooling networks. First, different generation technologies and a storage are developed in order to improve to their integration into DHC networks. Second, the integration of different technologies, including those which are not improved in the project, is studied in order to propose the optimal combination in different scenarios. Finally, all the systems are connected through a smart management control, which is a facilitator technology to guarantee the optimal operation.

The EuroHeat&Power association developed guidelines for evaluation of DHC through the Ecoheat4cities project [1]. This considers as system boundaries on one side the primary energy input to the production, including all kinds of thermal energy production plants, including cogeneration and waste energy recovery, and on the other side the energy transfer devices included in the building/client substation. The evaluation scheme proposed in the Ecohet4cities guidelines is shown in Figure 2-2.

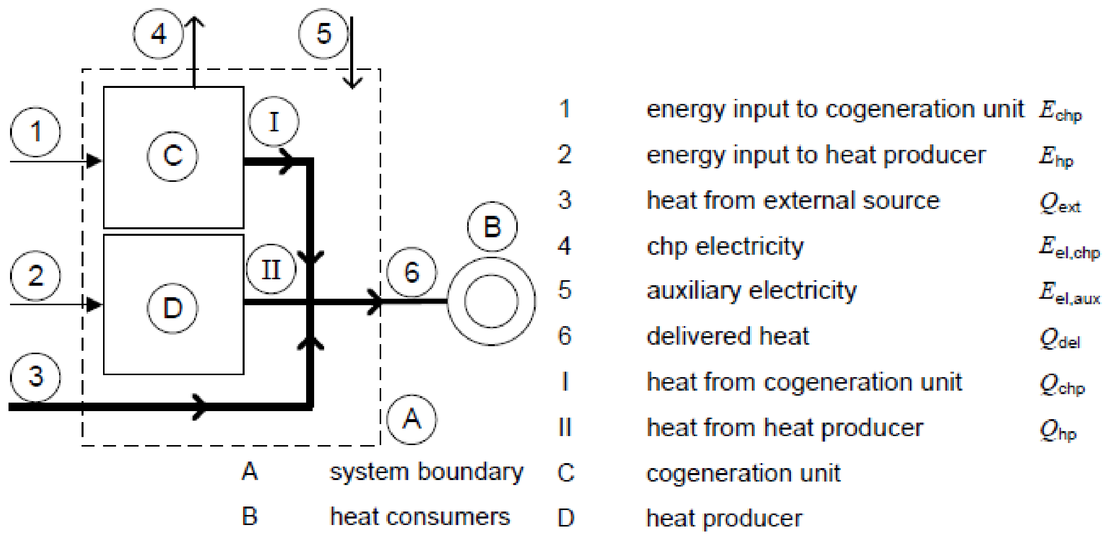

Figure 2-2 Ecoheat4cities analysis boundaries [1].

The implementation of the Euroheat&power boundaries to WEDISTRICT set of technologies is presented in Figure 2-3. As defined by the project objectives, the focus of the project is into the energy harvesting, storage, and conversion. Hence, most of the technologies are included into the production block, comparable to the usual heat only plants (HOP) and combined heat and power plants (CHP). However, the project moves beyond the usual DHC approach, also including technologies for energy conversion at user side as well as external heat inputs with waste heat recovery. The definition of the analysis boundaries highlights the importance of defining the evaluation approach of the renewable air cooling unit (RACU) and the waste heat recovery from fuel cell powered data centres (DaC+FC+WHR).

The RACU is placed in parallel to the heating substation, as it fulfils consumers cooling demand by using heat from the DHC network. Moreover, while the RACU fulfils a cooling demand, in terms of system evaluation is considered as a heat consumer. Consequently, the energy use for the RACU is accounted in the heating distribution and generation side.

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Heat recovery from fuel cell powered data centres technology (DaC+FC+WHR) lays outside the system boundaries, as it is an improvement on data centres that allows them to provide useful external heat (see number 4 on Figure 2-2) to the network. So, it is considered as an external source of waste heat.

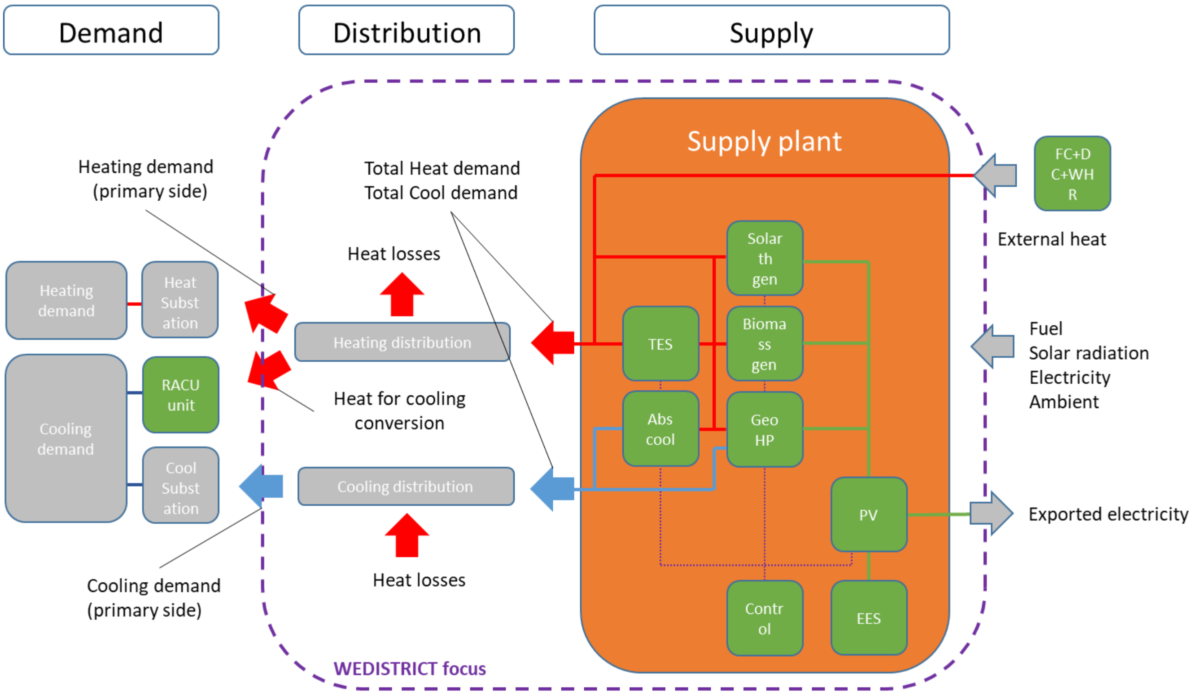

Figure 2-3 System boundaries for analysis of WEDISTRICT projects.

The project goals together with this analysis boundaries require to define KPIs at two different levels: system level, to consider the integration of technologies; and technology level, to evaluate the specifications and development of each compared to the current existing ones. While the KPIs for particular product/technology aim to evaluate the performance of each main element developed within the project, the system KPIs should be able to reflect, in a summarized and precise way, the most significant aspects of a district heating and cooling system. So, the system level KPIs deal with the evaluation of the performance and impact of overall system during a period of time (namely, one year, or lifetime set to 25 years [2]) from different perspectives: energy, environmental, economic and social one.

KPI definition

As clearly identified by the project objectives and stakeholders' interest, the evaluation requires defining KPIs at two levels: system and technology. The system level is focused on monitoring the progress towards the project overarching objectives. In these terms, it considers the evaluation boundaries defined in Figure 2-3 as a black box. That means it measures the performance of the integration of technologies considering the inputs and outputs from its borders. At the technology level, the goal is to provide parameters to evaluate the potential and capabilities of each proposed element, as well as its intended target goals. Therefore, the technologies are evaluated individually, although their performance is affected by their interaction with the system.

In order to ease the tracking of the KPI, a code is used along the document. The first capital letter identifies it as “system” (S) or “technology” (T). Then a combination of letters identifies the type of KPI as “energy” (En), “environmental” (Ev), “economic” (“Ec), “socio-economic” (Sc), or “technology specific” (Ts). Finally, a number identifies the specific KPI.

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3 System KPIs

The methodology section details the objectives to be monitored with the system KPI, as well as the analysis framework for the calculation. Related to this, the system level KPI section is divided in five parts: energy, environment, economics, and socio-economics. The energy chapter presents the indicators for analysing the implementation of renewable in district heating, on one hand establishing the calculation of the renewable energy ratio (RER) and on the other hand indicating its impact on the overall non-renewable energy use. Obviously, the final goal of the implementation of renewables is to reduce the GHG emissions and the local pollution. Hence, the environment chapter describes the calculation of the emissions related KPI. Moreover, the water availability is a rising concern, hence an indicator for this issue is included in the section. On top of achieving the environmental goals, the renewable DHC concept must be made economically feasible, hence the economics section addresses the indicators for measuring the investment required, the operation cost, as well as the cost of energy. Finally, financial evaluation of the DHC cost may not include the overall social economy benefits of introducing renewables, as the reduction of emissions and pollution lowers the negative impacts on health and environment. This can be related in reduced cost on the health system and agriculture sector, which is introduced in social cost indicator.

On top of the framework defined in the methodology section, it is important to consider that the calculation of the KPI highly dependent on:

- *System technologies configuration.*
- *Demand profile.*
- *Network configuration (losses).*
- *Location (weather).*

Cross-comparison of DHC networks KPI cannot be performed directly without considering these dependencies. Obviously, this imply that comparison of different DHC might not be accurate and fair. Hence, the system KPI are better use to assess the evolution and improvement of a DHC compared to previous conditions (in case of retrofitting) or to different configurations (in case of new systems). Yet, the KPI are proposed as normalized to nominal capacity or demand in order to provide information of the best practices.

The system KPI present the general calculation method for each. However, WEDISTRICT approaches on evaluation of DHC networks are the following three:

- *Demo site evaluation*
  - *Calculations on measured data.*
  - *Evaluation of technologies under demonstration conditions.*
  - *Evaluation of the system as deployed.*
- *Demo followers*
  - *Demand profiles and grid characteristics from existing networks, and corresponding climate conditions.*
  - *Technologies data as validated from demo site evaluation.*
  - *Calculation on simulated data.*
  - *Parametric study to select best set of technologies and operation strategy.*
- *WEDISTRICT tool*
  - *Location (weather as input).*
  - *Demand profile as input or generic profile.*

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- *Selection of best set of technologies.*

Consequently, the input parameters for calculating the KPI vary in each stage. The energy flows will be obtained from the measurements of simulation. For the other parameters, such as primary energy factor or emission coefficient, the following sections describe the preferred methodologies. For simplicity, a first section is included to describe the parameters that are shared between several KPI.

Parameters for calculating system KPI

In general terms, the KPI will be calculated with the measured from the field sensors or simulated data, Annex 1 presents the more details of the energy fluxes at the system boundaries. This section presents the parameters required for the calculation of the KPI that are external to the system or that are used for multiple indicators.

Cooling share (α_C)

The WEDISTRICT project considers networks for distributing heating and cooling. Moreover, it also considers technologies for energy conversion from heating to cooling at the demand side. Moreover, the objectives of the project imply comparison with individual systems and between DHC networks with different layouts. In order to make fair and complete comparisons, it is important that the system KPI in WEDISTRICT project are calculated separately for heating and cooling.

However, as shown in Figure 2-3, the proposed concept has multiple elements that are shared between the heat generation, cooling conversion, and distribution. Hence, separating the economic, energy, and environmental impact of the heating and cooling is not evident. Therefore, a cooling share parameter is proposed for dividing the impact of the elements that are shared between the cooling and heating. It represents the percentage of the energy, environmental or economic impact of cooling service of the shared elements. The division between cooling and heating impact is based on the energy balance of the system, as shown in Figure 3-1, and calculated according to Equation 1.

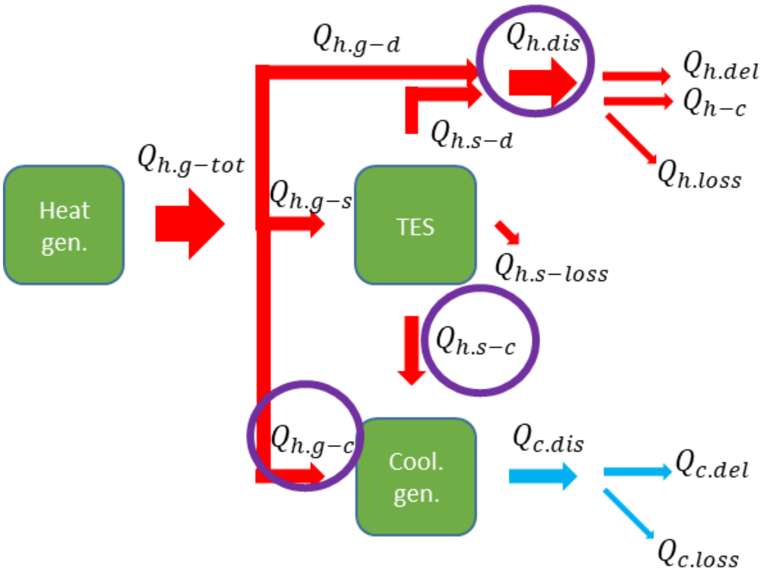

Figure 3-1. WEDISTRICT generic heat fluxes (Highlighted are the fluxes used for the ponderation ratio).

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$$\propto_C = \frac{Q_{h.g-c}+Q_{h.s-c}}{Q_{h.g-c}+Q_{h.s-c}+Q_{h.dis}}$$ ***Equation 1***

Where the terms in the equations:

- $\propto_C$: *Cooling share [-].*
- $Q_{h.g-c}$: *Heat supplied by the generator equipment to the cooling generation equipment in the plant side of the district [kWh].*
- $Q_{h.s-c}$: *Heat supplied by the thermal energy storage equipment to the cooling generation equipment in the plant side of the district [kWh].*
- $Q_{h.dis}$: *Heat supplied to the heating distribution network [kWh].*

And the rest of terms in the graph are:

- $Q_{h.g-tot}$: *Total generated heat [kWh].*
- $Q_{h.g-d}$: *Heat supplied by the generating equipment directly to the heating distribution [kWh].*
- $Q_{h.g-s}$: *Heat supplied by the generating equipment to the storage equipment [kWh].*
- $Q_{h.s-d}$: *Heat supplied by the thermal energy storage equipment to the heating distribution [kWh].*
- $Q_{h.s-loss}$: *Heat losses of the thermal energy storage equipment [kWh].*
- $Q_{h.del}$: *Heat delivered to end users [kWh].*
- Q_{h-c}: *Heat delivered to cooling generation equipment at users side [kWh].*
- $Q_{h.loss}$: *Heat losses at the heating distribution network [kWh].*
- $Q_{c.dis}$: *Cooling supplied to the cooling distribution network [kWh].*
- $Q_{h.del}$: *Cooling delivered to end users [kWh].*
- $Q_{c.loss}$: *Heat losses at the cooling distribution network [kWh].*

The cooling share is used in order to calculate energy, environmental and economic KPIs, always when some common elements exist for both cooling and heating service. Besides this, all other elements (equipment, piping, control system) which are clearly used only for one of the services are assigned totally to the corresponding one.

Primary energy factors

The concept proposed in the WEDISTRICT project implies energies of different natures and sources. In order to make fair comparisons and to better assess the impact of each technology, primary energy is used in the calculations.

The primary energy is the energy that has not been subject to any conversion or transformation process. According to ISO-52000 [3] the primary energy can be divided into non-renewable and renewable energy, as summarized in Figure 3-2, if both are taken into account it is referred to as total primary energy.

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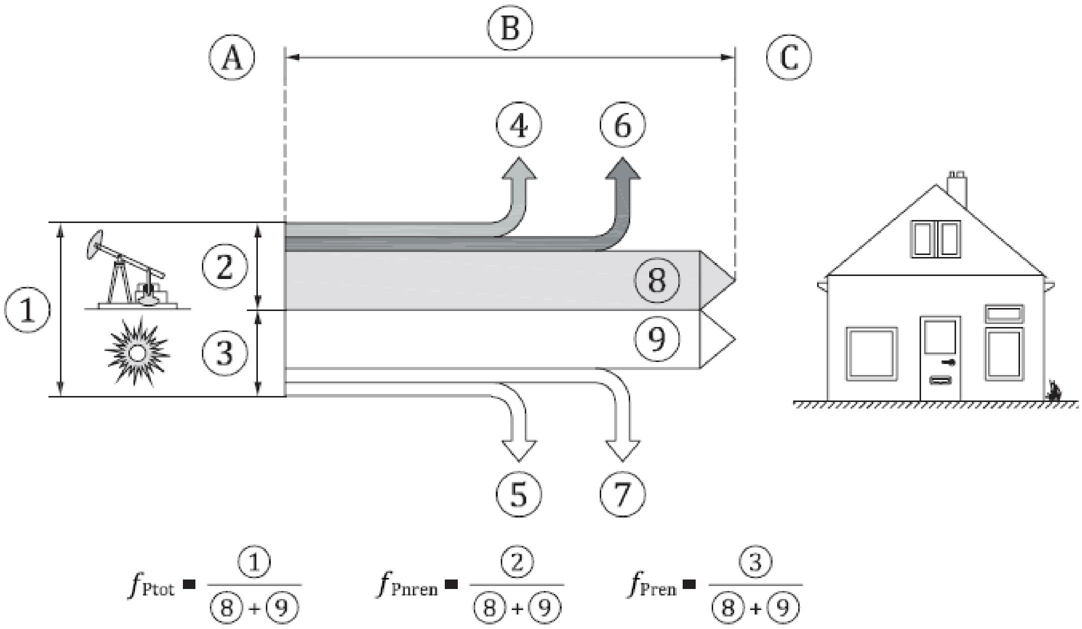

Key

A	energy source	4	non-renewable infrastructure related energy
B	upstream chain of energy supply	5	renewable infrastructure related energy
C	inside the assessment boundary	6	non-renewable energy to extract, refine, convert and transport
1	total primary energy	7	renewable energy to extract, refine, convert and transport
2	non-renewable primary energy	8	delivered non-renewable energy
3	renewable primary energy	9	delivered renewable energy

Figure 3-2. Primary energy factors approach according ISO-52000 [3].

The values of the primary energy factor can be dynamic. This is the case of imported electricity, which depends on the energy mix at each instant. Yet, this level of detail is beyond the scope of the project. Hence, the primary energy factor used in the evaluation of WEDISTRICT systems are applied considering average values according to the values suggested in ISO 52000 [3]. If available, values from national indexes must be applied, otherwise the ISO proposes generic values. Annex 1 summarizes the generic and country specific primary energy factors used in WEDISTRICT project. The KPI description indicate whether renewable, non-renewable, or total primary energy factors are used.

