PLANHEAT D2.6 - Methods to quantify and map unconventional heating and cooling sources

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PU	Public	X
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)	

Contents

List of abbreviations

Abbreviation	Definition
ATES	Aquifer Thermal Energy Storage
BE	Belgium
BTES	Borehole Thermal Energy Storage
CMM	City Mapping Module (PLANHEAT mapping module component)
COP	Coefficient of Performance (heat pumps)
CDH	Cooling Degree Hours
CH	Switzerland
CTES	Cavern Thermal Energy Storage
DE	Germany
DHW	Domestic Hot Water
DMM	District Mapping Module (PLANHEAT mapping module component)
EAWAG	Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz (Swiss Federal Institute for Environmental Science and Technology)
EC	European Commission (EU)
EEA	European Environment Agency (EU)
EPBD	Energy Performance in Buildings Directive (EU)
ESTMAP	Energy Storage Mapping and Planning (H2020 project)
EU	European Union
GR	Greece
GSHP	Ground Source Heat Pump
H2020	Horizon 2020 (EU research framework programme)
HC, H/C, H&C	Heating and Cooling
HDH	Heating Degree Hours
IT	Italy
LCP	Large Combustion Plants (EU Directive)
LowEx	Low Exergy
NEN	Nederlandse Norm (Dutch national standard)
NL	Netherlands
NOA	National Observatory of Athens (PLANHEAT partner)
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
SST	Sea Surface Temperature
STOWA	Stichting Toegepast Onderzoek Waterbeheer (Foundation for Applied Water Research)
TUD	Technische Universiteit Delft (Delft University of Technology, PLANHEAT partner)
UHI	Urban Heat Island (effect)
UK	United Kingdom
UWWTP	Urban Wastewater Treatment Plants (EEA database)

VITO	Vlaamse Instelling voor Technologisch Onderzoek (Flemish institute for technological research, PLANHEAT partner)
WFD	Water Framework Directive (EU)
WP	Work Package

List of units and variables

Abbreviation	Definition
°C	degree Celsius
CON	share of population connected to sewage networks [-]
CPwD	Cooling Power Density [W/m^2]
ED	Electricity Demand [kWh/yr]
E_{PC}	Electricity demand for Product Cooling [kWh/m^2/yr]
FSU	Floor Space Utilisation [-] (data centres)
h	hour
J	Joule
K	Kelvin
kg	kilogram
kJ	kilojoule
kW	kilowatt
kWh	kilowatthour
l	liter
LL	Load Level [%] (data centres)
m	meter
m^2	square meter
m^3	cubic meter
mo	month
P	power [kW]
p.e. / PE	population equivalent [l] (sewage)
PD	Population Density [km^{-1}]
PwD	Power Density [W/m^2]
Q	flow rate [m^3/h]
s	second
T	temperature [either °C or K]
t	time [s, mo or yr]
yr	year
ΔT	temperature difference [K]
ρc	heat capacity [kJ/m^3·K]

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1 Introduction

This document represents deliverable 2.6 of the PLANHEAT project, a result of task 2.2.2 on unconventional sources, part of Work Package 2 on the Mapping Module. The purpose of this task is to develop simple and detailed models for mapping local energy sources and to allocate and map sources and information (heating and cooling factor).

This report focuses on a category of heating and cooling (HC) sources referred to within the PLANHEAT project as ‘unconventional sources’. The following unconventional source categories can be distinguished:

1. Heat and cold from outside air and exhaust ventilation air (e.g. subway stations)
2. Heat from cooling processes (data centres, supermarkets and refrigerated storage facilities)
3. Heat from sewage systems and sewage treatment plants
4. Heat and cold from surface water bodies
5. Heat and cold from groundwater and shallow underground (effectively energy storage)

Characteristic for these unconventional sources is the fact that their temperature is often not sufficient to cool or heat with just a heat exchanger. A heat pump and some extra energy will usually be necessary to decrease (cooling) or increase (heating) the temperature to the required level. A second characteristic is the fact that the temperature of the source sometimes fluctuates significantly during the day and/or year. This means that the amount of available energy is also fluctuating, as is the extra energy needed for the heat pumps. Although for the mapping module the focus is on theoretical potential, this does require attention in the planning and especially the simulation modules. Where applicable, guidelines have been included for implementation.

1.1 Factors, variables and algorithms

The unconventional sources considered in this report have in common that their energy potential originates from extracting thermal energy from a medium (air or water), thereby creating a temperature drop or rise in that medium. The main variables are these:

- Flow rate [m^3/h]
- Temperature difference [K]
- Density [kg/m^3]
- Specific heat [J/kg·K]

Density and specific heat are qualities associated with the medium, and therefore will always be the same pairs of variables. The following generic algorithm therefore forms the basis for the unconventional sources maps:

$$E = Q \times \rho c \times \Delta T \times t / (3.6 * 10^3) [kWh]$$

Where:

- E = energy potential [kWh]
- Q = Flow [m^3/h]
- ρc = heat capacity of medium [$kJ/m^3 \cdot K$] (4200 for water, 1.2 for air)
- ΔT = Temperature difference [K]
- t = time period considered [h] (per month or per year)

Please note that although K is used to denote temperature and temperature differences, in some cases Celsius (°C) is used if that specific variable uses the Celsius temperature scale.

Although the climate data used is based on calendar months with varying lengths (28 to 31 days), in order to reduce the number of calculation steps per raster unit, the number of hours in a month is considered to be a fixed 1/12 of the total number of hours in a year, i.e. 730.
Because this monthly length variation is staggered, annual and seasonal potentials will not be affected. For simulation purposes however the actual number of hours of each month should be used. As mentioned, this is just a matter of using a data source (for example temperature) with an hourly resolution and increasing calculation steps from 12 (months) to 8760 (hours) to follow suit.

In some cases the output will either not fluctuate or very little over a year. In that case, a single calculation step will be sufficient for the 'theoretical' output of these potentials. Others are more directly related to the ambient temperature, and therefore require using monthly averages.
For purposes of clarity and application of theoretical and technical potential, as much uniformity as possible was applied. The basic calculation mechanism is therefore the same, however, what the variables involved represent, as well as what their default values are (if any), may also vary.

The COP for the heat pump (needed for electricity demand and system thermal output) depends on the input and output temperatures of the heat pump. This is essentially a multiplier that could be read from a table or modelled as a function, and therefore does not require additional spatial data.

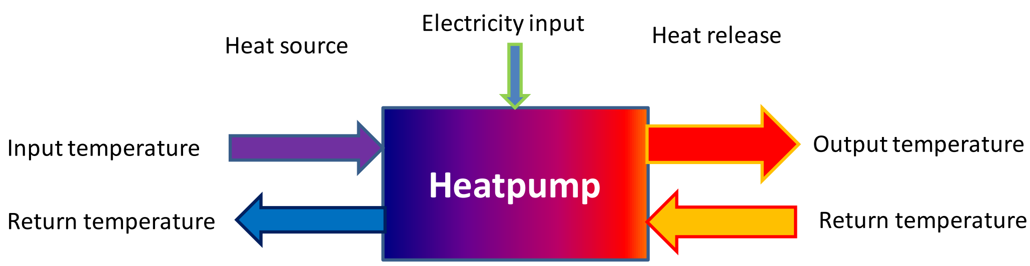

Figure 1: heat pump flows

1.2 Mapping and environmental constraints

In order to map a resource, spatial constraints related to the environment are required. In some cases however, these are not available. These supply sources are marked as 'installation' in the Level of Detail field. If the user specifies a location, the heating or cooling potential of an installation using this source can be calculated based on a default flow value, or one that the user provides. Table 1 shows an overview of the algorithms and their output types.

SOURCE CATEGORY	SOURCE TYPE	OUTPUT		ALGORITHM / MAP TYPE
HC from ambient and exhaust air (fluctuating)	Air sourced heat pumps	H	C	installation*
	Direct free (air) cooling	H	C	installation*
	Subway networks	H	C	point
Heat from cooling processes	Data centres	H		point
	Supermarkets	H		point
	cold storage warehouses	H		point
Sewage	sewage network	H		raster*
	sewage treatment plants	H		point
Surface water	lakes	H	C	raster
	rivers	H	C	line
	sea (coastline)	H	C	installation*

Table 1: output types per algorithm

A few sources do not have sufficient spatial constraints, and would therefore not result in map layers in the mapping module. These algorithm types are labelled as *'installation'* in the overview.

Although these sources cannot mapped, the algorithms that allow calculating annual theoretical potential can directly be used for the planning module (where the user specifies said location and numbers), and using hourly input values can also be used in the simulation module.

1.3 System boundaries: theoretical and technical potentials

The PLANHEAT tool consists of three separate modules, the mapping, planning and simulation modules. The output of the mapping module, of which these unconventional sources are part, is provided to the planning and simulation modules.