Primary equivalent CO_2, and air pollutant emission coefficient

The emission coefficient refers to the tons released of a pollutant per unit of primary energy of an energy carrier. The primary equivalent CO_2 emission coefficient describes the amount GHG of equivalent tons of CO_2, while $PM_{2,5}$ describes the amount of particles of a size smaller than 2.5 micrometres, NO_x is the weighed sum of NO_2 and NO, and SO_x is related to the sulphur contents of a fuel. These parameters are directly related to the nature of the fuel and to the characteristics of the combustion technology. For the electricity coming for the grid, emission coefficients depend on the energy mix of the region or country.

The WEDISTRICT approach for the emissions coefficients is the “Tier 3 Technology-specific emission factors” according to IPCC 2019 guidelines [4]. This means using the data provided by the WEDISTRICT technology developers according the technology specific KPI.

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In the case of the technologies integrated in WEDISTRICT but not developed within it, if technology specific data is not available from the suppliers, country specific data or default data from ISO 52000 [3] or IPCC 2019 guidelines [4] will be used for CO_2 and GHG emissions, and IEA air pollutant inventory [5] will be used for air pollutants. Annex 1 summarizes the generic and country specific non-renewable primary emission coefficients used in WEDISTRICT project.

Energy

SEn1 - Renewable energy ratio (RER)

Description

The renewable energy ratio (RER), or share of renewables, is the fraction of renewable primary energy used by network compared to total primary energy consumed by in order to fulfil the heating and cooling demand.

Calculation

The Energy performance of buildings directive (EPBD) [6] establishes a definition of the RER for buildings in ISO 52000 [3]. This is adapted to DHC considering the analysis boundaries described in Figure 2-3. Then the energy fluxes considered are the inputs for the main plant (fuel, electricity imports, solar radiation) and the external heat, while subtracting the electricity exports. The general calculation of the RER is described in Equation 2.

$$RER = \frac{E_{Pren}}{E_{Ptot}}$$

Equation 2

Where:

- E_{Pren}: *Renewable primary energy used by the district energy network.*
- E_{Ptot}: *Total primary energy used by the district energy network.*

Equation 3 and Equation 4 describe the calculation of the RER applied to the technologies of the WEDISTRICT project for respectively cooling (RER_c) and heating (RER_h) generation.

$$\boldsymbol{RER_c} = \frac{\sum_i \boldsymbol{E_{r.c.i}} + \sum_i(\boldsymbol{f_{r.i}E_{i.c}}) + \boldsymbol{\alpha_c}[\sum_i \boldsymbol{E_{r.hc.i}} + \sum_i(\boldsymbol{f_{r.i}E_{i.hc}})]}{\sum_i \boldsymbol{E_{r.c.i}} + \sum_i(\boldsymbol{f_{t.i}E_{i.c}}) + \boldsymbol{\alpha_c}[\sum_i \boldsymbol{E_{r.hc.i}} + \sum_i(\boldsymbol{f_{t.i}E_{i.hc}}) - \sum_i(\boldsymbol{f_{t.exp.i}E_{exp.i}})]}$$

Equation 3

$$\boldsymbol{RER_h} = \frac{\sum_i \boldsymbol{E_{r.h.i}} + \sum_i(\boldsymbol{f_{r.i}E_{i.h}}) + (\boldsymbol{1-\alpha_c})[\sum_i \boldsymbol{E_{r.hc.i}} + \sum_i(\boldsymbol{f_{r.i}E_{i.hc}})]}{\sum_i \boldsymbol{E_{r.h.i}} + \sum_i(\boldsymbol{f_{t.i}E_{i.h}}) + (\boldsymbol{1-\alpha_c})[\sum_i \boldsymbol{E_{r.hc.i}} + \sum_i(\boldsymbol{f_{t.i}E_{i.hc}}) - \sum_i(\boldsymbol{f_{exp.i}E_{exp.i}})]}$$

Equation 4

Where:

- RER_c: *Cooling renewable energy ratio [-].*
- RER_h: *Heating renewable energy ratio [-].*
- $E_{r.c.i}$: *Renewable energy produced by energy carrier "i" and consumed exclusively for cooling generation [kWh].*
- $f_{r.i}$: *Renewable primary energy factor for energy carrier "i" [-].*

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- $E_{i.c}$: *Energy produced for non 100% renewable energy carrier "i" consumed exclusively for cooling generation [kWh].*
- α_c: *Cooling share factor [-].*
- $E_{r.hc.i}$: *Renewable energy produced by energy carrier "i" and consumed for both cooling and heating generation [kWh].*
- $E_{i.hc}$: *Energy produced for non-100% energy carrier "i" consumed for cooling and heating generation [kWh].*
- $f_{t.i}$: *Total primary energy factor for energy carrier "i" [-].*
- $f_{t.exp.i}$: *Total primary energy factor of exported energy carrier "i" [-].*
- $E_{exp.i}$: *Exported energy of carrier "i" [kWh].*
- $E_{r.h.i}$: *Renewable energy produced by energy carrier "i" and consumed exclusively for heating generation [kWh].*
- $E_{i.h}$: *Energy produced for non 100% renewable energy carrier "i" consumed exclusively for heating generation [kWh].*
-

Note that renewable energy carriers ($E_{r.c.i}$, $E_{r.h.i}$, and $E_{r.hc.i}$) are considered for on-site harvesting of solar, wind, hydro, or ambient energies. The equations effectively consider these renewable energy sources as having a renewable primary energy factor of "1". In contrast, the rest of carriers, which include biofuels and electricity, are considered to have a non-renewable part, hence the corresponding renewable and total primary energy factors are used. Moreover, the energy exports, such excess PV energy in WEDISITRCT project, are considered to compensate the total primary energy use of the DHC with a primary energy factor equivalent to the network carrier.

Finally, according to EU 2018/2001 [7], the HP in heating mode may be considered to harvest renewable energy from the ambient if their coefficient of performance is high enough. The method for calculating the renewable energy harvested is presented in Equation 5. This is only applicable if the conditions of Equation 6 are met.

$$\boldsymbol{E_{r.HP} = Q_{del}\left(1 - \frac{1}{SPF}\right)}$$

Equation 5

$$\boldsymbol{SPF > 1.15 f_{el}}$$

Equation 6

Where:

- $E_{r.HP}$: *Renewable energy harvested by the HP [kWh].*
- Q_{del}: *Delivered useful heat by HP [kWh].*
- SPF: *HP seasonal performance factor [-].*
- f_{el}: *Electricity primary energy factor [-].*

SEn2 - Non-renewable primary energy factor (f_{nr})

Description

Primary energy accounts for the energy that has not be subjected to any conversion or transformation process. In terms of DHC it is useful for direct comparison with individual heating and cooling systems, as it accounts for all energy chain.

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Non- renewable primary energy factor sums up all delivered and exported energy for all energy carries into a single indicator with corresponding primary energy weighting factors. A value of “0” indicates a 100% renewable DHC network.

Calculation

The calculation of the non-renewable primary energy factor according Ecoheat4cities guidelines [1] is presented in Equation 7.

$$f_{P,nren} = \frac{\sum_i E_i \cdot f_{P,nren,i} + Q_{ext} \cdot f_{P,nren,ext} + (E_{el,aux} - E_{el,chp}) \cdot f_{el}}{\sum_j Q_{del,j}}$$

Equation 7

Where:

- $f_{P,nren}$: *non-renewable primary energy factor [-].*
- $\sum_i E_i \cdot f_{P,nren,i}$: *energy input [kWh] multiplied by non-renewable primary energy factor [-] of the carrier.*
- $Q_{ext} \cdot f$: *External heat input [kWh] multiplied by non-renewable primary energy factor [-] of the external heat input.*
- $(E_{el,aux} - E_{el,chp}) \cdot f_{el}$: *Auxiliary electrical energy minus generated electricity [kWh] and non-renewable primary energy factor of electricity mix [-].*
- $\sum_j Q_{del,j}$: *Delivered heat [kWh].*

This equation can be translated to WEDISTRICT technologies as Equation 8 and Equation 9, which distinguish between the non-renewable primary energy factors for heating service and cooling service.

$$\boldsymbol{f_{nr.c} = \frac{\left(\sum_i E_{i.c} f_{nr.i} + \sum_j Q_{j.c} f_{nr.j} + E_{imp.c} f_{nr.el}\right) + \alpha_c\left(\sum_i E_{i.hc} f_{nr.i} + \sum_j Q_{j.hc} f_{nr.j} + \left(E_{imp.hc} - E_{exp}\right) f_{nr.el}\right)}{Q_{c.del}}}$$

Equation 8

$$\boldsymbol{f_{nr.h} = \frac{\left(\sum_i E_{i.h} f_{nr.i} + \sum_j Q_{j.h} f_{nr.j} + E_{imp.h} f_{nr.el}\right) + (1 - \alpha_c)\left(\sum_i E_{i.hc} f_{nr.i} + \sum_j Q_{j.hc} f_{nr.j} + \left(E_{imp.hc} - E_{exp}\right) f_{nr.e}\right.}{Q_{h.del} + Q_{h-c}}}$$

Equation 9

Where:

- $f_{nr.c}$: *cooling non-renewable primary energy factor [-].*
- $f_{nr.h}$: *heating non-renewable primary energy factor [-].*
- α_c: *cooling share factor [-].*
- $E_{i.c} \cdot f_{nr.i}$: *fuel “i" energy input [kWh] multiplied by corresponding non-renewable primary energy factor [-] of equipment used exclusively for cooling generation.*
- $E_{i.h} \cdot f_{nr.i}$: *fuel “i" energy input [kWh] multiplied by corresponding non-renewable primary energy factor [-] of equipment used exclusively for heating generation.*

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- $E_{i.hc} \cdot f_{nr.i}$: *fuel "i" energy input [kWh] multiplied by corresponding non-renewable primary energy factor [-] of equipment used for both heating and cooling purposes (shared).*
- $Q_{j.c}f_{nr.j}$: *external heat [kWh] multiplied by corresponding non-renewable energy factor [-] used exclusively for cooling generation.*
- $Q_{j.h}f_{nr.j}$: *external heat [kWh] multiplied by corresponding non-renewable energy factor [-] used exclusively for heating generation.*
- $Q_{j.hc}f_{nr.j}$: *external heat [kWh] multiplied by corresponding non-renewable energy factor [-] used for both heating and cooling generation (shared)*
- $E_{el,imp.c}$: *Electrical auxiliary energy imported from the grid by equipment used exclusively for cooling generation [kWh]. It does not include the electrical energy from self-consumption of PV generated electricity.*
- $E_{el,imp.h}$: *Electrical auxiliary energy imported from the grid by equipment used exclusively for heating generation [kWh]. It does not include the electrical energy from self-consumption of PV generated electricity.*
- $E_{el,imp.hc}$: *Electrical auxiliary energy imported from the grid by equipment used for both heating and cooling generation [kWh]. It does not include the electrical energy from self-consumption of PV generated electricity.*
- $E_{el,exp}$: *Net exported electricity [kWh].*
- $f_{nr.el}$: *Non-renewable primary energy factor of electricity mix [-].*
- $Q_{h.del}$: *Heat delivered to consumers [kWh].*
- $Q_{c.del}$: *Cooling delivered to consumers [kWh].*
- Q_{h-c}: *Heat consumed for cooling production at consumer side [kWh].*

Note that solar technologies are considered to have a non-renewable primary energy factor of zero, therefore these are not included in the equation. The energy required for heat pumps (HP) or other needs is included in the imported electrical energy. Moreover, usually waste heat recovery from industry is considered fully renewable and then non-renewable primary energy factor is zero. However, in cases of combined heat and power (CHP) where heat is planned to be sold, the energy factor might be taken into account if the fuel is not renewable. This energy factor must consider the fraction of production of electricity and heat.

Environmental

SEv1 - Equivalent CO_2 emission coefficient (k_{CO2})

Description

The equivalent emission coefficient represents GHG emissions of a DHC. It is calculated as the primary non-renewable emissions of the greenhouse gasses in terms of CO_2 equivalent emissions of a district heating system. Therefore, carbon neutral emissions of biofuels are not taken into account, but emissions related to extraction, transformation, and transportation are included.

Calculation

The calculation of the non-renewable primary emission coefficient according Ecoheat4cities guidelines [1] is presented in Equation 10.

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$$k_{CO_2,nren} = \frac{\sum_i E_i \cdot K_{P,nren,i} + Q_{ext} \cdot K_{ext} + E_{el,aux} \cdot K_{el} - \left(\sum_i \frac{E_{el,chp,i} \cdot K_{P,nren,chp,i}}{\eta_{el,i}}\right)}{\sum_j Q_{del,j}}$$

Equation 10

Where:

- $k_{CO_2,nren}$ *non-renewable primary emission coefficient of district heating (kg/ MWh)*
- $\sum_i E_i \cdot K_{P,nren,i}$ *energy content of input energy carriers [kWh] multiplied by non-renewable primary CO_2-emission coefficient [kg/kWh] for each.*
- $Q_{ext} \cdot K_{ext}$ *heat from external sources [kWh] multiplied by non-renewable CO_2-emission coefficient [kg/kWh] for external heat.*
- $E_{el,aux} \cdot K_{el}$ *auxiliary electricity [kWh] multiplied by non-renewable CO_2-emission coefficient [kg/kWh] for external heat.*
- $\sum_i \frac{E_{el,chp,i} \cdot K_{P,nren,chp,i}}{\eta_{el,i}}$ *cogenerated electricity [kWh] by non-renewable primary energy CO_2-emission of CHP fuel [kg/kWh], divided by electric efficiency of CHP [-].*
- $\sum_j Q_{del,j}$ *heat delivered [kWh].*

This equation can be translated to DHC systems applying the WEDISTRICT technologies as Equation 11 and Equation 12.

$$k_{CO_2.c} = \frac{\left(\sum_i E_{i.c} k_i + \sum_j Q_{j.c} k_j + E_{imp.c} k_{el}\right) + \alpha_c \left(\sum_i E_{i.hc} k_i + \sum_j Q_{j.hc} k_j + E_{imp.hc} k_{el} - \sum_i \frac{E_{el.exp} k_i}{\eta_{el.i}}\right)}{Q_{c.del}}$$

Equation 11

$$k_{CO_2.h} = \frac{\left(\sum_i E_{i.h} k_i + \sum_j Q_{j.h} k_j + E_{imp.h} k_{el}\right) + (1-\alpha_c) \left(\sum_i E_{i.hc} k_i + \sum_j Q_{j.hc} k_j + E_{imp.hc} k_{el} - \sum_i \frac{E_{el.exp} k_i}{\eta_{el.i}}\right)}{Q_{h.del} + Q_{h-c}}$$

Equation 12

Where:

- $k_{CO_2.c}$*: cooling service equivalent CO_2 emission coefficient [kg/kWh].*
- $k_{CO_2.h}$*: heating service equivalent CO_2 emission coefficient [kg/kWh].*
- α_c*: cooling share factor [-].*
- $E_{i.c} \cdot k_i$*: fuel "i" energy input [kWh] multiplied by corresponding non-renewable CO_2 primary emission coefficient [kg/kWh] of equipment used exclusively for cooling generation.*
- $E_{i.h} \cdot k_i$*: fuel "i" energy input [kWh] multiplied by corresponding non-renewable CO_2 primary emission coefficient [kg/kWh] of equipment used exclusively for generation.*

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- $E_{i.hc} \cdot k_i$: *fuel "i" energy input [kWh] multiplied by corresponding non-renewable CO_2 primary emission coefficient [kg/kWh] of equipment used for both heating and cooling purposes (shared).*
- $Q_{j.c}k_j$: *external heat from source "j" [kWh] multiplied by corresponding non-renewable CO_2 primary emission coefficient [kg/kWh] used exclusively for cooling generation.*
- $Q_{j.h}k_j$: *external heat from source "j" [kWh] multiplied by corresponding non-renewable CO_2 primary emission coefficient [kg/kWh] used exclusively for heating generation.*
- $Q_{j.hc}k_j$: *external heat from source "j" [kWh] multiplied by corresponding non-renewable CO_2 primary emission coefficient [kg/kWh] used for both heating and cooling generation (shared)*
- $E_{el,imp.c}$: *Electrical auxiliary energy imported from the grid by equipment used exclusively for cooling generation [kWh]. It does not include the electrical energy from self-consumption of PV generated electricity.*
- $E_{el,imp.h}$: *Electrical auxiliary energy imported from the grid by equipment used exclusively for heating generation [kWh]. It does not include the electrical energy from self-consumption of PV generated electricity.*
- $E_{el,imp.hc}$: *Electrical auxiliary energy imported from the grid by equipment used for both heating and cooling generation [kWh]. It does not include the electrical energy from self-consumption of PV generated electricity.*
- $\sum_i \frac{E_{el.exp}K_i}{\eta_{el.i}}$: *Net exported electricity produced with energy carrier "i" [kWh] multiplied by corresponding fuel "i" non-renewable CO_2 primary emission coefficient [kg/kWh], and considering electricity conversion efficiency ($\eta_{el.i}$) [-].*
- f_{el}: *Non-renewable CO_2 primary emission coefficient of electricity mix [kg/kWh].*
- $Q_{h.del}$: *Heat delivered to consumers [kWh].*
- $Q_{c.del}$: *Cooling delivered to consumers [kWh].*
- Q_{h-c}: *Heat consumed for cooling production at consumer side [kWh].*

Note that in WEDISTRICT project electricity is produced only by PV panels, hence its emission coefficient is zero. Yet the PV electricity exports compensates for the emissions related to imported electricity. In terms of Equation 11 and Equation 12 the PV electricity export is considered to have and efficiency of "1" and an emission coefficient equal to the electricity grid.

The emission factor is calculated with an equivalent method to the primary energy coefficient. Solar technologies are considered to have an emission factor of zero, the electricity consumed by the heat pumps is included in the imported electricity. The waste heat recovered is proposed to be considered as renewable, so with emission coefficient of zero. However, emissions from waste heat recovery can be taken into account in cases of CHP already planned to sell heat.

SEv2 / SEv3 / SEv4 - Local air pollutants emission coefficients

- *SEV2 – $PM_{2.5}$ emission coefficient ($k_{PM2.5}$)*
- *SEV3 – NO_x emission coefficient (k_{NOx})*
- *SEV4 – SO_2 emission coefficient (k_{SO2})*

Description

The pollutants emission coefficients represent the mass of a particular pollutant that is emitted per unit of energy delivered by a given set of technologies in the system. In WEDISTRICT, the

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relevant air pollution substances are those related to combustion processes: small particles ($PM_{2.5}$), nitrogen oxides (NO_x), and sulphur dioxide (SO_2).

$PM_{2,5}$ are small particle with a size inferior of 25 microns strongly related to heart and lung diseases. Moreover, $PM_{2,5}$ are the main component of smog, which affect the crops production.