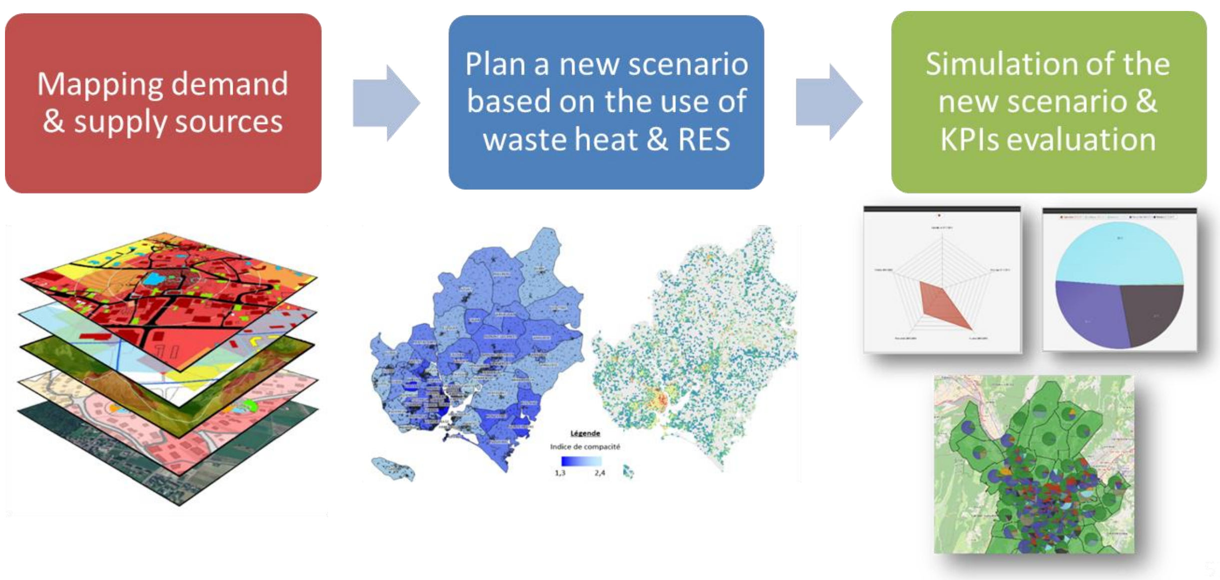

Figure 2: PLANHEAT module workflow, on the left the mapping module

Because technology choices are made in the planning module, a distinction has been made between 'theoretical' and 'technical' potentials. In the context of PLANHEAT, theoretical potential will involve spatial limitations (for example Natura 2000 excluded areas), but not a HC potential that includes for example heat pump characteristics or other aspects that are considered technology choices (which can be made in the planning and simulation modules).

Although the main internal output towards the other modules will be this theoretical output, for the user it may be better to communicate a more realistic potential, referred to within PLANHEAT as a 'technical' potential. This involves limited default technology choices with as few calculation steps as possible, in order to keep map generation time to a minimum.

In the context of these unconventional sources, technical potential includes not just the conversion technologies involved but also seasonal storage capabilities. Because 'unconventional' source temperatures are close to the reference (outside) temperature, part of the potential yield will be in the off-season for space heating and cooling. If no seasonal storage is available (or built), this would not be usable. Conversely, domestic hot water (DHW) demand is relatively constant throughout the year and will therefore be able to make use of this off-season supply.

A combination was therefore made of readily available (geo)data sources, in order to approximate this technical potential. DHW demand can be estimated using the number of inhabitants, for storage potential a combination was made of the HDH and CDH data from NOA and the data from the ESTMAP project. Because low temperature subsurface storage potential data even in ESTMAP is limited, the output towards the user should visualise the technical potential with and without thermal storage. More details on technical potential calculations will be discussed in chapter 6.
This technical potential can be used in the visualisation process of the mapping module, as an alternative to the theoretical potential (although this technical output will not be used as output to the planning module, which revolves around user based technology choices). As this will involve adjustments to the output structure of this module, discussions on the subject are ongoing.

1.4 Temperature levels

The output of the PLANHEAT mapping module will consist of annual yields and omit exact temperatures, as for the planning module only temperature categories (i.e. "<40°C", "40-70°C" and ">70°C") are relevant, and for practical purposes (i.e. output temperature towards the network) all these sources fall in the <40°C category.

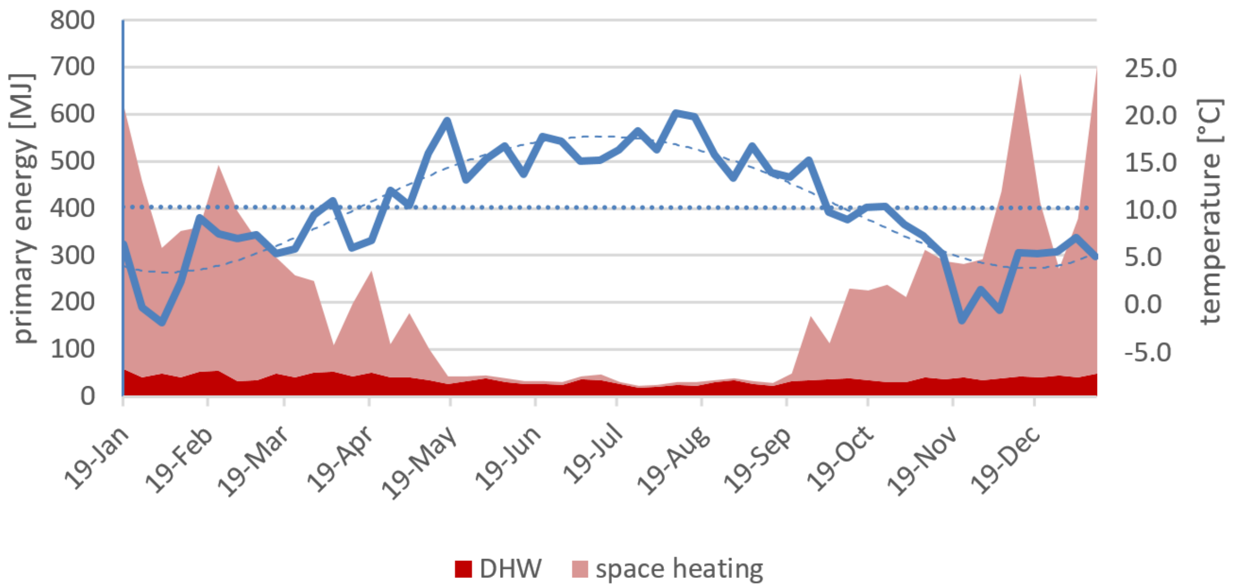

Figure 3: space heating/cooling demand and the outdoor temperature follow an inverse relation. In this figure, outdoor temperature (blue) is projected on gas consumption for space heating and for DHW of the home of one of the authors over a year.