NO_x are formed in combustion processes due to a combination the oxygen and nitrogen in the combustion air, especially at high temperatures. The coefficient represents a weighted sum of NO_2 and NO, where NO is converted to NO_2 in weight-equivalents. NO_x contribute to oxidation of volatile organic compound in a photochemical process which creates ozone. This is related to the formation of smog, hence human respiratory problems and other diseases. It also affects negatively to agriculture due to smog reducing sunlight.

Combustion of fuels containing sulphur produces SO_2. This has local and regional impacts. On one side, it is related to human heart and lung diseases. Moreover, it causes acidification that affects forests, lakes, and buildings.

The pollutants emissions depend on the fuel as well as the combustion technology. Combustion chamber architectures, catalysts, and filters, among other, affect the pollutants emissions.

Calculation

The pollutant emission coefficient is the sum of energy input for each technology multiplied by the particle emission coefficients, divided by the total delivered energy. The calculation is carried out according Equation 13 and Equation 14, which are equivalent for all pollutants.

$$k_{xx.c} = \frac{\left(\sum_i E_{i.c} k_{xx.i} + \sum_j Q_{j.c} k_{xx.j}\right) + \alpha_c \left(\sum_i E_{i.hc} k_{xx.i} + \sum_j Q_{j.hc} k_{xx.j}\right)}{Q_{c.del}}$$ ***Equation 13***

$$k_{xx.h} = \frac{\left(\sum_i E_{i.h} k_{xx.i} + \sum_j Q_{j.\mathrm{h}} k_{xx.j}\right) + (1-\alpha_c)\left(\sum_i E_{i.hc} k_{xx.i} + \sum_j Q_{j.hc} k_{xx.j}\right)}{Q_{\boldsymbol{h}.del} + Q_{h-c}}$$ ***Equation 14***

Where:

- $k_{xx.c}$*: cooling service pollutant “xx” emission coefficient [kg/kWh].*
- $k_{xx.h}$*: heating service pollutant “xx” emission coefficient [kg/kWh].*
- α_c*: cooling share factor [-].*
- $E_{i.c}k_{xx.i}$*: fuel “i" energy input [kWh] multiplied by corresponding pollutant “xx” emission coefficient [kg/kWh] of equipment used exclusively for cooling generation.*
- $E_{i.h}k_{xx.i}$*: fuel “i" energy input [kWh] multiplied by corresponding pollutant “xx” emission coefficient [kg/kWh] of equipment used exclusively for heating generation.*
- $E_{i.hc}k_{xx.i}$*: fuel “i" energy input [kWh] multiplied by corresponding pollutant “xx” emission coefficient [kg/kWh] of equipment used exclusively for both cooling and heating generation.*
- $Q_{j.c}k_{xx.j}$*: external heat from source “j” [kWh] multiplied by corresponding pollutant “xx” emission coefficient [kg/kWh] used exclusively for cooling generation.*
- $Q_{j.h}k_{xx.j}$*: external heat from source “j” [kWh] multiplied by corresponding pollutant emission coefficient [kg/kWh] used exclusively for heating generation.*

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- $Q_{j.hc}k_{xx.j}$: *external heat from source "j" [kWh] multiplied by corresponding emission coefficient [kg/kWh] used exclusively for both cooling and heating generation.*
- $Q_{h.del}$: *Heat delivered to consumers [kWh].*
- $Q_{c.del}$: *Cooling delivered to consumers [kWh].*
- Q_{h-c}: *Heat consumed for cooling production at consumer side [kWh].*

Note that the pollutants taken into account are considered due to their local impact in health, agriculture, and others. Therefore, the electricity imported and exported to the grid is not considered in the equations, as this is considered to have an impact elsewhere. The focus of WEDISTRICT is to evaluate the impact of the renewable DHC in the local pollution, in comparison to individual systems.

Economics

SEc1 - Capital expenditures (CAPEX)

Description

The capital expenditures (CAPEX) includes all the cost involved in acquiring and installing all the assets for starting up the plant, as well as the cost for improving existing assets. This involves:

- *Direct construction costs*
- *Project engineering*
- *Project development*
- *Project financing costs*
- *Contingency*

CAPEX is expressed in terms of cost per capacity of the district heating or cooling system [€ / kW]. In case the system counts with both heating and cooling, this indicator should be split, having one for providing heating service and another for providing cooling service.

Calculation

Calculation is explained for the generic case when both heating and cooling services are provided.

Here we suggest splitting CAPEX of the direct construction costs, referred to the shared elements, in a similar way as for the case of energy or environmental KPIs. Thus, the CAPEX of the technologies applied for both heating and cooling services (eg. solar thermal, mid temperature waste heat recovery, mid temperature storage, etc) should be split after the cooling share factor.

Yet, we consider that the rest of the CAPEX components: Project engineering, project development, Project financing costs, and contingency should be split considering the proportion of the total CAPEX of Direct construction costs dedicated, on one side for heating and on another for cooling. The percentages are calculated considering Equation 15, Equation 16, and Equation 17.

$$\beta_c = \frac{C_{d.c} + \alpha_c C_{d.hc}}{C_{d.c} + C_{d.h} + C_{d.hc}}$$ ***Equation 15***

$$CAPEX_c = \frac{\left[C_{d.c} + \beta_c\left(C_{d.hc} + C_{pe} + C_{pd} + C_{pf} + C_{pc}\right)\right]}{P_c}$$ ***Equation 16***

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$$CAPEX_h = \frac{\left[C_{d.h} + (1-\beta_c)\left(C_{d.hc} + C_{pe} + C_{pd} + C_{pf} + C_{pc}\right)\right]}{P_h}$$ ***Equation 17***

Where the parameters are described as:

- $CAPEX_c$ *: Total normalized CAPEX for the equipment providing cooling service [€/kW].*
- $CAPEX_h$*: Total normalized CAPEX for the equipment providing heating service [€/kW].*
- β_c*: CAPEX cooling share factor [-].*
- $C_{d.c}$*: Direct construction costs for the equipment used for cooling only [€].*
- $C_{d.h}$*: Direct construction costs for equipment used for heating only [€].*
- $C_{d.hc}$*: Direct construction costs for the equipment used for both heating and cooling [€].*
- C_{pe}*: Project engineering costs [€].*
- C_{pd}*: Project development costs [€].*
- C_{pf}*: Project finance costs [€].*
- C_{pc}*: Project contingency costs [€].*
- P_c*: Total system cooling capacity [kW].*
- P_h*: Total system heating capacity [kW].*

SEc2 / SEc3 - Operational expenditures (OPEX)

- *SEc2 – Fixed operational cost ($OPEX_F$)*
- *SEc3 – Variable operational cost ($OPEX_V$)*

Description

The operational expenditures (OPEX) involve the ongoing cost for the operation of the district heating and cooling network, including energy, license, maintenance, labour, utilities, and replacements costs. The OPEX is divided in two parts:

- *Fixed cost: related to the size of the plant and expressed in terms of cost per thermal capacity [€ / kW]. It includes:*
  - *Labour cost.*
  - *Maintenance cost.*
  - *Plant performance monitoring costs.*
  - *Indirect operation and maintenance cost (i.e. subcontracted tasks).*
- *Variable costs: related to the heating and cooling production of the plant and expressed in terms of cost per thermal energy delivered [€ / kWh]. It includes:*
  - *Fuel.*
  - *Electricity.*
  - *Consumables as Chemicals, etc., including their wastes disposal.*

Calculation

For the generic case where the system counts with both heating and cooling, this indicator should be split, having one for providing heating service and another for providing cooling service. All the operational costs are shared in the same way as the total CAPEX. In this way the calculation of fixed operational costs according Equation 18 and Equation 19.

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$$OPEX_{F.c} = \frac{[\sum_i O_{Fc.i} + \beta_c(\sum_i O_{Fhc.i})]}{P_c}$$ ***Equation 18***

$$OPEX_{F.h} = \frac{[\sum_i O_{Fh.i} + (1-\beta_c)(\sum_i O_{Fhc.i})]}{P_h}$$ ***Equation 19***

Where:

- $OPEX_{F.c}$: *Total normalized fix operational costs for cooling [€/kW].*
- $OPEX_{F.h}$: *Total normalized fix operational costs for heating [€/kW].*
- $\sum_i O_{Fc.i}$: *Sum of fix operational costs for cooling service only [€].*
- $\sum_i O_{Fh.i}$: *Sum of fix operational costs for heating service only [€].*
- $\sum_i O_{Fhc.i}$: *Sum of fix operational costs shared between heating and cooling [€].*
- P_c : *Total system cooling capacity [kW].*
- P_h: *Total system heating capacity [kW].*
- β_c: *CAPEX cooling share factor [-] (see Equation 15).*

While the variable OPEX for cooling and heating are calculated after Equation 20 and Equation 21.

$$OPEX_{V.c} = \frac{\left[\sum_i O_{Vc.i} + \alpha_c\left(\sum_i O_{Vhc.i} - \sum_i E_{exp.i} p_{exp.i}\right)\right]}{Q_c}$$ ***Equation 20***

$$OPEX_{V.h} = \frac{\left[\sum_i O_{Vh.i} + (1-\alpha_c)\left(\sum_i O_{Vhc.i} - \sum_i E_{exp.i} p_{exp.i}\right)\right]}{Q_h}$$ ***Equation 21***

Where:

- $OPEX_{V.c}$: *Total normalized variable operational costs for cooling [€/kWh].*
- $OPEX_{V.h}$: *Total normalized variable operational costs for heating [€/kWh].*
- $\sum_i O_{Fc.i}$: *Sum of variable operational costs for cooling service only [€].*
- $\sum_i O_{Fh.i}$: *Sum of variable operational costs for heating service only [€].*
- $\sum_i O_{Fhc.i}$: *Sum of variable operational costs shared between heating and cooling [€].*
- $E_{exp.i}$: *Exported energy of carrier "i" [kWh].*
- $p_{exp.i}$: *Selling price of exported carrier "i" [€/kWh].*
- Q_c : *Cooling delivered to consumers [kWh].*
- Q_h: *Heat delivered to consumers [kWh].*
- α_c: *cooling share factor [-].*

SEc4 - Levelized cost of energy (LCoE).

Description

Levelized cost of energy (LCOE) is a measure of the average net present cost of energy over the system lifetime. It is frequently used to compare technology alternatives for energy generation. LCOE is particularly useful when a high upfront investment is required while a reduced operation costs exist, as it is the case with systems with a high renewable energy share.

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The levelized cost of energy calculation is a methodology that discounts the time series of expenditures and incomes to their present values in a specific base year [8]. It provides the costs per unit of energy generated which are the ratios of total lifetime expenses (net present value) versus total expected energy generation, the latter also expressed in terms of net present value. These costs are equivalent to the average price that would have to be paid by consumers to repay all costs with a rate of return equal to the discount rate. NREL proposes a similar approach, which is referred to simple levelized cost of energy (sLCoE) [9], which is an economic assessment of the cost of the energy-generating system including all the cost over its lifetime: initial investment, operations, and maintenance, cost of fuel, and cost of capital, without considering externalities. LCOE is also frequently used for district energy analysis [10,11,12]. In case the system counts with both heating and cooling, this indicator should be split, having one for providing heating service and another for providing cooling service.

Calculation

Levelized cost of energy (sLCoE) [13] uses the Equation 22.

$$\boldsymbol{LCOE} = \frac{\{(\boldsymbol{overnight\_capital\_cost} \cdot \boldsymbol{capital\_recovery\_factor} + \boldsymbol{fixed\_O\&M_{cost}} - \boldsymbol{final\_value})\}}{(\boldsymbol{8760} \cdot \boldsymbol{capacitiy_{factor}})} + (\boldsymbol{fuel\_cost} \cdot \boldsymbol{heat\_rate}) + \boldsymbol{variable\_O\&M\_cost}$$

Equation 22

Where:

- *Overnight capital cost: Cost per installed capacity [€/ kW].*
- *Capital recovery factor: Ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Considering and interest rate "i" and a number of annuities received "n".*
- *Fixed O&M: fixed operation and maintenance cost per year related to the installed capacity [€/ kW / year].*
- *Final value: Residual value of the components at the end of the lifetime of the plant [€/kW].*
- *Capacity factor: Proportion of the year the power plant is generating power.*
- *Fuel cost: fuel cost related to LHV [€/ kWh].*
- *Heat rate: system efficiency, ratio between delivered heat and fuel consumed [-].*
- *Variable O&M: variable operation and maintenance cost related to the energy production (excluding fuel cost) [€/ kWh].*

The LCOE for WEDISTRICT systems is calculated in a similar way. For the purpose of clear comparison with conventional technologies, it is distinguished between the heating energy LCOE and cooling energy LCOE as in Equation 26 and Equation 27, respectively.

$$rv_c = \frac{[(RV_c - C_{dec.c}) + \beta_c(RV_{hc} - C_{dec.hc})]}{P_c}$$

Equation 23

$$rv_h = \frac{[(RV_h - C_{dec.h}) + (1 - \beta_c)(RV_{hc} - C_{dec.hc})]}{P_h}$$

Equation 24

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$$\mathrm{CRF} = \frac{\{\mathrm{i} \cdot (1+\mathrm{i})^{\mathrm{n}}\}}{\{[(1+\mathrm{i})^{\mathrm{n}}] - 1\}}$$ ***Equation 25***

$$LCOE_c = \frac{\left(\mathrm{CAPEX_c} CRF + OPEX_{F.c} - \frac{rv_c}{n}\right) P_c}{Q_{c.del}} + OPEX_{V.c}$$ ***Equation 26***

$$LCOE_h = \frac{\left(CAPEX_h CRF + OPEX_{F.h} - \frac{rv_h}{n}\right) P_h}{Q_{c.del}} + OPEX_{V.h}$$ ***Equation 27***

Where:

- $LCOE_c$*: Levelized cost of cooling energy [€/kWh].*
- $LCOE_h$ *: Levelized cost of heating energy [€/kWh].*
- $CAPEX_c$*: Total normalized CAPEX for the equipment providing cooling service [€/kW].*
- $CAPEX_h$ *Total normalized CAPEX for the equipment providing heating service [€/kW].*
- $OPEX_{F.c}$*: Total normalized fix operational costs for cooling [€/kW].*
- $OPEX_{F.c}$*: Total normalized fix operational costs for heating [€/kW].*
- $OPEX_{V.c}$*: Total normalized variable operational costs for cooling [€/kWh].*
- $OPEX_{V.h}$*: Total normalized variable operational costs of for heating [€/kWh].*
- CRF*: Capital recovery factor: Ratio of a constant annuity to the present value of receiving that annuity for a given project lifetime "n". Considering and interest rate "i" and a number of annuities received "n".*
- rv_c*: Normalized Residual Value of the cooling system components at the end of the considered system lifetime including decommissioning cost [€/kW].*
- rv_h*: Normalized Residual Value of the heating system components at the end of the considered system lifetime including decommissioning cost [€/kW].*
- RV_c*: Residual value of the cooling specific system components at the end of the considered lifetime [€].*
- RV_h*: Residual value of the heating specific system components at the end of the considered lifetime [€].*
- RV_{hc}*: Residual value of the system components used for both heating and cooling generation at the end of the considered lifetime [€].*
- $C_{dec.c}$*: Decommissioning cost of the cooling specific system components at the end of the considered lifetime [€].*
- $C_{dec.h}$*: Decommissioning cost of the heating specific system components at the end of the considered lifetime [€].*
- $C_{dec.hc}$*: Decommissioning cost of the system components used for both heating and cooling generation at the end of the considered lifetime [€].*
- $Q_{c.del}$*: Cooling delivered to consumers per year [kWh].*
- $Q_{h.del}$*: Heat delivered to consumers per year [kWh].*
- Q_{h-c}*: Heat consumed for cooling production at consumer side [kWh].*
- n*: Lifetime of the system [year].*
- β_c*: CAPEX cooling share factor [-] (see Equation 15).*
- P_c*: Total system cooling capacity [kW].*

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- P_h: *Total system heating capacity [kW].*

Socio-economic

SSc1 - Environmental social cost (sc)

Description

Environmental and Social cost represents the externalities related to the climate change and health costs of greenhouse gas and local health-impact emissions. This comprehends local and global impact. This cost is not reflected on the financial aspects of the energy services, then this are not reflected within the price. Yet, the environmental impacts generate cost to the society related to health and climate change.

On one side, greenhouse gasses emissions, such as CO_2, CH_4, and N_2O are the main cause of global warming and climate change. On the other, SO_2, NO_x, and particles cause local impact mainly related to health issues, such as heart and lung diseases that increase morbidity and mortality, but also acidification impacting forest, lakes and building materials, eutrophication, and generation of smog.

The concept is used in DHC by the Danish Energy Agency LCOE calculator as part of the externalities [13]. Moreover, the concept is in a studies of green building impact in indoor and climate change [14] and external health impact of transportation [15]. Finally, the European Environment Agency presents the cost of air pollution from European industrial facilities [16].

Calculation

The climate change and health cost KPI is calculated considering the emissions factors of each pollutant, according the corresponding technology KPI, and using the emission cost factors for each pollutant, as described generically in Equation 28.

$$sc = \frac{\sum_i \sum_x (c_{e.x} \cdot k_{i.x} \cdot E_i)}{Q_{del}}$$

Equation 28

Where:

- sc: *Environmental social cost.*
- $c_{e.x}$: *Emission cost of pollutant "x" [€ / kg].*
- $k_{i.x}$: *Emission coefficients of pollutant "x" from carrier "i" [kg / kWh].*
- E_i: *Energy input of carrier "i".*
- Q_{del}: *Delivered energy of the system [kWh].*

Specifically to WEDISTRICT project relevant carrier and pollutants, the social cost can be calculated according Equation 29 and Equation 30. The emission factors are considered in the same way as in non-renewable primary energy factor KPI. For the pollutant cost the values of EEA are considered [16].

$$\boldsymbol{sc_c} = \frac{\sum_i \boldsymbol{E_{i.c}} (\sum_x \boldsymbol{c_{e.x}} \cdot \boldsymbol{K_{i.x}}) + \boldsymbol{\alpha_c} (\sum_i \boldsymbol{E_{i.hc}} (\sum_x \boldsymbol{c_{e.x}} \cdot \boldsymbol{K_{i.x}}))}{\boldsymbol{Q_{c.del}}}$$

Equation 29

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$$\boldsymbol{sc_h} = \frac{\sum_i \boldsymbol{E_{i.h}}(\sum_x \boldsymbol{c_{e.x}} \cdot \boldsymbol{k_{i.x}}) + (\mathbf{1} - \boldsymbol{\alpha_c})(\sum_i \boldsymbol{E_{i.hc}}(\sum_x \boldsymbol{c_{e.x}} \cdot \boldsymbol{k_{i.x}}))}{\boldsymbol{Q_{h.del}} + \boldsymbol{Q_{h-c}}}$$

Equation 30

Where:

- sc_c: *Cooling environmental social cost [€/kWh].*
- sc_h: *Heating environmental social cost [€/kWh].*
- $c_{e.x}$: *Emission cost of pollutant "x" [€/kg].*
- $k_{i.x}$: *Emission coefficients [kg/MWh] of pollutant "x" for fuel and combustion technology "i" [kg/KWh].*
- $E_{i.c}$: *Energy input of carrier [kWh] "i" used exclusively for cooling generation.*
- $E_{i.h}$: *Energy input of carrier [kWh] "i" used exclusively for heating generation.*
- $E_{i.hc}$: *Energy input of carrier [kWh] "i" used exclusively for both cooling and heating generation.*
- $Q_{h.del}$: *Heat delivered to consumers [kWh].*
- $Q_{c.del}$: *Cooling delivered to consumers [kWh].*
- Q_{h-c}: *Heat consumed for cooling production at consumer side [kWh].*

The emission cost of pollutants are taken from the European Environment Agency [16], the values are summarized in Annex 2.

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4 Technology KPIs

4.1 General considerations

The technology specific KPIs presentation is organized in four chapters, according to the role of each technology within the energy chain of the system: heat generation, waste energy recovery, cooling generation, storage, and advanced digitalization.
For each technology the KPI rationale is structured in the same way, distinguishing 6 parts: starting with a brief technology description, followed by the energy, economics, environmental, and technology indicators, and finally adding some technology specific operational performance indicators (OPI), if necessary. Even if the focus is to keep the same KPIs for all the technologies as much as possible, due to the same nature of their function and their particularities, the content of all these parts may vary from technology to technology. Firstly, the description ofthe KPIs applicable to all the technologies are presented, then the separated sectiongo through those necessary for enlightening each particular technology under the specific technology corresponding chapter.

Energy

TEn1 - Auxiliary energy ratio (r_{aux})
Ratio between the auxiliary electrical energy consumed by the equipment to the delivered thermal energy. It includes the energy consumption of electronics, pumps, fans, servos, and other components required to run the equipment.

$$r_{aux} = \frac{\sum E_{aux}}{|Q_{del}|} \qquad \textit{Equation 31}$$

Where:

- r_{aux}: *Auxiliary energy ratio [kWh$_{el}$/kWh$_{th}$].*
- $\sum E_{aux}$: *Auxiliary electrical energy use [kWh$_{el}$].*
- Q_{del}: *Delivered thermal energy [kWh$_{th}$].*

Economics

TEc1 - Equipment cost (c)
Gross amount paid by the company to the manufacturer. It includes the manufacture cost and the commercial margin as well as all applicable sales taxes and delivery charges as invoiced.

The equipment cost is normalized to its size, being either the technology nominal capacity [€/kW] for energy harvesting and energy conversion technologies, or storage capacity [€/kWh].

TEc2 - Fixed operating and maintenance cost (o_F)
Equipment annual cost independent to operation and performance. It includes operation cost that due no change in the short term as well as cost of measures for preserving and restoring the desired quality of the equipment that are related exclusively to the size of the equipment and not to its operation. It includes annual cost for inspection, cleaning, adjustments, preventive maintenance, and consumable items, but not fuel, electricity use, or other cost related to the energy harvested, converted, or stored.

Equivalent to equipment cost, fixed operating and maintenance cost is normalized to its size, being either the technology nominal capacity [€/kW] for energy harvesting and energy

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conversion technologies, or storage capacity [€/kWh] thermal and electrical storage technologies.

TEc3 - Variable operating and maintenance cost (o_V)

Cost related to the energy harvesting, conversion, or storage of the equipment. It includes maintenance, operational, and energy cost directly related to the activity of the equipment. These involve fuel and electricity use, inspection, cleaning, adjustments, preventive maintenance, consumable items, labour, insurance, and taxes.

Variable operating and maintenance cost is normalized to unit of energy delivered [€/kWh].

TEc4 - Technical lifetime (LF)

Total time for which the equipment is technically designed to operative from its first commissioning.

Technical lifetime is expressed in years [y].

TEc5 - Decommissioning cost (c_{dec})

Cost of dismantling and retirement of all the equipment and assets related to the technology applied. Includes all measures to be taken to restore the landscape or ground, if affected. Decommissioning cost is normalized to the technology nominal capacity [€/kW].

TEc6 - Residual value (rv)

Estimated value of the equipment at the end of its technical lifetime. Residual value is normalized to the technology nominal capacity [€/kW].

Technology specific

TTs1 - Technology readiness level (TRL)

Qualitative indicator of the maturity level of particular technologies defined by the European Commission [17]. It provides a common understanding of technology status and addresses the entire innovation chain in nine levels, as summarized in Table 4-1.

Table 4-1. Horizon 2020 TRL definitions [17].

TRL 1	Basic principles observed.
TRL 2	Technology concept formulated.
TRL 3	Experimental proof of concept.
TRL 4	Technology validated in lab.
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in operational environment.
TRL 8	System complete and qualified.
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies).

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Environmental

TEv1 - Space requirement (s)
Required area necessary to install and properly maintain given technology. For solar, or any other "extensive" technologies, it includes overall land use necessary to install a certain capacity [18]. Area requirement is normalized per nominal capacity of the equipment [m^2/kW] or energy storage capacity [m^2/kWh].

4.2 Heat generation

WEDISTRICT project includes 4 technologies dedicated to the renewable energy harvesting for district heating and cooling system:

- *Concentration solar: Parabolic trough collectors*
- *Concentration solar: Fresnel collectors*
- *Concentration solar: Low concentration flat plate collectors*
- *Low emission biomass boiler*

4.2.1 Concentration solar technologies

Technology description, Parabolic through collectors (PTC)
Parabolic trough collectors (PTC) are the most widely deployed linear concentrating technology. PTCs consist of parabolic trough shaped mirrors (collectors) that concentrate the solar radiation along a heat receiver tube (absorber). This tube is thermally efficient and placed in the collectors' focal line. Single axis sun tracking systems are typically used in PTC systems to orient the solar collectors, together with the receiver tubes, towards the sun and increase energy absorption. Through the use of a heat transfer fluid (often thermal oil) and a heat transfer fluid system these individual solar collectors are connected in a loop and deliver the heat to heat exchangers. The PTC technology to be implemented in WEDISTRICT has a starting TRL of 5.

Figure 4-1. Parabolic through collectors.

Technology description, Fresnel collectors (FTC)
Fresnel collectors are another type of technology based on linear concentration of solar radiation. These are similar to PTCs, but they use an array of almost flat mirrors (reflectors) instead of parabolic trough-shaped-mirrors; the array is designed to approximate the "ideal" parabolic form. In Fresnel systems, mirrors concentrate the sun's rays onto elevated linear receivers that are not directly connected to them but are located several metres above the

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primary mirror field. The long narrow mirror strips are pivot-mounted so that each one is oriented in a chosen angle in such way that the sunlight is focused onto the receiver during the whole day. The FTC technology to be implemented in WEDISTRICT has a starting TRL of 5.

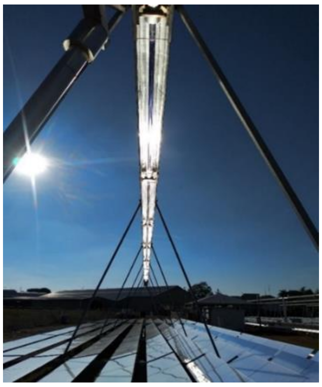

Figure 4-2. Fresnel collectors.

Technology description, Low concentration flat plate collectors (LCC)

A typical flat plate solar thermal collector is a metal box with a glass or plastic cover (called glazing) on top and a dark-coloured absorber plate on the bottom with the sides and bottom of the collector are usually insulated to minimize heat loss (flat plate collector). Sunlight passes through the glazing and strikes the absorber plate, which heats up, converting solar energy into thermal energy. The heat is transferred to liquid passing through pipes attached to the absorber plate. The essential feature of new design is that flat mirrors are added on the flat plate collector laterals, acting as a concentrator. The concentrator is moving to homogeneously redistribute on the absorber the radiation available on the collector aperture. The aperture is defined as the area of the section of the incident solar beam redirected by the mirrors and contained in a plane parallel to the absorber). This design avoids high local concentrations characteristic of focusing concentrators. The LCC technology to be implemented in WEDISTRICT has a starting TRL of 5.

Figure 4-3. Low concentration flat place collectors.

Energy

TEn2 - Collector energy output (p_{col})

Solar energy harvested and delivered in form of heat, on annual basis, per square meter of collector surface. The KPI assumes measured or reference year calculation conditions. It depends on climatic conditions of the site where the solar technology is installed.

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TEn3 - Total efficiency ($\eta_{col.t}$)
Ratio between the collector energy output and the total incident radiation on the collector surface. Measured on annual base.

Technology specific

TTs2 - Characteristic Efficiency curve (η_{col})
Efficiency at different conditions of radiation, ambient temperature and average temperature. Under a constant radiation the collector efficiency decreases as its temperature output is forced to be higher. This KPI, in form of a curve, allows the comparison of the technology performance. The characteristic efficiency curve results from the standard testing procedures defined in:

- *EN 12975-1:2006+A1:2010 - Thermal solar systems and components - Solar collectors - Part 1: General requirements [19].*
- *EN 12975-2:2006 Thermal solar systems and components. Solar collectors. Part 2: Test methods [20].*

TTs3 - Yearly performance drop (pd)
This indicator measures the performance degradation over the collector lifetime. Namely, the collector output under the same environmental conditions may change over the time due to the equipment aging.

TTs4 - Optical collector efficiency (η0)
Represents the amount of energy that reaches a solar collector, divided by the energy coming from the solar source.

TTs5 - Loss coefficient (a1)
Heat loss coefficient at collector fluid temperature equal to ambient temperature [W/K]

TTs6 - Loss coefficient (a2)
Temperature dependent term of heat loss coefficient [W/K^2].

4.2.2 Low emissions biomass boiler

Technology description

Biomass boilers are technologies using the combustion of plant material for generation of hot water for district heat or low-pressure steam (in case of HOP) or electricity and heat as steam or warm water (in case of CHP). Fuel are usually residues from wood industries, wood chips from forestry, straw and energy crops (eg. willow or poplar). Less common fuels include empty fruit bunch pellets, palm kernel shells, and chipped park and garden waste. Despite being a renewable source biomass still generates harmful toxins that may be released into the atmosphere as it is combusted. One of the main challenges is to reduce the local pollution from biomass burning, as NOx and particle emissions. The new biomass boiler design consists in an optimized furnace for improved air distribution and pressure. The boiler will be adapted to most adequate local biomass, considering the content of N_2 and compatibility with catalyst. The boiler is aiming to incorporate innovative filters with selective catalytic reduction and dust retention with premium filtration. The low emission biomass boiler technology to be implemented in WEDISTRICT has a starting TRL of 4.

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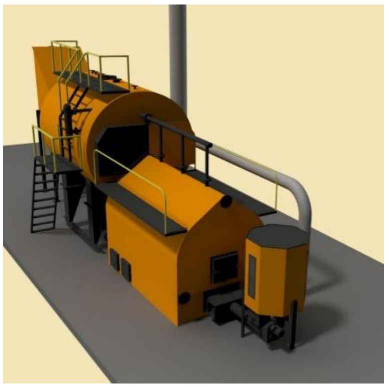

Figure 4-4. Low-emissions biomass boiler (render).

Energy

TEn4 - Total boiler efficiency (η_{LHV})

Ratio between delivered thermal energy and consumed fuel chemical energy, in terms of fuel Low Heating Value (LHV).

$$\eta_{LHV} = \frac{Q_{del}}{Q_{fuel}} \quad \textit{Equation 32}$$

Where:

- η_{LHV} : *Total boiler efficiency referred to low heating value [-].*
- Q_{del}: *Heat delivered to the DHC network [kWh].*
- Q_{fuel}: *Fuel consumption [kWh].*

TEn5 - Heat capacity (P_h)

Range of boiler design capacity at nominal conditions, expressed per unit of equipment.

Environmental KPIs

TEv2 - GHG emission value (ev_{CO2})

Emission of greenhouse gases per normalized cubic meter of flue gasses, measured in terms of equivalent CO2 mass [mg/Nm^3].

TEv3 - NOx emission value (ev_{NOX})

This factor accounts for nitrogen oxides emission mass per normalized cubic meter of flue gasses [mg/Nm^3].

TEv4 - Particles emission value ($ev_{PM2,5}$)

The factor of particle emission refers to emitted particles mass normalized cubic meter of flue gasses [mg/Nm^3].

TEv5 - SO_2 Emission value (ev_{SO2})

This factor accounts for sulphur oxide emission mass normalized cubic meter of flue gasses [mg/Nm^3].

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4.3 Waste heat recovery technologies

4.3.1 WHR Fuel cell powered data centres

Technology description

Fuel cell powered data centres with waste heat recovery for district heating is a concept for reducing environmental impact and increase profitability of data centres. The data centre power needs are covered by fuel cells consuming renewably produced hydrogen or biogas, hence minimizing the greenhouse gasses emissions and environmental impact. In order to increase the feasibility of the concept, fuel cells with high operation temperatures are used (such as SOFC, 600-900 ºC) for allowing waste heat recovery to district heating network. Moreover, the heat output of the fuel cell is increased by using the heat generated in the data centre server room for preheating the fuel and air input streams, consequently reducing the fuel cell internal reheating of input gasses with flue gasses.

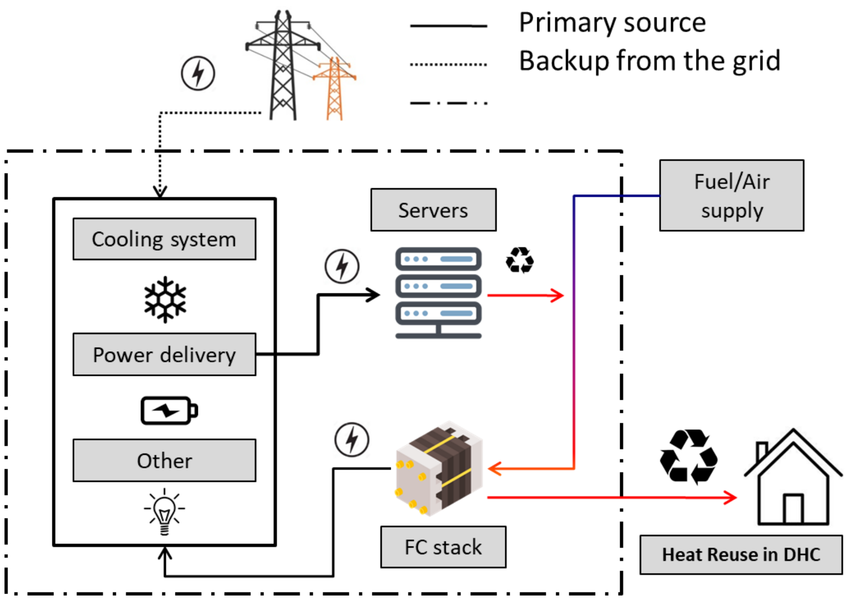

Figure 4-5. Scheme of Fuel cell powered data centre with waste heat recovery for DHC.

Energy

TEn6 - Primary energy (PE_{DaC})

This indicator takes into consideration all types of energy consumed and generated by the system, and its exchange with the energy networks. It is calculated using Equation 33.

$$P_{eDC_{tot}} = \sum_i \{[E_{del_i} \cdot f_{del.t.i}] - [E_{exp.i} \cdot f_{exp.t.i}]\} \qquad \textit{Equation 33}$$

Where:

- $P_{DaC.t}$: *Total primary energy consumption [kWh].*
- $E_{del.i}$: *Delivered energy of the carrier "i" [kWh].*
- $f_{del.t.i}$: *Total primary energy factor of delivered energy of the carrier "i" [kWh].*
- $f_{exp.t.i}$: *Total primary energy factor of exported energy of the carrier "i" [kWh].*
- $E_{exp.i}$: *Exported energy of the carrier "i" [kWh].*

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TEn7 - Energy reuse factor (ERF_{DaC})

The International Organization for Standardization (ISO) is proposing the Energy Reuse Factor (ERF) metric [21]. With ERF, the data centre under consideration shall be viewed as a closed control volume bounded by interfaces through with the energy flows.

According to [22], the ERF could be evaluated taking into account the primary energy according Equation 34.

$$ERF = \frac{PE_{reused}}{P_{DaC.t}} \qquad \textit{Equation 34}$$

Where:

- PE_{reused}*: is the excess primary energy from the data centre used outside of the control volume (annual), in kWh.*
- $P_{DaC.t}$*: is the total data centre primary energy consumption (annual), in kWh.*

These are calculated by multiplying energy consumption with primary energy weighting factors, as shown in Equation 35 and Equation 36.

$$PE_{reused} = \sum_i E_{reused.t}\ f_{reuse.t} \qquad \textit{Equation 35}$$

$$PE_{DC} = \sum_i E_{DaC.t.i}\ f_{DaC.t.i} \qquad \textit{Equation 36}$$

Where:

- E_{reused_i} *: Energy flux going out of the control volume (annual) [kWh].*
- $E_{DaC.t.i}$ *: Total data centre energy consumption (annual) [kWh].*
- $f_{reuse.t}$*: Primary energy weighting factor of the reused energy [-].*
- $f_{DaC.t.i}$*: Primary energy weighting factor of the energy used in the data centre [-].*

The reused energy is considered as the utilization of energy used in the data centre to an alternate purpose outside the data centre boundary. In the case of WEDISTRICT project, the reused energy is the heat recovered and fed to the DHC network.

TEn8 - Renewable energy ratio (RER_{DaC})

The renewable energy ratio (RER) is the metric that allows calculating the share of renewable energy use in a Data Centre. The renewable energy ratio is calculated relative to all energy use in the Data Centre, in terms of total primary energy, as summarized in Equation 37.

$$RER_{PE} = \frac{\sum_i E_{r.i} + \sum_i [(f_{del.t.i} - f_{del.nr.i}) E_{del.i}]}{\sum_i E_{r.i} + \sum_i (f_{del.t.i} E_{del.i}) - \sum_i (f_{exp.t.i} E_{exp.i})} \qquad \textit{Equation 37}$$

Where:

- RER_{DaC} *: Data centre primary energy renewable energy ratio [-].*
- $E_{r.i}$ *: Renewable energy consumed on-site of the energy carrier "i" [kWh].*
- $f_{del.t.i}$*: Total weight factor of imported energy of the energy carrier "i" [kWh].*
- $f_{del.nr.i}$ *: Non-renewable weight factor of the energy carrier "i" [kWh].*
- $E_{del.i}$ *: Imported energy of the energy carrier "i" [kWh].*

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- $f_{exp.t.i}$: *Total weight factor of exported energy of the energy carrier "i" [kWh].*
- $E_{exp.i}$: *Exported energy of the energy carrier "i" [kWh].*

Economics

Unlike other technologies in WEDISTRICT, the waste heat recovery from fuel cell powered data centres is outside the boundaries of the DHC, as shown in Figure 2-3. In this case the economic evaluation must be focused in the DaC owner, that is interested in an economical feasible DaC in which waste heat recovery is a way to increase the feasibility. Therefore, in this case the two new economic KPI are proposed: total cost of ownership if focused on DaC owners point of view, while levelised cost of energy is implemented for the DHC network point of view.