Furthermore, in the case of fluctuating environment based HC sources, a single annual average temperature will mean very little (as the available thermal energy by definition follows the seasons).

Figure 4 illustrates the differences in system boundaries between the high temperature sources and the low temperature ones, and the distinction between constant and fluctuating ones. The mapping module output towards the planning module will provide the energetic output at the 'source temperature' boundary.

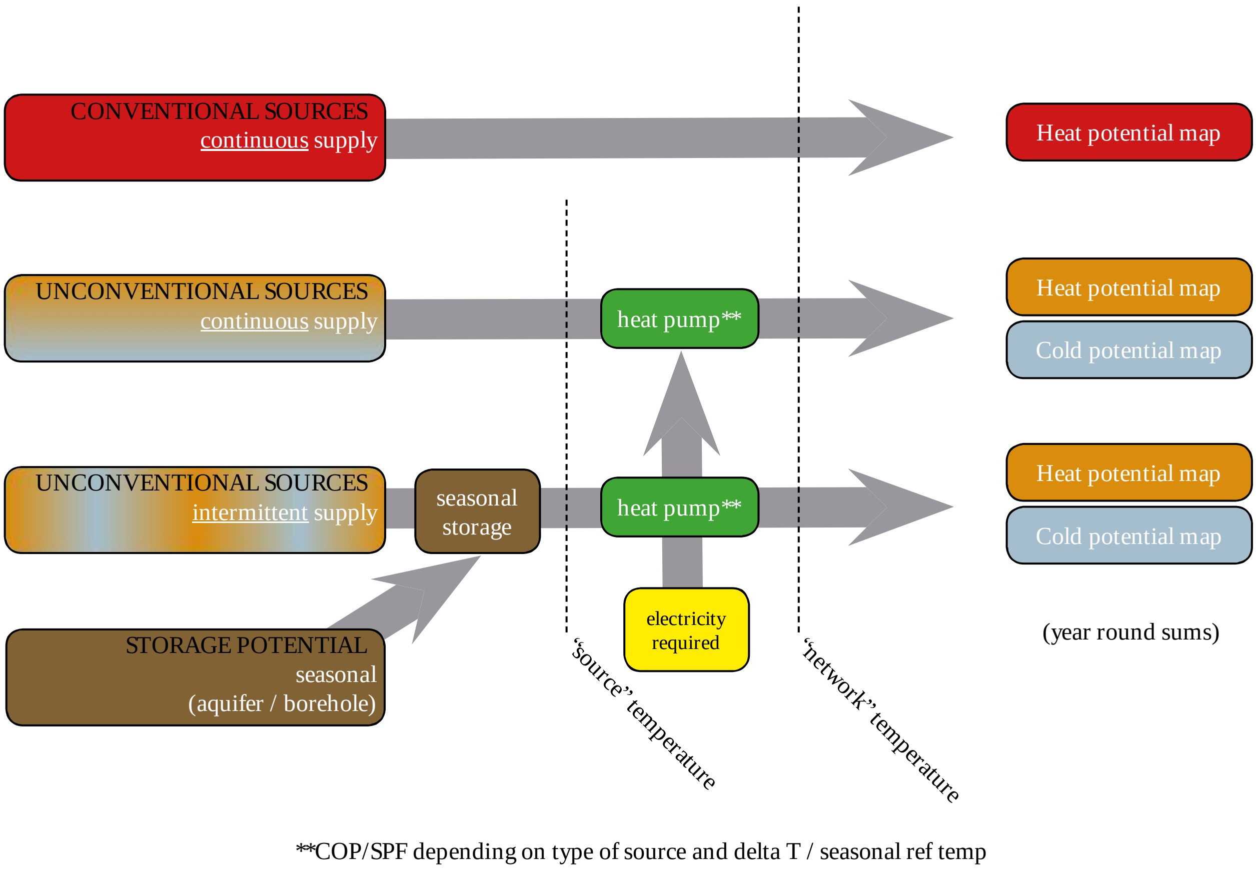

Figure 4: from theoretical to technical potential for different types of sources in PLANHEAT

Although this figure illustrates the principles, the boundaries between the categories displayed are not rigid. For constant sources for example, the availability of seasonal storage is not as necessary as for intermittent unconventional ones, but they could benefit from this as well (storing up otherwise unused heat in the summer season and releasing it in winter for example). Furthermore, a rough vertical designation based on temperature levels is possible, but some 'conventional' sources may sometimes provide low temperature output. These considerations however are dynamic and therefore not applicable to the mapping module, which focuses on annual potential.