TEc7 - Total cost of ownership (TCO_{DaC})

The total cost of ownership is defined as the present value of the initial investment costs (CAPEX) and the sum of running and operational cost (OPEX), replacements cost, and residual value. Therefore, it is useful to assess the true total cost of building, owning, and operating a data centre. TCO is calculated according Equation 38.

$$TCO(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a.i}(j) R_d(i) \right) - V_{f.\tau}(j) \right] \qquad \textit{Equation 38}$$

Where:

- $TCO(\tau)$: *Total cost of ownership at the end of the evaluation period "τ"[€]*
- C_I: *Initial investment cost (CAPEX) [€]*
- $C_{a.i}(j)$: *Annual cost for the year "i" and component "j" including operational, replacement cost, as well as incomes from exported energy [€]*
- $R_d(i)$: *Discount rate for the year "i" [-].*
- $V_{f.\tau}(j)$: *Residual value of component "j" at the end of period "τ"[€].*

Note that the income from selling heat is included as a negative term into the annual cost per year ($C_{a.i}(j)$).

Environmental

TEv6 - Data centre CO_2 emission ($K_{DaC.CO2}$)

Data centre CO_2 emissions can be evaluated using adequate conversion factors for each energy carrier, using a methodology similar to the primary energy evaluation. The weighting factors to be used are the CO_2 emission coefficient which represents the quantity of CO_2 emitted to the atmosphere per unit of energy, for a given carrier.

$$K_{DaC.CO_2} = \sum_i \left(E_{del.i} k_{del.CO_2.i} \right) - \sum_i \left(E_{exp.i} K_{exp.CO_2.i} \right) \qquad \textit{Equation 39}$$

Where:

- $K_{DaC.CO_2}$: *Data centre CO_2 emissions [kg].*
- $E_{del.i}$: *Imported energy of the energy carrier "i" [kWh].*
- $k_{del.CO_2.i}$: *CO2 emission factor of imported energy of the energy carrier "i" [kg/kWh].*

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- $E_{exp.i}$: *Exported energy of the energy carrier "i" [kWh].*
- $k_{exp.CO_2.i}$: *CO2 emission factor of exported energy of the energy carrier "i" [kg/kWh].*

4.4 Cooling generation

4.4.1 Absorption chiller (ACh)

Technology description

Absorption chillers are thermally activated cooling devices. A thermochemical process is used to drive a vapour compression cycle. The refrigerant in an absorption chiller dissolves in an absorbent solution for which it has a high chemical affinity. Thermal energy for the absorption process can be supplied in different ways, for example, by gas burners and by recovering thermal energy from concentrated solar thermal power plants (cogeneration). The number of heat exchangers within the absorption chiller distinguishes the system as either single-effect or double-effect absorption chiller. Single-effect absorption chiller systems consist of an evaporator, an absorber, a generator, a separator, and a condenser. The main innovation in this absorption chiller is the inclusion of packed bed material in the condenser and the preheater, Figure 4-6. In this way, most of the energy of the condensation process that in conventional absorption chiller would be wasted is used to preheat the diluted solution before it arrives at the generator. This fact increases the cycle COP and reduces the cooling tower size. Moreover, the inclusion of packed bed material in these two components allows the system to get a temperature stratification, which enhances the operational conditions of the cycle. The ACh technology to be implemented in WEDISTRICT has a starting TRL of 5.

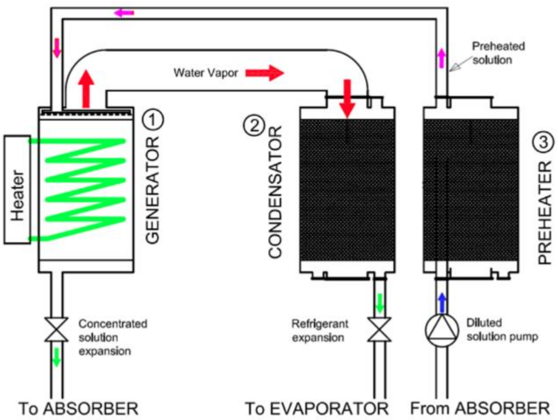

Figure 4-6. Scheme of absorption chiller with internal heat recovery.

Energy

TEn9 - Cooling capacity (P_c)

Design peak delivered cooling power to the cool water circuit at nominal operation conditions per unit [kW/unit]. The nominal operation conditions are described in the KPIs of source, mid loop, and cooling loop temperature levels.

TEn10 - Absorption chiller Coefficient of Performance (COP_{ACH})

The coefficient of performance is defined as the ratio between the energy output to the input [23]. In the case of absorption chillers, the output is the useful heat at lower temperature than the surroundings. On the other side, the energy input is the heat supplied to drive the absorption cycle, so the heat used to generate the vapour from the concentrated solution. In

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WEDISTRICT case, the output is the cooling delivered to the cold water distribution circuit, while the input is the heat supplied from the TES, CS, or BB.

The COP_{ACH} is calculated according Equation 40.

$$COP_{ACH} = \frac{Q_{del}}{Q_{input}} \quad \textit{Equation 40}$$

Where:

- *COP_{ACH}: Absorption chiller coefficient of performance [-].*
- *Q_{del}: useful cooling delivered to the cold water circuit [kWh].*
- *Q_{input}: heat supplied by the TES, CS, or BB to drive the absorption chiller [kWh].*

Technology specific

TTs7 - Source loop temperature levels

Inlet and return temperature of fluid flowing through the generator for generating steam and concentrated solution from the preheated diluted solution.

The source loop temperature levels are expressed with two value separated by slash, the first indicating the inlet temperature and the second the return temperature, both expressed in [ºC].

TTs8 - Cooling loop temperature levels

Inlet and return temperature of fluid flowing through the condenser and absorber for producing liquid refrigerant and diluted solution, respectively.

The cooling loop temperature levels are expressed with two value separated by slash, the first indicating the inlet temperature and the second the return temperature, both expressed in [ºC].

TTs9 - Chilled loop temperature levels

Inlet and return temperatures of the fluid flowing through the evaporator loop.

The chiller loop temperature levels are expressed with two value separated by slash, the first indicating the inlet temperature and the second the return temperature, both expressed in [ºC].

4.4.2 Renewable air cooling unit (RACU)

Technology description

The renewable air cooling unit (RACU) is a desiccant indirect evaporative renewable cooling unit for supplying cool air by using low temperature renewable heat, Figure 4-7. It is composed of an indirect evaporative cooler (IEC) and a desiccant wheel (DW). The main innovation is the incorporation of silica gel into the desiccant wheel. This allows activation at temperatures levels of 80-85ºC, which makes the system becoming compatible with renewable low temperature sources. Moreover, only air and water are required as working fluids. Consequently, the environmental impact of the cooling equipment is reduced by the lack of fluorocarbons and other substances with Global Warning Potential (GWP). Additionally, it has reduced energy consumption compared to conventional HVAC systems as it does not use compressors. The RACU technology to be implemented in WEDISTRICT has a starting TRL of 5.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

This technology is conceived for HVAC applications, complementing heat only networks with cooling capacities. It is capable of controlling the sensible and latent loads in buildings, thereby optimizing indoor air conditions. RACU has four control modes: 1, Ventilation (Indoor Air Quality); 2, Ventilation and air temperature control; 3, Ventilation and air humidity control; and 4, Ventilation, air temperature and humidity control.

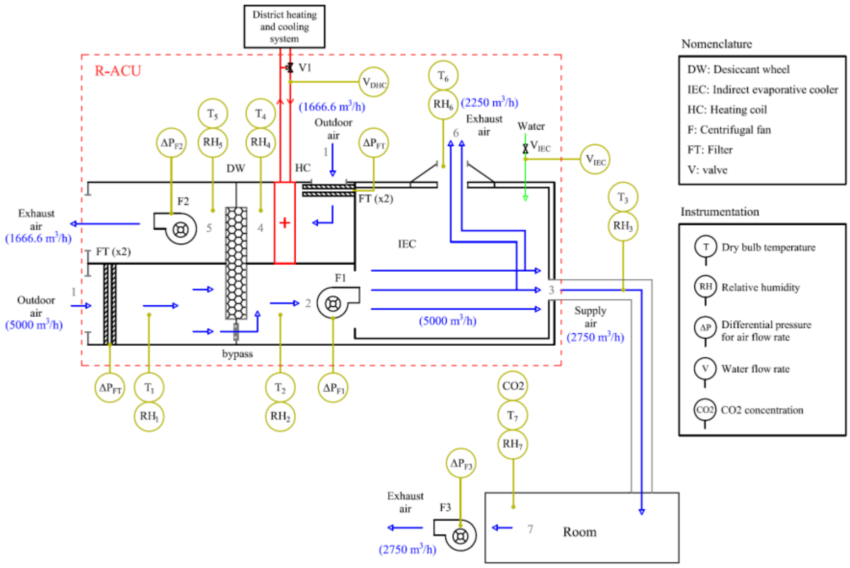

Figure 4-7. Scheme of renewable air cooling unit.

Energy

TEn11 - Cooling capacity (P_c)

Peak cooling power delivered from RACU to the room at nominal operation conditions per unit [kW/unit]. The nominal operation conditions are described in the KPIs of source, mid loop, and cooling loop temperature levels.

TEn12 - District heat to cooling ratio (r_{DH})

Ratio between the useful delivered energy and the heat consumed from the source, see Figure 4-8. In WEDISTRICT project, the source refers to the heat supplied by the district heating to activate the desiccant wheel and heating coil. The useful delivered energy refers to both the sensible and latent cooling demands covered by the unit.

The district heat to cooling ratio is calculated according Equation 41.

$$r_{DH} = \frac{Q_{DH}}{Q_{\tau.del}} \qquad \textit{Equation 41}$$

Where:

- r_{DH}: *District heat to cooling ratio [-]*
- Q_{DH}: *Sensible thermal energy delivered from the district heating to RACU [kWh]*
- $Q_{\tau.del}$: *Sensible and latent thermal energy delivered from RACU to the room [kWh].*

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TEn13 - Consumed heat to cooling ratio (r_{HtC})

Ratio between the useful delivered energy and all the thermal energy used, which includes energy from district heating, the sensible thermal energy from internal evaporation cooling, and sensible and latent thermal energy from outdoor air.

The consumed heat to cooling ratio is calculated according Equation 42

$$r_{HtC} = \frac{Q_{DH}+Q_{S.dl.IEC}+Q_{S.air}+Q_{L.air}}{Q_{\tau.del}} \cdot 100$$ ***Equation 42***

Where:

- r_{HtC}: *consumed heat to cooling ratio [%].*
- Q_{DH}: *Sensible thermal energy delivered from the district heating to RACU [kWh].*
- $Q_{S.dl.IEC}$: *Sensible thermal energy delivered due to thermal exchange between air and water [kWh].*
- $Q_{S.air}$: *Sensible thermal energy delivered from outdoor air [kWh].*
- $Q_{L.air}$: *Latent thermal energy delivered from outdoor air [kWh].*
- $Q_{\tau.del}$: *Sensible and latent cooling thermal energy delivered from RACU to the room [kWh].*

Figure 4-8 summarizes the heat flows of the RACU.

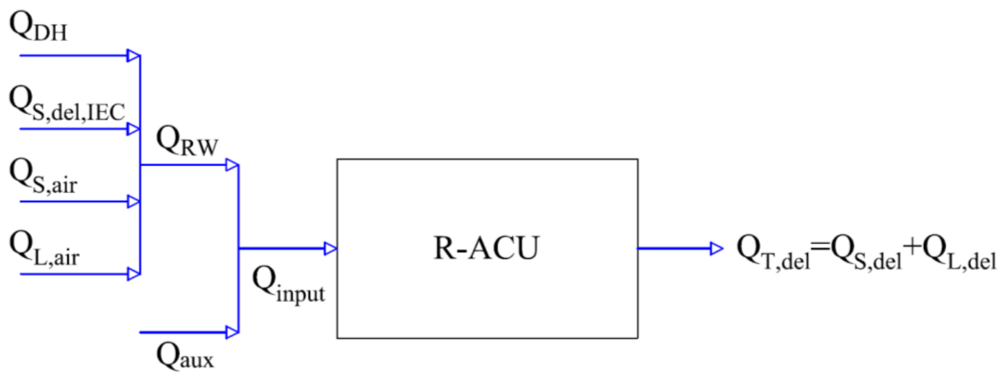

Figure 4-8. RACU heat flows.

Environmental

TEv7 - Water consumption (w)

Mass of water consumed per unit of cooling demand covered. The water consumption is calculated according Equation 43.

$$w_C = \frac{m_w}{Q_{\tau.del}}$$ ***Equation 43***

Where:

- w_C: *Water consumption [kg/kWh].*
- m_w: *Mass of water [kg].*
- $Q_{\tau.del}$: *Sensible and latent thermal energy delivered from RACU to the room [kWh].*

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Technology specific

TTs10 - Source loop temperature levels
Inlet and return temperature of fluid flowing through the water to air heat exchanger used to increase the air temperature before the desiccant wheel.

The source loop temperature levels are expressed with two value separated by slash, the first indicating the inlet temperature and the second the return temperature, both expressed in [ºC].

4.5 Storage technologies

Technology description, Molten salts thermocline tank (MSTTES)
Thermocline tanks are single-tank systems able to combining the hot and cold thermal fluids reservoirs into a single-tank. Thermoclines represent a low cost alternative to conventional two-tanks system, in which volumes of hot and cold molten salts are maintained in separate tanks. In thermoclines, stable thermal stratification of the fluid region is maintained by large buoyancy forces (generated by differences in density between the hot and cold molten salts). As a result, cold molten salts remains in the lower portion of the tank while hot molten salts remains in the upper portion. Transitional temperatures between the hot and cold values are observed within a thin layer of large temperature gradient known as the thermocline or heat-exchange region. The vertical location of this region varies in time as the tank is charged with hot and cold molten salts.

Molten salts appear as an advantageous alternative to water as heat storage material. These have a similar specific heat than water while being able to operate in a much higher temperature range and having higher density, making it possible to store much higher amounts of energy in smaller tanks. Moreover, innovative quaternary eutectic component molten salts used in WEDISTRICT project will allow to work at lower temperature range the state-of-the art solar salts (60% sodium nitrate 40% potassium nitrate), going down from a minimum of 240 ºC to as low as 100ºC. This increases the efficiency of thermal energy storage. The MTES technology to be implemented in WEDISTRICT has a starting TRL of 4.

Figure 4-9 presents the scheme of the molten salts thermocline tank.

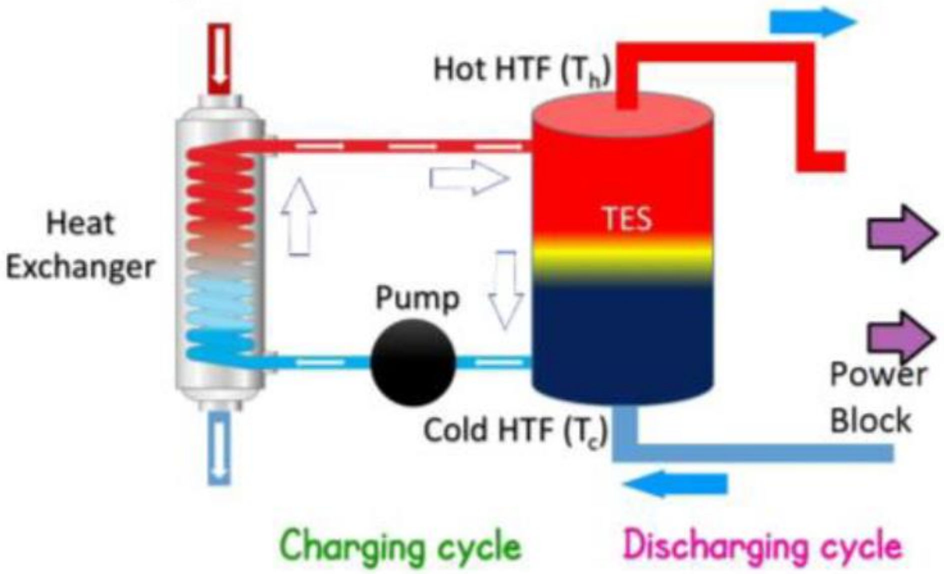

Figure 4-9. Scheme of molten salts thermocline tank.

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Technology description, Hot water tank (WTES)

Hot water tanks are sensible thermal energy storages consisting of insulated vessels using water a heat storage medium, Figure 4-10. Water is a low-cost and non-toxic thermal storage material with a high specific heat. A tank with optimized volume, shape, and insulation can store hot water up to 100ºC for daily cycles. The hot water tanks can be used in combination with generation units working at lower temperatures, such as Fresnel, concentrated solar flat collectors, geothermal heat pumps, and DHW solar collectors in order to collect the excess heat energy during periods with high production and low demand. The WTES technology to be implemented in WEDISTRICT has a starting TRL of 9.

Figure 4-10. Hot water tank picture.

Energy

TEn14 - Nominal power capacity (P_h)

Design thermal power of the discharge of the TES [24] expressed in [kW]. If relevant for the TES system, the nominal power of the charge can be indicated next to the discharge value.

TEn15 - Storage energy efficiency (ϵ_{TES})

Ratio between the heat released to the system (network or conversion elements) during discharging ($Q_{sys.discharge}$) and the energy absorbed by the storage during charging [24] (from the generation technologies). This last parameter considers the heat delivered by the heat source(s) to the system in charging ($Q_{sys.charge}$) and heat from the system components ($Q_{sys.aux}$). This last parameter only includes the heat intentionally generated by the components (i.e. electrical heaters, Peltier cell, etc.) not any heat generated indirectly by the operation of other components (joule effect on electric cables, friction of moving parts, etc.).

Storage energy efficiency is calculated according Equation 44.

$$\varepsilon_{TES} = \frac{|Q_{sys.discharge}|}{|Q_{sys.charge}|+|Q_{sys.aux}|} \cdot 100$$

Equation 44

Where:

- ε_{TES}: *Storage energy efficiency [%].*
- $Q_{sys.discharge}$: *Heat delivered to the system during discharging [kWh].*
- $Q_{sys.charge}$: *Heat absorbed from generation technologies during charging [kWh].*

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- $Q_{sys.aux}$: *Heat from the system components [kWh].*

TEn16 - Energy storage capacity (ESC_{TES})
Total amount of heat that can be absorbed during charging under nominal conditions [24]. The energy is mainly stored in the material; however, some set-ups may contain components in contact with the material, which inevitably heat up, hence storing sensible heat. Therefore, the ESC_{TES} takes into account the heat stored in the material and the heat stored in the components of the system.