Detailed temperature levels will however play a role in the simulation module. Although the algorithms developed for the unconventional sources are used in the mapping module to calculate a sum of twelve monthly averages, they can also be used for hourly values in the simulation module, by using input data that has that temporal resolution. In that case, exact temperatures can be provided as output. In the simulation module these are required to determine the COP (which varies depending on the input and output temperature, see for an example of this Figure 6 on p17), and therefore electricity usage and total heat output of the unconventional source considered.

1.5 Low temperature sources and seasonal thermal storage

Low temperature sources benefit greatly from the availability of seasonal storage. Although this is most evident in the case of fluctuating sources where anthropogenic thermal demand patterns follow ambient temperatures closely, even in the case of relatively constant sources (for example datacenters) the available heat would be used more efficiently if the excess residual heat in summer could be stored. The most cost effective option for low temperature networks are soil based, for example ATES and BTES. Although the availability of datasets on these relatively low depth systems does not appear to be universal, local and national data on soil capacities and permeability may be available to the user.

1.6 Data acquisition

Although for most HC potential maps public sources of data are provided, in a few cases these are not available. PLANHEAT deliverable D1.7 *"Overcoming barriers in data acquisition"* (Fremouw M. , 2017) provides guidelines on how to approach these issues, to which one addition can made specifically for the unconventional sources described in this report: if *temperature measurements* need to be commissioned, they should be done at (at least) an hourly basis over a year. The resulting dataset would then be able to cater to not just mapping module requirements, but also to the planning and particularly simulation modules.

2 Heat and cold from ambient and exhaust air (fluctuating)

These heat sources have in common that their medium is air and that their temperature fluctuates over the year. The difference between what goes into the heat exchanger and what comes out of it should be at least 1K, or the amount of electricity required for the ventilator will be more than the thermal energy gained for the heat pump.

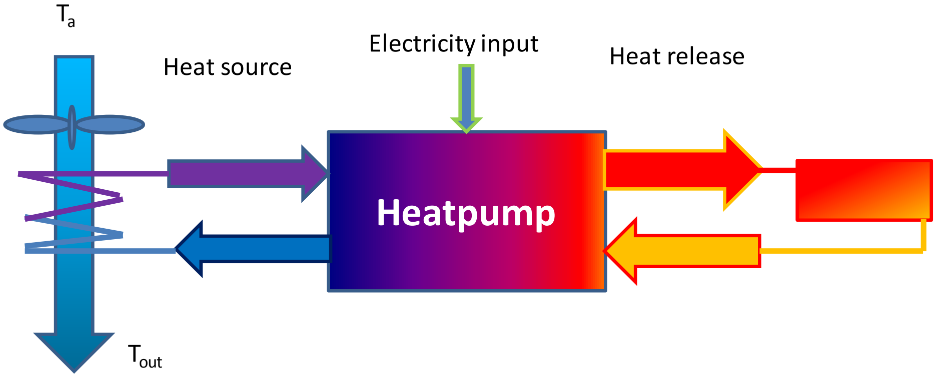

Figure 5: extracting heat from air flow, principle

2.1 Air sourced heat pumps

Related H/C demand: Heating / cooling
Level of detail: installation

For the scope of human settlements and energy potentials, the atmosphere can be considered an unlimited heat sink, where the only limiting factor would be the amount of electricity available for the heat pumps and the ambient temperature. Translating individual (point) potential as described in this section to a potential map, would require additional spatial constraints.

The total thermal output of the designed system would also include the amount of electric energy used by the heat pump. However, as the choice of heat pump type and therefore the COP used depends on system choices made in the planning and simulation modules, the amount of potential thermal energy calculated is purely the environmental component (i.e. based on changing the temperature of the medium). This is further discussed in sections 1.4 and 6.

Required support maps

In order to determine air sourced heat pump potential, the average ambient temperature is required.

Map	Mapped variable [unit]	Data specification	Default maps
1	T_a [°C]	Average monthly temperature	NOA's NowCasting service (PLANHEAT internal) (Tecnalia, 2018)

Required data

Data	Variable [unit]	Data specification	Default values
1	T_a [°C]	outside air temperature	(map)
2	T_{out} [°C]	Desired minimum heat pump exhaust temperature.	-20 (heating) +40 (cooling)
3	Q [m^3/h]	Ventilation flow (average)	100 (depends on demand)
4	ρc [[kJ/m^3·K]]	heat capacity air	1.2
6	t_{month} [h]	Number of hours in the month considered	730

The higher the temperature difference a heat pump has to create, the higher its electricity consumption. For heating, the default exhaust temperature is therefore set to -20 °C (giving a maximum heating temperature of 60 °C) in order to calculate a maximum feasible potential. Below -20 the COP will reach 1, which would make it as inefficient as electric resistance heating. Similarly, for cooling purposes the default exhaust temperature is set to +40 °C.
Smaller temperature differences would make the process more efficient (i.e. a higher COP and therefore a smaller share of electricity for the same amount of heat provided), albeit also lowering the total quantifiable heat potential. Although for reasons of interface simplicity it's better to limit the number of variables asked from the user, it may be beneficial to additionally allow them to define these values for scenarios with either ample (renewable) electricity availability or higher systemic efficiency.

Note that these temperature differences are what the heat pump creates from and towards the source medium, so in case of cooling potential 40 °C worth of heat energy is added to the exhaust towards the outdoor environment. These are considered feasible maximum values and are exclusively used to determine energy potential. Under simulation conditions the ΔT will depend on the combination of the current outdoor temperature and the desired indoor temperature.

Also note that as these potential calculations are about the interaction with the ambient environment, T_{out} therefore represents the exhaust temperature towards the heat sink (i.e. said ambient environment), not the network temperature towards the user.

Finally, air flow depends on installation size and noise restrictions. The default value represents a single household heat pump. Installations outside residential zones may be able to produce more (industrial) or less (natural habitat) noise (and therefore energy).

Data processing

For an individual heat pump, the T_{amb} values for each month need to be extracted from the temperature maps, based on its geolocation.

Algorithm

$$E_{heat} = (T_a - T_{out}) \times Q \times \rho c \times t_{month} / (3.6 * 10^3) [kWh]$$

This calculation needs to be run twelve times, once for each month. The sum is the annual potential.

Application and validation / case study

There are different types and brands of conventional air-water heat pumps on the market. Although they all have slightly differing specifications, they generally behave the same way. Figure 6 shows the coefficient of performance (COP) of a heat pump from Dimplex for producing different temperatures from different outside air temperatures. The graph shows that, when the outdoor air temperature is under minus 20°C, the COP narrows 1. This means that the same heat can be produced, even at a lower outside temperature and a higher system temperature with a simple electric conduction heater. This is the reason why the exhaust towards the outside air (and therefore the heating potential) has been limited to minus 20°C.

Airflow (Q)	100	m^3/h	**Algorithm:** $E_{heat} = (T_a - T_{out}) \times Q \times 1.2 \times t_{month} / (3.6 * 10^3)$ [kWh]
Minimal outlet temperature [T_{out}]	-20	°C	

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total	
T_a = Average outside temperature [°C]	1.8	2.3	5.4	8.9	12.7	15.8	17.4	17.2	14.7	10.4	6.1	3.0	9.64	°C
Temperature difference [K]	21.8	22.3	25.4	28.9	32.7	35.8	37.4	37.2	34.7	30.4	26.1	23	30	K
Extractable Thermal power [kW]	0.73	0.74	0.85	0.96	1.09	1.19	1.25	1.24	1.16	1.01	0.87	0.77	0.99	kW
Extractable Thermal energy per month [kWh/mo]	541	500	630	694	811	859	928	923	833	754	626	570	722	kWh/mo
Extractable Thermal energy year [kWh/yr]													**8,667**	**kWh/yr**

Table 2: Extractable thermal energy for heating from outside air with a heat pump in the Netherlands (De Bilt).

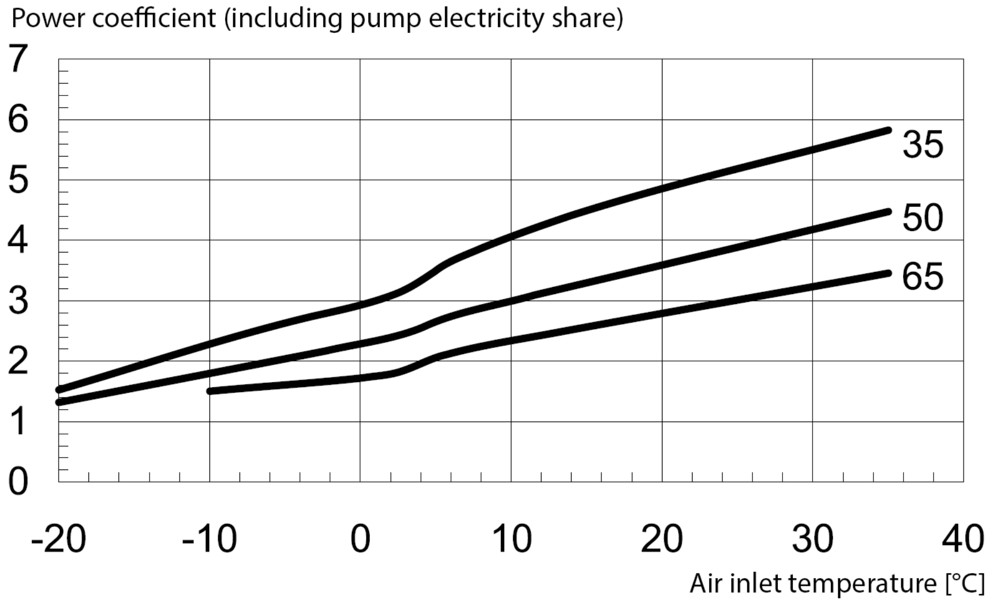

Figure 6: Heat pump COP using air of different temperatures as a source for different system temperatures. The slight bend in the curve is related to keeping the heat exchanger frost free [for Dimplex LA 11PS air/water heat pump]. (Dimplex, 2008) (reproduced with kind permission from Dimplex GmbH)

There is no defined upper limit for the amount of air going through the evaporator of the heat pump. A translation to spatial potential therefore requires further environmental or technical constraints.