Energy storage capacity is calculated according Equation 45.

$$ESC_{TES} = ESC_{mat} + ESC_{comp}$$ ***Equation 45***

Where:
- ESC_{TES}: *Energy storage capacity [kWh].*
- ESC_{mat}: *Storage material energy storage capacity [kWh].*
- ESC_{comp}: *Sum of components energy storage capacity [kWh].*

TEn17 - Storage energy density (ED_{TES})
TES storage capacity divided by TES total volume including auxiliary components and insulation. Does no refer to material energy density, but to system storage capacity compared to the space (volume) it requires.

Storage energy density is calculated according Equation 46.

$$ED_{TES} = \frac{ESC_{TES}}{V_{TES}}$$ ***Equation 46***

Where:
- ED_{TES}: *Storage energy density [kWh/m^3].*
- ESC_{TES}: *Energy storage capacity [kWh].*
- V_{TES}: *Storage volume [m^3].*

Technology specific

TTs11 - Storage temperature operative range (T_{TES})
Design maximum and minimum operative temperatures of the TES. The storage temperature operative range is expressed in [ºC] with two values separated by slash, the first and second being the maximum and minimum temperature respectively.

TTs12 -Maximum temperature difference inside the tank (ΔT_{TES})
Maximum temperature difference of the storage material inside the tank achievable through stratification expressed in [K].

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4.6 Advanced digitalization

In line with current trends, DHC sector is currently undergoing a transformation related to the rise of digital technologies. These are expected to increase smartness, efficiency, resilience, and reliability of DHC systems, as well as being the key to the integration of renewables into the system. Internet of things (IoT), automation, artificial intelligence (AI), and big data will help improve the optimization of plant and network operation, as well as engaging the end consumers.

Advanced digitalization is a key component of WEDISTRICT project. This is a key technology for the integration and optimal operation of the project upgraded technologies at the various demo-sites. However, despite the trends onto digitalization in most sectors, the implementation planned into WEDISTRICT is a very innovative approach for DHC. Here, it can be considered that a TRL of 4. Moreover, its capabilities and performance are strongly related to the system layout, the demand profile, and the weather conditions. Concerning the project goals, the advanced digitalization can yield a better operation and integration of the underlying DHC based technologies, thus leading to more efficient, environment friendly, and cost-effective conditions. In this sense, its main impacts are on the system level, namely helping in the reduction of the peak demand, energy losses, and levelised cost of energy. Moreover, in contrast to the energy related technologies, stablishing (at the time of writing this document) specific KPI for advanced digitalization that help measuring and monitoring the progress towards the project objectives is difficult. Namely, the inherent challenges are tightly bound to the specifics of information technologies (IT), as well as security, privacy, and data ownership issues.

In terms of defining the impact DHC digitalization, Euroheat&Power defined a roadmap [25] identifying the state of the art, challenges, and next steps for different domains. Still, it does not define parameters (i.e. quantitative) for measuring the impact of digitalization. However, in the building sector, the EC is promoting the so-called smart readiness indicator (SRI) [26], a qualitative parameter for measuring the capacity of buildings to accept smart controls, integration to the grid, and demand side management. The approach of the SRI could also be implemented into DHC, considering that the digitalization roadmap already settles the starting point. Anyway, this requires a deep work that is beyond the WEDISTRICT project.

The approach for evaluating the performance of advanced digitalization in WEDISTRICT project will be to consider its impact in improving the system KPI defined in section 3. Hence, the monitoring and evaluation will consider the different levels of complexity and detail of the developed advanced digitalization.

4.7 Other technologies

Beyond the nine technologies developed within WEDISTRICT, the project also considers other technologies to be integrated in the renewable district concept. These include PV, PVT, electrical storage, heat pumps, among others. Being outside of the project developments goals, no specific KPI are defined for these technologies. In order to show their capabilities and impact on the systems, indicators commonly found in the literature will be used. For this, usual standards applied for each technology will be taken as reference. The Danish Energy Agency provides a DHC technologies catalogue that is also useful to identify the most relevant indicators for each case [27].

5 Summary and conclusions

The present report describes the framework for evaluation of the performance of the WEDISTRICT upgraded technologies and demonstrators. The project objectives and relevant

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stakeholders are identified. Then the framework is completed with the definition of the system analysis boundaries. Finally, according to this, the KPI for the project evaluation are selected.

According to the project approach, there are two main points of view. On one side the technology developers, which focus in the improvement of their products for better integration into DHC. On the other side, the promoters, builders, and managers of DHC, which are interested in fulfilling the heating and cooling needs with the most environmental friendly and economically feasible way. Therefore, two levels of KPI are defined: technology specific and overall DHC system.

On the system level, the methodology is to follow the existing guidelines and standard, mainly taking information from Euroheat&Power association and the Danish Energy Agency. However, most of the literature available is focused in the production of a single product, either electricity of heat. Little information is available for system the produce combined generation of heating and cooling. Consequentially, a method for calculating separately the cooling and heating impact in terms of energy, environment, and economics is proposed.

On the technology level, the approach is to use the specifics standards already existing for the main technologies. In case no standards exist or in order to evaluate project specific goals, direct interaction with the technology developers is used to define and select the relevant KPI.

As special case, the advanced digitalization is a key technology for achieving 100% fossil fuel free DHC through integration of renewable solutions. Yet, in terms of the project goals the KPI of this technology are directly related to the system KPI. Therefore, no specific KPI are defined for the advanced digitalization, although the relevance of developing and evaluation framework is identified.

Outputs for other work-packages

The KPI will be calculated at different stages of the project. The demo sites and the demo followers will be evaluated at their initial state and after the integration of the WEDISTRICT project. Moreover, for the WEDISTRICT tool, the KPI will be used to select the best technology combination.

Specifically, the KPI will be used in task 2.4 to define the specifications of demo-sites and technologies. Therefore, these will have direct influence in the development of technologies in WP3, especially when taking into account that the KPI monitor the progress towards the main research goals. Then, WP6 will use the KPI to measure and evaluate the performance of the demo-sites and the technologies implemented in each case. Finally, the KPI will be the main outputs of the WEDISTRICT open source tool developed in WP8. Furthermore, while no KPI are defined for the AD in this deliverable, the knowledge acquired during this task will be used to identify key parameters along the development of WP4.

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Annex 1. WEDISTRICT energy fluxes

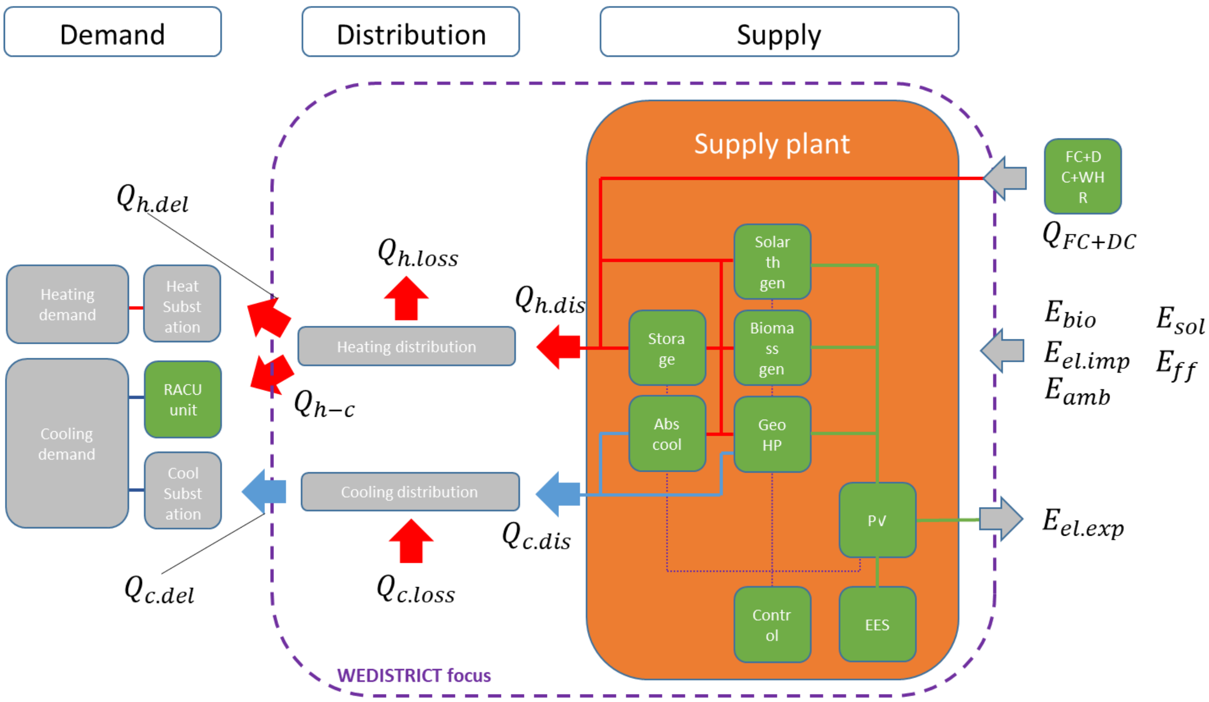

Figure A1- 1. Energy fluxes in WEDISTRICT project.

Where:

- *Main plant inputs:*
- E_{bio}: *Biomass fuel final energy input.*
- E_{sol}: *Solar energy harvested.*
- E_{ff}: *Fossil fuel fuel final energy input.*
- $E_{el.imp}$: *Electricity imports.*
- $E_{el.exp}$: *Electricity export.*
- E_{amb}: *Energy harvested from ambient (geothermal, air, etc…).*
- Q_{FC+DC}: *Waste heat recovered from fuel cell powered data centres.*
- *Distribution energy balance:*
- $Q_{h.dis}$: *Energy supplied to the heat distribution network.*
- $Q_{c.dis}$: *Energy supplied to the cooling distribution network.*
- $Q_{h.loss}$: *Energy losses in the heat distribution network.*
- $Q_{c.loss}$: *Energy losses in the cooling distribution network.*
- $Q_{h.del}$: *Energy delivered to the primary side of the heating substations.*
- $Q_{c.del}$: *Energy delivered to the primary side of the cooling substations.*
- Q_{h-c}: *heat used by the cooling generation units at user side.*

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Annex 2. Reference values

This section summarizes the generic and country specific primary energy factor, non-renewable primary energy factors, and non-renewable emission coefficient used in WEDISRICT project.

Generic primary energy factor and emission coefficients

Table A2- 1. Default primary energy factor and non-renewable emission coefficient from ISO-52000 [3] table B-16 (informative).

	Energy carrier Delivered from distant		Primary energy factor			Non-renewable CO_2 emission coefficient
			Non-renewable	Renewable	Total	g/ kWh
1	Fossil fuels	Solid	1.1	0	1.1	360
2		Liquid	1.1	0	1.1	290
3		Gaseous	1.1	0	1.1	220
4	Bio fuels	Solid	0.2	1	1.2	40
5		Liquid	0.5	1	1.5	70
6		Gaseous	0.4	1	1.4	100
7	Electricity [c]		2.3	0.2	2.5	420
	Delivered from nearby					
8	District heating [a]		1.3	0	1.3	260
9	District cooling		1.3	0	1.3	260
	Delivered from on-site					
10	Solar	PV-electricity	0	1	1	0
11		Thermal	0	1	1	0
12	Wind		0	1	1	0
13	Geo-, aero-, hydrothermal		0	1	1	0
	Exported					
14	Electricity [b c]	To the grid	2.3	0.2	2.5	420
15		To non EPB uses	2.3	0.2	2.5	420

[a] Default value based on natural gas boiler. Specific values are calculated according M3.8.5.
[b] It is possible to differentiate between different sources of electricity like wind or solar.
[c] These values are established in line with the default coefficient provided in Annex IV of Directive 2012/27/EU. This default coefficient is currently being reviewed and a later amendment of the above factor could be needed.

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Table A2- 2. Total suspended particles (TSP) emission coefficient [5].

Source [1]	Fuel type [2]	New or existing plant [3]	Boiler size or technology, MW_{th}	Reference O_2 content, %v/v dry	AEL or ELV concentration, mg.m-3 at STP (0°C, 101.3 kPa) dry at reference O_2 content		Emission factor[4], $g \cdot GJ^{-1}$ (net thermal input)	
					Low	High	Low	High
BREF	coal	new	50-100	6	5	20	1.8	7.2
BREF	coal	new	100-300	6	5	20	1.8	7.2
BREF	coal	new	> 300	6	5	20	1.8	7.2
LCPD	coal	new	50-500	6	100		36.2	
LCPD	coal	new	> 500	6	50		18.1	
LCPD	coal	new	50-100	6	50		18.1	
LCPD	coal	new	> 100	6	30		10.9	
BREF	coal	existing	50-100	6	5	30	1.8	10.9
BREF	coal	existing	100-300	6	5	30	1.8	10.9
BREF	coal	existing	> 300	6	5	30	1.8	10.9
LCPD	coal	existing	50-500	6	100		36.2	
LCPD	coal	existing	> 500	6	50		18.1	
BREF	wood	new	50-100	6	5	20	1.9	7.7
BREF	wood	new	100-300	6	5	20	1.9	7.7
BREF	wood	new	> 300	6	5	20	1.9	7.7
BREF	wood	existing	50-100	6	5	20	1.9	7.7
BREF	wood	existing	100-300	6	5	20	1.9	7.7
BREF	wood	existing	> 300	6	5	20	1.9	7.7
BREF	oil	new	50-100	3	5	20	1.4	5.7
BREF	oil	new	100-300	3	5	20	1.4	5.7
BREF	oil	new	> 300	3	5	10	1.4	2.8
LCPD	oil	new	> 50	3	50		14.1	
LCPD	oil	new	50-100	6	50		17.0	
LCPD	oil	new	> 100	6	30		10.2	
BREF	oil	existing	50-100	3	5	30	1.4	8.5
BREF	oil	existing	100-300	3	5	25	1.4	7.1
BREF	oil	existing	> 300	3	5	20	1.4	5.7
LCPD	oil	existing	> 50	3	50		14.1	
LCPD	gas	new	> 50	3	5		1.4	
LCPD	gas	new	> 50	3	5		1.4	
LCPD	gas	existing	> 50	3	5		1.4	

Notes:

1) BREF denotes the large combustion plant BAT reference document, LCPD denotes Directive 2001/80/EC.
2) Fuel is main classification only, limits may be for 'solid fuels' rather than coal or wood. Limits for gaseous fuels are for natural gas and may not be applicable to derived or other gaseous fuels.
3) Note that new and existing plant have specific meanings under LCPD.
4) Emission factors calculated from emission concentrations using USEPA methodology (See Appendix E for details).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Table A2- 3. Nitrogen oxides emission coefficients [5].

Source [1]	Fuel type [2]	New or existing plant [3]	Boiler size or technology, MW_{th}	Reference O_2 content, %v/v dry	AEL or ELV concentration, mg $NO_2.m^{-3}$ at STP (0ºC, 101.3 kPa) dry at reference O_2 content		Emission factor [4], $g \cdot GJ^{-1}$ (net thermal input)	
					Low	High	Low	High
BREF	coal	new	50-100	6	90	300	32.6	108.7
BREF	coal	new	100-300	6	90	200	32.6	72.5
BREF	coal	new	> 300	6	50	150	18.1	54.3
LCPD	coal	new	50-500	6	600		217.4	
LCPD	coal	new	> 500	6	500		181.1	
LCPD	coal	New 2016	> 500	6	200		72.5	
Goburg	coal	new	50-100	6	400		144.9	
Goburg	coal	new	100-300	6	300		108.7	
Goburg	coal	new	> 300	6	200		72.5	
BREF	coal	existing	50-100	6	90	300	32.6	108.7
BREF	coal	existing	100-300	6	90	200	32.6	72.5
BREF	coal	existing	> 300	6	50	200	18.1	72.5
LCPD	coal	existing	50-500	6	600		217.4	
LCPD	coal	existing	> 500	6	500		181.1	
LCPD	coal	Ex. 2016	> 500	6	200		72.5	
Goburg	coal	existing	> 50	6	650		235.5	
BREF	wood	new	50-100	6	150	250	57.9	96.4
BREF	wood	new	100-300	6	150	200	57.9	77.1
BREF	wood	new	> 300	6	50	150	19.3	57.9
LCPD	wood	new	50-100	6	400		154.3	
LCPD	wood	new	100-500	6	300		115.7	
LCPD	wood	new	> 500	6	200		77.1	
Goburg	wood	new	50-100	6	400		154.3	
Goburg	wood	new	100-300	6	300		115.7	
Goburg	wood	new	> 300	6	200		77.1	
BREF	wood	existing	50-100	6	150	300	57.9	115.7
BREF	wood	existing	100-300	6	150	250	57.9	96.4
BREF	wood	existing	> 300	6	50	200	19.3	77.1
Goburg	wood	existing	> 50	6	650		250.7	
BREF	oil	new	50-100	3	150	300	42.4	84.9
BREF	oil	new	100-300	3	50	150	14.1	42.4
BREF	oil	new	> 300	3	50	100	14.1	28.3
LCPD	oil	new	50-100	3	400		113.2	
LCPD	oil	new	100-300	3	200		56.6	
LCPD	oil	new	> 300	3	200		56.6	
Goburg	oil	new	50-100	3	400		113.2	
Goburg	oil	new	100-300	3	300		84.9	
Goburg	oil	new	> 300	3	200		56.6	
BREF	oil	existing	50-100	3	150	450	42.4	127.3
BREF	oil	existing	100-300	3	50	200	14.1	56.6
BREF	oil	existing	> 300	3	50	150	14.1	42.4
LCPD	oil	existing	50-500	3	450		127.3	
LCPD	oil	existing	> 500	3	400		113.2	
Goburg	oil	existing	> 50	3	450		127.3	
BREF	gas	new	> 50	3	50	100	14.2	28.3
LCPD	gas	new	50-300	3	150		42.5	
LCPD	gas	new	> 300	3	100		28.3	
Goburg	gas	new	50-300	3	150		42.5	
Goburg	gas	new	> 300	3	100		28.3	
BREF	gas	existing	> 50	3	50	100	14.2	28.3
LCPD	gas	existing	50-500	3	300		85.0	
LCPD	gas	existing	> 500	3	200		56.6	
Goburg	gas	existing	> 50	3	350		99.1	

Notes :

1) BREF denotes the large combustion plant BAT reference document, LCPD denotes Directive 2001/80/EC, Goburg denotes the Gothenburg protocol of 1999.
2) Fuel is main classification only, limits may be for 'solid fuels' rather than coal or wood. Limits for gaseous fuels are for natural gas and may not be applicable to derived or other gaseous fuels.
3) Note that new and existing plant have specific meanings under LCPD.
4) Emission factors calculated from emission concentrations using USEPA methodology (See Appendix E for details).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°857801

Table A2- 4. Sulphur oxides/dioxides emission coefficients [5].