Using a heat pump to extract cold from outside air

For cooling with outside air the same argument can be used, albeit in reverse. In this case the maximum outlet temperature of the heat pump/chiller at the condenser is suggested to be set to +40°C as a practical maximum, to generate a cooling temperature of 5°C. The available thermal energy for cooling is:

$$E_{cooling} = (T_a - T_{out}) \times Q \times \rho c \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

This calculation needs to be run twelve times, once for each month. The sum is the annual potential. This then results in an annually available thermal energy supply (cold) when using a heat pump (see Table 3 for the Dutch climate).

The input variables are:

- Ta = The average outdoor temperature per month for the location
- Tout = Maximum outlet temperature, set at 40 oC
- Q = Airflow in m3/hour

Airflow (Q) 100 m^3/h

Maximal outlet temperature [T_{out}] 40 °C

Algorithm: $E_{cooling} = (T_a - T_{out}) \times Q \times 1.2 \times t_{month} / (3.6 * 10^3)$ [kWh]

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total	
T_a = Average outside temperature [°C]	1.8	2.3	5.4	8.9	12.7	15.8	17.4	17.2	14.7	10.4	6.1	3.0	9.64	°C
Temperature difference [K]	-38.2	-37.7	-34.6	-31.1	-27.3	-24.2	-22.6	-22.8	-25.3	-29.6	-33.9	-37	-30	K
Extractable Thermal power [kW]	-1.27	-1.26	-1.15	-1.04	-0.91	-0.81	-0.75	-0.76	-0.84	-0.99	-1.13	-1.23	-1.01	kW
Extractable Thermal energy per month [kWh/mo]	-947	-844	-858	-746	-677	-581	-560	-565	-607	-734	-814	-918	-738	kWh/mo
Extractable Thermal energy year [kWh/yr]													**-8,853**	**kWh/yr**

Table 3: Extractable thermal energy for cooling from outside air with a heat pump in the Netherlands (De Bilt)

2.2 Direct free (air) cooling

Cooling directly with outside air is sometimes also possible (at night most of the year, continuously in the winter season), removing the additional electricity that a heat pump requires and just requiring a very limited amount of energy for ventilation, therefore providing much cheaper cooling.

The requirement is that the outdoor temperature is lower than the indoor temperature (night ventilation). For buildings that are cooled outside the normal cooling season (spring, winter and fall) it is also possible to cool during the day, when the outdoor temperature is lower than the desired indoor temperature in the building. Although potential cooling energy from fans will be much lower than from heat pumps, both investment costs and electricity consumption will also be much lower. This could be interesting for buildings that need cooling during the whole year, like data centres.

As with air source heat pump potential, at the urban scale the atmosphere is effectively an unlimited heat sink, therefore producing a spatial map would require additional environmental constraints.

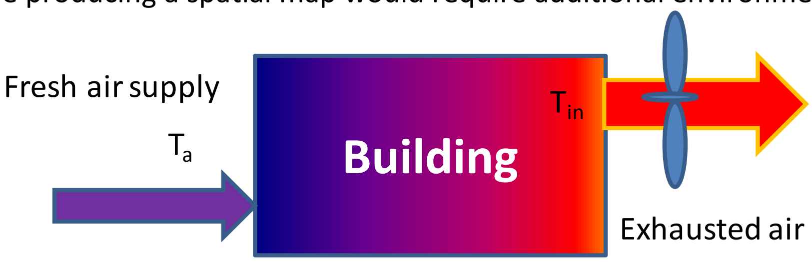

Figure 7: direct (free) air cooling principle

Related H/C demand: cooling

Level of detail: installation

Required support maps

Map	Mapped variable [unit]	Data specification	Default maps
1	T_a [°C]	Average monthly temperature	NOA's NowCasting service (PLANHEAT internal) (Tecnalia, 2018)

Required data

Data	Variable [unit]	Data specification	Default values
1	T_a [°C]	Outdoor air temperature	(map)
2	T_i [°C]	Maximum indoor temperature.	24
3	Q [m^3/h]	Ventilation flow (average)	100
4	ρ [kg/m^3]	Medium density	1.2
5	C [kJ/kg·K]	Specific heat of medium	1.01
6	t_{month} [h]	Number of hours in the month considered	730

Data processing

Like the heat pump calculations, the local ambient temperature forms the basis of the cooling potential, therefore twelve values need to be retrieved from the NOA support map. The main difference to heat pump based cooling is that direct cooling is not a three way system, therefore, here the system's output temperature is the desired maximum indoor temperature.

Algorithm

$$E_{cooling} = (T_{in} - T_{out}) \times Q \times \rho c \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

This calculation needs to be run twelve times, once for each month. The sum is the annual potential.