Source [1]	Fuel type [2]	New or existing plant [3]	Boiler size or technology, MW_{th}	Reference O_2 content, %v/v dry	AEL or ELV concentration, $mg.m^{-3}$ at STP (0ºC, 101.3 kPa) dry at reference O_2 content		Emission factor [4], $g.GJ^{-1}$ (net thermal input)	
					Low	High	Low	High
BREF	coal	new	50-100	6	150	400	54.3	144.9
BREF	coal	new	100-300	6	100	200	36.2	72.5
BREF	coal	new	> 300	6	20	200	7.2	72.5
LCPD	coal	new	50-100	6	2000		724.5	
LCPD	coal	new	100-500	6	400	2000	144.9	724.5
LCPD	coal	new	> 500	6	400		144.9	
Goburg	coal	new	50-100	6	850		307.9	
Goburg	coal	new	100-300	6	200	850	72.5	307.9
Goburg	coal	new	> 300	6	200		72.5	
BREF	coal	existing	50-100	6	150	400	54.3	144.9
BREF	coal	existing	100-300	6	100	250	36.2	90.6
BREF	coal	existing	> 300	6	20	200	7.2	72.5
LCPD	coal	existing	50-100	6	2000		724.5	0.0
LCPD	coal	existing	100-500	6	400	2000	144.9	724.5
LCPD	coal	existing	> 500	6	400		144.9	
Goburg	coal	existing	50-100	6	2000		724.5	
Goburg	coal	existing	100-500	6	400	2000	144.9	724.5
Goburg	coal	existing	> 500	6	400		144.9	0.0
BREF	wood	new	50-100	6	200	300	77.1	115.7
BREF	wood	new	100-300	6	150	300	57.9	115.7
BREF	wood	new	> 300	6	50	200	19.3	77.1
LCPD	wood	new	50-100	6	200		77.1	
LCPD	wood	new	100-500	6	200		77.1	
LCPD	wood	new	> 500	6	200		77.1	
Goburg	wood	new	50-100	6	850		327.8	
Goburg	wood	new	100-300	6	200	850	77.1	327.8
Goburg	wood	new	> 300	6	200		77.1	
BREF	wood	existing	50-100	6	200	300	77.1	115.7
BREF	wood	existing	100-300	6	150	300	57.9	115.7
BREF	wood	existing	> 300	6	50	200	19.3	77.1
Goburg	wood	existing	50-100	6	2000		771.4	
Goburg	wood	existing	100-500	6	400	2000	154.3	771.4
Goburg	wood	existing	> 500	6	400		154.3	
BREF	oil	new	50-100	3	100	350	28.3	99.0
BREF	oil	new	100-300	3	100	200	28.3	56.6
BREF	oil	new	> 300	3	50	150	14.1	42.4
LCPD	oil	new	50-100	3	850		240.5	
LCPD	oil	new	100-300	3	200	400	56.6	113.2
LCPD	oil	new	> 300	3	200		56.6	
Goburg	oil	new	50-100	3	850		240.5	
Goburg	oil	new	100-300	3	200	850	56.6	240.5
Goburg	oil	new	> 300	3	200		56.6	
BREF	oil	existing	50-100	3	100	350	28.3	99.0
BREF	oil	existing	100-300	3	100	250	28.3	70.7
BREF	oil	existing	> 300	3	50	200	14.1	56.6
LCPD	oil	existing	50-300	3	1700		481.0	
LCPD	oil	existing	300-500	3	400	1700	113.2	481.0
LCPD	oil	existing	> 500	3	400		113.2	
Goburg	oil	existing	50-300	3	1700		481.0	
Goburg	oil	existing	300-500	3	400	1700	113.2	481.0
Goburg	oil	existing	> 500	3	400		113.2	
Goburg	gas	new	> 50	3	35		9.9	
LCPD	gas	new	> 50	3	35		9.9	
LCPD	gas	existing	> 50	3	35		9.9	
Goburg	gas	existing	> 50	3	35		9.9	

Notes :

1) BREF denotes the large combustion plant BAT reference document, LCPD denotes Directive 2001/80/EC, Goburg denotes the Gothenburg protocol of 1999.
2) Fuel is main classification only, limits may be for 'solid fuels' rather than coal or wood. Limits for gaseous fuels are for natural gas and may not be applicable to derived or other gaseous fuels.
3) Note that new and existing plant have specific meanings under LCPD.
4) Emission factors calculated from emission concentrations using USEPA methodology (See Appendix E for details).

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Spain specific primary energy factor and emission coefficients

Table A2- 5. Spain primary energy factor and CO2 emission coefficient. Adapted from "Documentos reconocidos del RITE [28]".

Energy vector	renewable fP [kWh_P/kWh_F]	non-renewable fP [kWh_P/kWh_F]	Total fP [kWh_P/kWh_F]	K_{CO2} [kg_{CO2}/kWh_F]
National conventional electricity	0.396	2.007	2.403	0.357
Peninsular conventional electricity	0.414	1.954	2.368	0.331
Extra-peninsular conventional electricity	0.075	2.937	3.011	0.833
Balearic islands conventional electricity	0.082	2.968	3.049	0.932
Canary islands conventional electricity	0.070	2.924	2.994	0.776
Ceuta and Melilla conventional electricity	0.072	2.718	2.790	0.721
Heating diesel oil	0.003	1.179	1.182	0.311
Liquefied petroleum gas	0.003	1.201	1.204	0.254
Natural gas	0.005	1.190	1.195	0.252
Coal	0.002	1.082	1.084	0.472
Non-densified biomass	1.003	0.034	1.037	0.018
Densified biomass (pellet)	1.028	0.085	1.113	0.018

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Poland specific primary energy factor and emission coefficients

Table A2- 6. Poland non-renewable primary energy factor and CO2 emission factor [29,30,31]

Energy carrier	Non-renewable primary energy factor (w_p)	Carbon dioxide (CO_2) emission factor [kg/GJ]
Heating oil	1,1	77,40
Natural gas	1,1	55,41
LPG	1,1	63,10
Hard coal	1,1	95,07
Lignite	1,1	110,34
Biomass	0,2	0 (112,00)
Biogas	0,5	0 (54,60)
Solar energy	0	0
Wind energy	0	0
Geothermal energy	0	0
Derived heat	0,05	N/A
Energy carrier	Non-renewable primary energy factor (w_{el})	Carbon dioxide (CO2) emission factor [kg/MWh]
Electricity (from national grid)	2,5	765[1]
Electricity (individual buildings)	3	765[1]
For household consumers when no other data is available		
Energy carrier	Non-renewable primary energy factor (w_p)	
Heat from DH network (hard coal)	1,3	
Heat from DH network (natural gas or heating oil)	1,2	
Heat from DH network (CHP fuelled by coal or natural gas)	0,8	
Heat from DH network (biomass or biogas)	0,15	

[1]For final consumers of electricity in 2018 [32].

Calculation methodology for emission factors (SO_x, NO_x, CO, CO_2, benzo(a)pyrene, total particle matter) for small installations (≤5 MW) used for reporting is presented in KOBiZE [33]

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Sweden specific primary energy factor and emission coefficients

The Swedish Energy Agency does not distinguish between renewable and non-renewable primary energy factors of energy carriers. According to the implementation of the European EPBD it proposes the primary energy factors per energy carrier summarized in Table A2- 7

Table A2- 7. Sweden primary energy factors [34].

Energy carrier	Primary energy factor (w_p)
Forest waste	1,05
Biogas	1,05
Peat	1,01
Spent liquor	1.0
Waste	1,04
Carbon products	1,15
Natural gas	1,09
Fuel-oil	1,11
Nucler power	2,92
Hydroelectric	1,1
Wind power	1,05
Photovoltaics	1,25
Solar thermal	1,22
Blast furnace, coke oven,	1.0
Industrial waste heat	0
Electricity	1.6
District heating	1.0
Biofuels	1.0
Natural gas	1.0
Oil	1.0

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Romania specific primary energy factor and emission coefficients

Table A2- 8. Romania primary energy factor and CO2 emission coefficient [35]

	Energy vector	Primary energy factor			Non-renewable CO_2 emission coefficient [kg CO_2/ kWh]
		Non-renewable	Renewable	Total	
1	Lignite*	1.3	0	1.3	0.334
2	Hard coal*	1.2	0	1.2	0.341
3	Heating oil*	1.1	0	1.1	0.279
4	Natural gas*	1.17	0	1.17	0.205
5	Biomass – Non-densified	0.18	0.9	1.08	0.019
6	Biomass – Densified (Pellets/Briquettes)	0.28	0.8	1.08	0.039
7	National conventional electricity	2.62	0	2.62	0.299
8	Cogeneration	0.92	0	0.92	0.220
9	Thermal energy produced from solar panels	0	1	1	0
10	Electrical energy produced from photovoltaic panels	0	2.62	2.62	0
11	Thermal energy for cooling (free cooling)	0	1	1	0
12	Thermal energy for heating from electric driven HP	0.86	0.67	1.53	0.257
*Considers lower calorific value of vector					

Pollutant emissions cost

Table A2- 9. CO_2 emissions cost [10].

Year	New policy (2015)	450ppm 2015	Current policies 2015
2015	7	7	7
2020	17	17	15
2030	28	75	23
2040	38	106	30

Table A2- 10. SO_2, NO_x, and $PM_{2.5}$ emission costs [10].

Pollutant	Danish Energy Agency [36] [€/kg]	European Environment Agency [37] [€/kg]
SO_2	12.7	9.8 - 28.6
NO_x	6.6	4.4 - 22
$PM_{2.5}$	3.2	PM_{10} 23 – 66.7* $PM_{2.5}$ 1.54 · PM_{10}

*EEA presents the cost impact of the PM10, offering a multiplying factor to convert the value into PM2.5 impact.

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Table A2- 11. Damage cost of main pollutants from transport (From table 15 of Update of Handbook on External Cost of Transport [15]).

Country	$PM_{2.5}$			NO_x	NMVOC	SO_2
	Rural	Suburban	Urban			
	€/t	€/t	€/t	€/t	€/t	€/t
Austria	37766	67839	215079	17285	2025	12659
Belgium	34788	60407	207647	10927	3228	13622
Bulgaria	34862	65635	212875	14454	756	12598
Croatia	31649	61539	208779	15149	1819	12317
Cyprus	25040	51200	198440	6465	112	12594
Czech Republic	43028	68427	215667	15788	1648	14112
Germany	48583	73221	220461	17039	1858	14516
Denmark	13275	40760	188000	6703	1531	7286
Estonia	15359	49948	197188	5221	1115	8441
Spain	14429	48012	195252	4964	1135	7052
Finland	8292	43997	191237	3328	781	4507
France	33303	64555	211795	13052	1695	12312
Greece	19329	50605	197845	3851	854	8210
Hungary	47205	74641	221881	19580	1569	14348
Ireland	16512	47420	194660	5688	1398	6959
Italy	24562	50121	197361	10824	1242	9875
Lithuania	23038	55535	202775	10790	1511	10945
Luxembourg	45688	71308	218548	18612	3506	12103
Latvia	19528	53638	200878	8109	1499	10000
Malta	NA	NA	98132	1983	1007	6420
Netherlands	29456	48352	195592	11574	2755	16738
Poland	47491	74215	221455	13434	1678	14435
Portugal	18371	49095	196335	195	1048	4950
Romania	56405	84380	231620	22893	1796	17524
Sweden	14578	20210	197450	5247	974	5389
Slovenia	39633	67670	214910	16067	1975	12422
Slovakia	54030	79270	226510	21491	1709	17134
United Kingdom	14026	47511	194751	6576	1780	9192
EU average	28108	70258	270178	10640	1566	10241

Note rural, suburban, and urban costs refer to population densities of 150 inhabitants/km^2, 300 inhabitants/km^2, and 1500 inhabitants/km^2 respectively.

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Table A1- 1. Damage (€) per tonne emission estimates for NOx and PM2.5 (According "Cost of air pollution from European industrial facilities 2008-2012" [16] with 2005 prices).

Country	NO_x		$PM_{2.5}$	
	Low VOLY	High VSL	Low VOLY	High VSL
Albania	4082	8308	26582	55419
Austria	8681	24442	38300	113642
Bosnia Herzegovina	5511	14031	20720	58677
Belgium	4152	12227	557327	170702
Bulgaria	4588	12581	24186	80806
Belarus	4033	10691	20200	59335
Switzerland	11997	33635	55427	160225
Cyprus	593	1196	7015	14917
Czech Republic	6420	17663	39882	115146
Germany	6817	19059	47310	147553
Denmark	3092	8515	16074	48050
Estonia	2159	5566	9418	27684
Spain	241	5183	26595	74455
Finland	1481	3780	5942	17139
France	5463	13951	33751	96917
Greece	1390	3142	18669	56883
Croatia	6802	18433	21353	65336
Hungary	7502	20354	38433	118336
Ireland	3736	9785	13461	40315
Italy	7798	23029	48288	154289
Lithuania	3778	9935	15979	47453
Luxembourg	6468	17974	36007	105895
Latvia	3021	7851	12412	37736
Moldova	5516	14667	29935	85455
Former Yugoslav Republic of Macedonia	3449	8349	19978	52814
Malta	736	1696	5625	15338
Netherlands	4854	14770	54535	154240
Norway	1675	4081	5638	15846
Poland	5131	13840	42153	117344
Portugal	1805	4367	21129	62483
Romania	7507	20361	35666	105101
Sweden	2197	5662	7644	23204
Slovenia	9127	25992	33836	101827
Slovakia	6729	17936	32503	92299
Ukraine	3800	10079	29870	91284
United Kingdom	3558	9948	38393	111766

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Table A2- 12. Valuation of 2010 emissions (damages per ton in $2007 US) [16].

Valuation; discount rate	CO_2	CH_4	N_2O	HFC-134a	BC	SO_2	CO	OC	NO_x	NH_3
Climate[a]; 5 %	10	490	2800	19,000	13,000	−900	42	−1800	−56	−240
Climate[a]; 3 %	32	910	9200	36,000	20,000	−1400	90	−2800	−220	−380
Climate[a]; 1.4 %	67	1400	19,000	56,000	30,000	−2100	160	−4200	−400	−560
Regional climate, aerosols; 5 %	0	0	0	0	19,000	3000	0	6100	90	820
Regional climate, aerosols; 3 %	0	0	0	0	26,000	4400	0	8700	350	1200
Regional climate, aerosols; 1.4 %	0	0	0	0	34,000	5900	0	12,000	600	1600
Additional climate-health[b]; 5 %	16	1600	8300	62,000	110,000	4500	140	9000	7	1200
Additional climate-health[b]; 3 %	45	2800	24,000	110,000	150,000	5700	260	11,000	30	1500
Additional climate-health[b]; 1.4 %	87	4000	47,000	160,000	190,000	6900	430	14,000	50	1900
Composition-health; 5 %	0	550	0	0	62,000	33,000	200	51,000	67,000	22,000
Composition-health; 3 %	0	670	0	0	62,000	33,000	240	51,000	67,000	22,000
Composition-health; 1.4 %	0	740	0	0	62,000	33,000	250	51,000	67,000	22,000
Median total; 5 %	27	2700	12,000	85,000	210,000	40,000	410	64,000	67,000	24,000
Median total; 3 %	84	4600	37,000	160,000	270,000	42,000	630	68,000	67,000	25,000
Median total; 1.4 %	150	6000	62,000	210,000	310,000	43,000	820	71,000	67,000	25,000
Median total; declining rate	110	4700	47,000	160,000	280,000	42,000	730	69,000	67,000	25,000

Notes: Composition-agriculture impacts via ozone are included in the sum for methane, valued at $22, $27 and $30 per ton for 5, 3 and 1.4 % discounting, respectively. Uncertainties are presented in Table S4

[a] This basic climate valuation includes IAM-based climate-health impacts

[b] This valuation of additional climate-health impacts is based on WHO analyses as described in the section 2.2

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Annex 3. KPI application example

System description

In the following example a district energy system with high renewable contribution is used as a showcase of System KPI calculation. The example is a real district heating and cooling system of small capacity, presently in operation in the city of Olot in Catalonia, Spain. The System integrates two biomass boilers, three heat pumps coupled with a geothermal field and a PV installation. The heat pumps are providing both heat in winter season and cooling in summer season. This configuration, with the figures included below, supplies five clients. Extensions for including new clients are in progress.

Figure A3- 1. Olot DHC System

The System concept is somewhat singular, trying to cover previously existing demands in the most efficient manner. It is based on the supply of high temperature heating, low temperature heating and cooling, providing all these services through two loops network (four pipes distribution). One loop is dedicated all year around to the high temperature heat demands (conventional heating systems and domestic hot water) and corresponds to the usual heat distribution in DHC systems. The other loop supplies the low temperature demands (floor heating systems) during the winter season and delivers cooling during the summer period.

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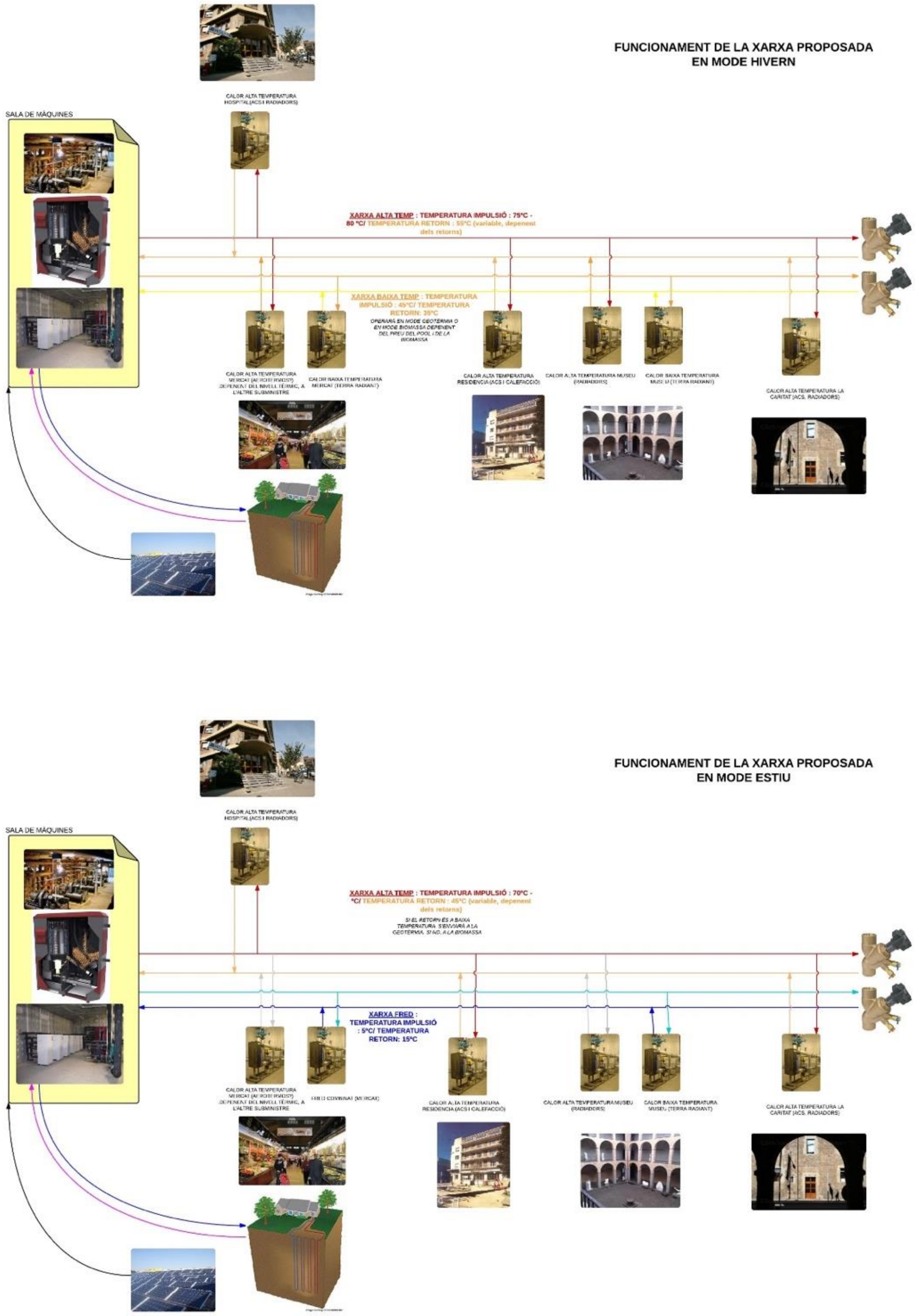

Figure A3- 2. Olot DHC System: Winter mode operation (top) and Summer mode operation (bottom)

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Calculation Inputs

Table A3- 1. Olot DHC input data.

Parameter	Units	Heating		Cooling	Total DHC
		High T	Low T		
		Biomass boiler	Heat pump		
Capacity	kW	600	164,4	193,5	-
Delivered thermal energy	kWh	1.878.202	83.663	72.300	-
Transformation Efficiency (Seasonal)	%	85%	495%	446%	-
Total Energy Consumption	kWh	2.209.649	16.902	16.229	-
Biomass Consumption	kg	634.313	-	-	-
Power Consumption for Thermal Conversion	kWh	-	16.902	16.229	-
Power Consumption Pumping	kW	56.346	7.530	6.507	-
Power Generation (PV)	kWh	41.510	-	1.530	43.040
Power Balance	kWh	14.836	7.530	4.977	
Environmental Heat	kWh	-	66.761	0	-
Emissions associated	kg CO2	44.684	8.087	7.019	59.790
System Primary non-renewable energy	kWh prim	106.015	50.865	47.335	204.215
System Primary renewable energy	kWh prim	2.221.337	8.331	7.753	2.237.421

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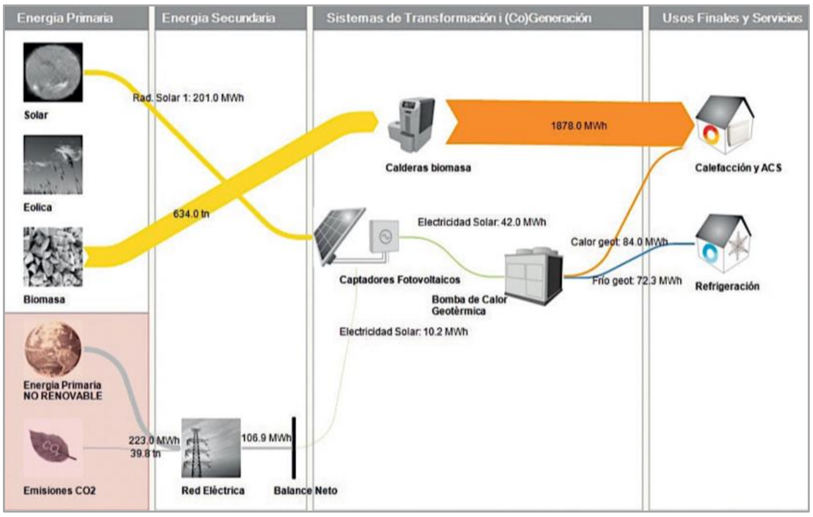

Figure A3- 3. Sankey diagram of the Olot DHC system.

Table A3- 2. Olot DHC energy and environment KPI.

Parameters		Units	Biomass	Electricity
Primary Energy	Renewable primary energy factor energy carrier	kWh E.prim / kWh E.final	1,003	0,414
	Non-Renewable primary energy factor energy carrier	kWh E.prim / kWh E.final	0,034	1,954
	Total (renewable and non-renewable) primary energy factor energy carrier	kWh E.prim / kWh E. final	1,037	2,368
Emissions	CO2 emission factors	kg CO_2 / kWh E. final	0,018	0,331
	NO_x	g/GJ	91	-
	SO_2	g/GJ	11	-
	PM2,5	g/GJ	140	-

Table A3- 3. Olot DHC inputs for economic KPI calculation.

Parameter		Units	Total H&C	Heating only	Common H&C	Cooling only
CAPEX	Direct Costs	€	1.023.441	296.411	641.921	85.109
	Other Costs	€	43.400	-	43.400	-
	Total CAPEX	€	1.066.841	296.411	685.321	85.109
OPEX	Fix	€ / kW	-	11.523	89.458	2.553
	Variable costs	€ / kWh	-	48.918	-	2.439
	Decommissioning	€ / kW	-	9.181	13.669	496
	Residual value	€	-	41.349	96.629	27.566

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Table A3- 4. Olot DHC inputs for environmental social cost KPI calculation.

Emission cost per pollutant	Units	Biomass
CO_2	€/T	17,00
SO_2	€/kg	7,05
NO_x	€/kg	4,96
PM2,5	€/kg	74,4

Calculation process

Cooling share ($\propto_C$)

$$\alpha_c = \frac{72.300}{1.878.202+83.663+72.300} = 0,036$$

Renewable energy ratio (RER)

$$RER_c = \frac{16.229 \cdot 0,414+4.977 \cdot 0,414+1.530}{16.229 \cdot 2,368+4.977 \cdot 2,368+1.530} = 0,199$$

$$RER_h = \frac{2.209.649 \cdot 1,003+16.902 \cdot 0,414+14.836 \cdot 0,414+7.530 \cdot 0,414+41.510+66.716}{2.209.649 \cdot 1,037+16.902 \cdot 2,368+14.836 \cdot 2,368+7.530 \cdot 2,368+41.510+66.716} = 0,939$$

Non-renewable primary energy factor (f_{nr})

$$f_{nr.c} = \frac{16.229 \cdot 1,954+4.977 \cdot 1,954}{72.300} = 0,573$$

$$f_{nr.h} = \frac{2.209.649 \cdot 0,034+14.836 \cdot 1,954}{1.878.202+83.663} = 0,077$$

Equivalent CO_2 emission coefficient (k_{CO2})

$$k_{CO_2.c} = \frac{16.229 \cdot 0,331+4.977 \cdot 0,331}{72.300} = 0,097 \text{ kg/ kWh}$$

$$k_{CO_2.h} = \frac{2.209.649 \cdot 0,018+(16.902+14.836+7.530) \cdot 0.331}{1.878.202+83.663} = 0,027 \text{ kg/ kWh}$$

Local air pollutants emission coefficients (k_{xx})

$$k_{NO_x.c} = 0$$
$$k_{SO_2.c} = 0$$
$$k_{PM_{2,5}.c} = 0$$

$$k_{NO_x.h} = \frac{2.209.649 \cdot \frac{91}{278}}{1.878.202+83.663} = 0,369 \text{ kg/kWh}$$

$$k_{SO_2.h} = \frac{2.209.649 \cdot \frac{11}{278}}{1.878.202+83.663} = 0,045 \text{ kg/kWh}$$

$$k_{PM_{2,5}.h} = \frac{2.209.649 \cdot \frac{140}{278}}{1.878.202+83.663} = 0,567 \text{ kg/kWh}$$

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(Note the unit conversion factors from GJ to kWh (1GJ = 278 kWh))

Capital expenditures (CAPEX)

$$\boldsymbol{\beta_c} = \frac{85.109+\alpha_c\cdot 641.912}{1.023.441} = \mathbf{0,105}$$

$$\boldsymbol{CAPEX_c} = \frac{85.109+0{,}10545\cdot 641.912}{193{,}5} = \mathbf{789{,}7\ €/kW}$$

$$\boldsymbol{CAPEX_h} = \frac{\mathbf{296.411+(1-0{,}10545)\cdot 641.912}}{764{,}4} = \mathbf{1.139{,}0\ €/kW}$$

Operational expenditures (OPEX)

$$\boldsymbol{OPEX_{F,c}} = \frac{2.553+0{,}10545\cdot 89.458}{193{,}5} = \mathbf{61{,}95\ €/kW}$$

$$\boldsymbol{OPEX_{F,h}} = \frac{11.523+(1-0{,}10545)\cdot 89.458}{764{,}4} = \mathbf{119{,}76\ €/kW}$$

$$\boldsymbol{OPEX_{V,c}} = \frac{2.439}{72.300} = \mathbf{0{,}034\ €/kWh}$$

$$\boldsymbol{OPEX_{F,h}} = \frac{48.918}{1.878.202+83.663} = \mathbf{0{,}025\ €/kWh}$$

Levelized cost of energy (LCoE).

$$\boldsymbol{rv_c} = \frac{27.566-496+0{,}10545\cdot(96.629-13.669)}{193{,}5} = \mathbf{185{,}1\ €/kW}$$

$$\boldsymbol{rv_h} = \frac{41.393-9.181+(1-0{,}10545)\cdot(96.629-13.669)}{764{,}4} = \mathbf{139{,}2\ €/kW}$$

$$\mathbf{CRF} = \frac{\{0{,}02\cdot(1+0{,}02)^{25}\}}{\{[(1+0{,}02)^{25}]-1\}} = \mathbf{0{,}051}$$

$$\boldsymbol{LCOE_c} = \frac{\left(789{,}7\cdot 0{,}05122+61{,}95-\frac{185{,}1}{25}\right)\cdot 193{,}5}{72.300} + 0{,}034 = \mathbf{0{,}288\ €/kWh}$$

$$\boldsymbol{LCOE_h} = \frac{\left(1.139\cdot 0{,}05122+119{,}765-\frac{139{,}2}{25}\right)\cdot 764{,}4}{1.878.202+83.663} + 0{,}025 = \mathbf{0{,}092\ €/kWh}$$

Environmental Social cost (sc)

$$\mathbf{sc_c} = \frac{(16.229+4.977)\cdot 0{,}331\cdot\frac{17}{1000}}{72.300} = \mathbf{0{,}0016\ €/kWh}$$

$$\mathbf{sc_h} = \frac{2.209.649\cdot(11\cdot 7{,}05+91\cdot 4{,}96+140\cdot 74{,}4)\frac{1}{1000\cdot 278}+(16.902+7.530+14.836)\cdot 0.331\frac{17}{1000}}{1.878.202+83.663} = \mathbf{0{,}0445\ €/kWh}$$

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(Note the unit conversion factors from GJ to kWh (1GJ = 278 kWh))

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Annex 4. KPI summary tables

Table A4- 1. System KPI.

	Concentration solar technologies (PTC. FTC, LCC)				
Category		**Abbreviation**	**Description**	**Units**	**Page**
Energy	SEn1	RER	Renewable energy ratio	-	21
	SEn2	f_{nr}	Non-renewable primary energy factor	-	22
Environmental	SEv1	k_{CO2}	Equivalent CO2 emission coefficient	kg/MWh	24
	SEv2	$k_{PM2,5}$	$PM_{2,5}$ emissions coefficient	kg/MWh	26
	SEv3	k_{NOX}	NO_x emission coefficient	kg/MWh	26
	SEv4	k_{SO2}	SO_2 emission coefficient	kg/MWh	26
Economics	SEc1	CAPEX	Capital expenditures	€/kW	28
	SEc2	$OPEX_F$	Fixed operational expenditures	€/MW	29
	SEc3	$OPEX_V$	Variable operational expenditures	€/MWh	29
	SEc4	LCOE	Levelized cost of energy	€/MWh	30
Socio-economics	SSc1	sc	Environmental social cost	€/MWh	33

Table A4- 2. Concentration solar KPI.

	Concentration solar technologies (PTC. FTC, LCC)				
Category		**Abbreviation**	**Description**	**Units**	**Page**
Energy	TEn1	r_{aux}	Auxiliary energy ratio	-	35
	TEn2	p_{col}	Collector energy output	kW/m^2	38
	TEn3	$\eta_{col.t}$	Collector total efficiency	-	39
Economics	TEc1	c	Equipment cost	€/kW	35
	TEc2	o_F	Fixed operation cost	€/kW	35
	TEc3	o_V	Variable operation cost	€/kWh	36
	TEc4	LF	Technical lifetime	years	36
	TEc5	c_{dec}	Decommissioning cost	€	36
	TEc6	rv	Residual value	€	36
Technology specific	TTs1	TRL	Technology readiness level	-	36
	TTs2	η_{col}	Characteristic efficiency curve	-	39
	TTs3	pd	Yearly performance drop	-	39
	TTs4	η_0	Optical collector efficiency	-	39
	TTs5	a1	Loss coefficient 1	-	39
	TTs6	a2	Loss coefficient 2	-	39
Environmental	TEv1	s	Space requirement	m^2/kW	37

Table A4- 3. Low emission biomass boiler KPI.

	Low emissions biomass boiler (BB)				
Category		**Abbreviation**	**Description**	**Units**	**Page**
Energy	TEn1	r_{aux}	Auxiliary energy ratio	-	35
	TEn4	η_{LHV}	Total boiler efficiency	-	40

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	TEn5	Ph	Heat capacity	kW	40
Economics	TEc1	c	Equipment cost	€/kW	35
	TEc2	o_F	Fixed operation cost	€/kW	35
	TEc3	o_V	Variable operation cost	€/kWh	36
	TEc4	LF	Technical lifetime	years	36
	TEc5	c_{dec}	Decommissioning cost	€	36
	TEc6	rv	Residual value	€	36
Technology specific	TTs1	TRL	Technology readiness level	-	36
Environmental	TEv1	s	Space requirement	m^2/kW	37
	TEv2	ev_{CO2}	GHG emission value	g/Nm^3	40
	TEv3	ev_{NOX}	NO_x emission value	g/Nm^3	40
	TEv4	$ev_{PM2,5}$	$PM_{2,5}$ emission value	g/Nm^3	40
	TEv5	ev_{SO2}	SO_2 emission value	g/Nm^3	40

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Table A4- 4. Waste heat recovery from data centres KPI.

	WHR from fuel cell powered data centres (DC+FC+WHR)				
Category		**Abbreviation**	**Description**	**Units**	**Page**
Energy	TEn6	PE_{DaC}	Primary energy use	kWh	41
	TEn7	ERF_{DaC}	Energy reuse factor	-	42
	TEn8	RER_{DaC}	Renewable Energy Ratio	-	42
Economics	TEc7	TCO_{DaC}	Total cost of ownership	€	43
Environmental	TEv6	$K_{DaC.CO2}$	CO2 emissions	kg	43

Table A4- 5. Absorption chiller KPI.

	Absorption chiller (ACh)				
Category		**Abbreviation**	**Description**	**Units**	**Page**
Energy	TEn1	r_{aux}	Auxiliary energy ratio	-	35
	TEn9	P_c	Cooling capacity	kW	44
	TEn10	COP_{Ach}	Absorption chiller coefficient of performance	-	44
Economics	TEc1	c	Equipment cost	€/kW	35
	TEc2	o_F	Fixed operation cost	€/kW	35
	TEc3	o_V	Variable operation cost	€/kWh	36
	TEc4	LF	Technical lifetime	years	36
	TEc5	c_{dec}	Decommissioning cost	€	36
	TEc6	rv	Residual value	€	36
Technology specific	TTs1	TRL	Technology readiness level	-	36
	TTs7	T_{sou}	Source loop temperature	ºC	45
	TTs8	T_{cool}	Cooling loop temperature	ºC	45
	TTs9	T_{chi}	Chilled loop temperature	ºC	45
Environmental	TEv1	s	Space requirement	m^2/kW	37

Table A4- 6. Renewable air cooling unit KPI.

	Renewable air cooling unit (RACU)				
Category		**Abbreviation**	**Description**	**Units**	**Page**
Energy	TEn1	r_{aux}	Auxiliary energy ratio	-	35
	TEn11	P_c	Cooling capacity	kW	46
	TEn12	r_{DH}	District heat to cooling ratio	-	46
	TEn13	r_{HtC}	Consumed heat to cooling ratio	-	47
Economics	TEc1	c	Equipment cost	€/kW	35
	TEc2	o_F	Fixed operation cost	€/kW	35
	TEc3	o_V	Variable operation cost	€/kWh	36
	TEc4	LF	Technical lifetime	years	36
	TEc5	c_{dec}	Decommissioning cost	€	36
	TEc6	rv	Residual value	€	36
Technology specific	TTs1	TRL	Technology readiness level	-	36
	TTs10	T_{sou}	Source loop temperature	-	48
Environmental	TEv1	s	Space requirement	m^2/kW	37
	TEv7	w	Water consumption	kg/kWh	47

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Table A4- 7. Thermal energy storage KPI.

	Thermal energy storage (MSTES, WTES)				
Category		**Abbreviation**	**Description**	**Units**	**Page**
Energy	TEn1	r_{aux}	Auxiliary energy ratio	-	35
	TEn14	P_h	Nominal power capacity	kW	49
	TEn15	ϵ_{TES}	Storage energy efficiency	-	49
	TEn16	ESC_{TES}	Energy storage capacity	kWh	50
	TEn17	ED_{TES}	Storage energy efficiency	kWh/m^3	50
Economics	TEc1	c	Equipment cost	€/kW	35
	TEc2	o_F	Fixed operation cost	€/kW	35
	TEc3	o_V	Variable operation cost	€/kWh	36
	TEc4	LF	Technical lifetime	years	36
	TEc5	c_{dec}	Decommissioning cost	€	36
	TEc6	rv	Residual value	€	36
Technology specific	TTs1	TRL	Technology readiness level	-	36
	TTs11	T_{TES}	Storage temperature operative range	ºC	50
	TTs12	ΔT_{TES}	Maximum temperature difference inside the tank	K	50
Environmental	TEv1	s	Space requirement	m^2/kW	37

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