Application and validation / case study

The following table represents an energy potential calculation for a direct cooling system in the Netherlands.

Airflow (Q)	100	m^3/h	**Algorithm:** $E_{cooling} = (T_a - T_i) \times Q \times 1.2 \times t_{month} / (3.6 * 10^3)$ [kWh]
Maximal indoor temperature [T_i]	24	°C	

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total	
T_a = Average outside temperature [°C]	1.8	2.3	5.4	8.9	12.7	15.8	17.4	17.2	14.7	10.4	6.1	3.0	9.64	°C
Temperature difference [K]	-22.2	-21.7	-18.6	-15.1	-11.3	-8.2	-6.6	-6.8	-9.3	-13.6	-17.9	-21	-14	K
Extractable Thermal power [kW]	-0.74	-0.72	-0.62	-0.5	-0.38	-0.27	-0.22	-0.23	-0.31	-0.45	-0.6	-0.7	-0.48	kW
Extractable Thermal energy per month [kWh/mo]	-551	-486	-461	-362	-280	-197	-164	-169	-223	-337	-430	-521	-348	kWh/mo
Extractable Thermal energy year [kWh/yr]													**-4,181**	**kWh/yr**

Table 4: Example calculation for direct passive cooling with outside air

2.1 Indirect free (air) cooling

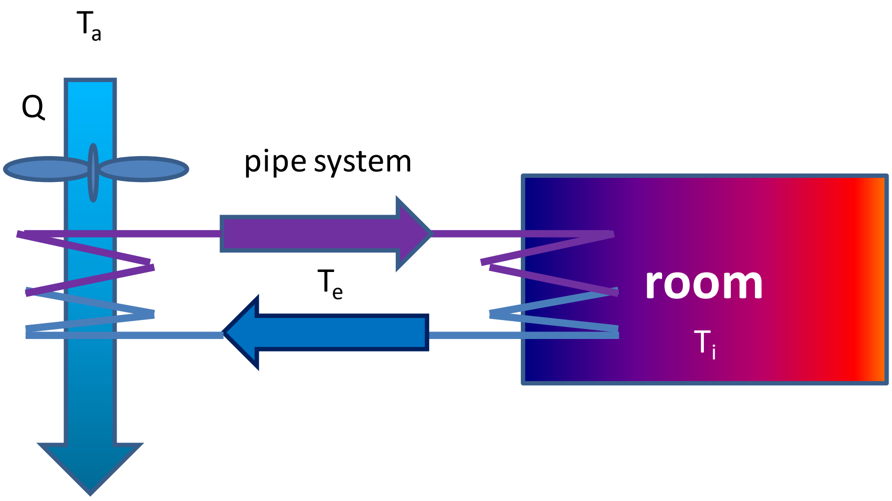

Figure 8: indirect (free) air cooling principle

Instead of using the ventilation air as an energy carrier, water can be used as an energy carrier. In this case an air-to-water heat exchanger is required to transmit the cold from the air into the cooling system and a heat exchanger to transmit the cold from the cooling system into the rooms where the cooling is needed. Because of these heat exchangers there is some exergy loss, estimated to be about 4K. The extractable thermal energy (cold) during the year is dependent on:

- T_a = The average outdoor temperature per month for the location:
- T_i = Maximum indoor temperature: set at 24 °C
- T_e = Exergy loss; set at 4K
- Q = Airflow in m^3/hour (V)

The available thermal energy for indirect passive cooling is:

$$E_{cooling} = (T_a - T_i + T_e) \times Q \times 1{,}2 \times t_{month} / (3.6 * 10^3) \quad \text{[kWh]}$$

The cooling capacity for indirect passive cooling is low because of the minimal temperature differences at the heat exchangers.

2.2 Extracting heat from subway network ventilation exhaust air

Underground transportation networks generate large amounts of heat that needs to be ventilated away. After decades of operation, there may even be a significant amount of heat stored in the tunnel walls, adding to both the ambient temperature in the networks and the potentially recoverable heat, and reducing temperature fluctuations.
For the London Underground for example, which has been operating for well over a century, only 10% of the heat generated is removed by ventilation, 90% is absorbed by the tunnel walls (Burn, 2015). This has resulted in the temperatures at the platforms and in the tunnels sometimes reaching uncomfortably high levels.
There is a spatial incentive to consider subways as heat sources as well. They are not only common in large cities, they will also, out of operational and commercial necessity, frequently follow routes under or near larger population (and therefore demand) densities, therefore making it relatively easy to connect demand and supply.

Related H/C demand: Heating
Level of detail: installation

The algorithm used is a variant of the basic air sourced heat pump algorithm as described in section 2.1. The main difference is that the input is not the ambient temperature, but the temperature drop of the exhausted air, after leaving the evaporator of the heat pump.

Required support maps

Location of subway ventilation exhaust(s). These are not normally part of topographic maps, and will therefore need to be provided by the end user.

Map	Mapped variable [unit]	Data specification	Default maps
1	Vent locations	Vector map showing subway ventilation exhaust shafts	n/a

Required data

Data	Variable [unit]	Data specification	Default values
2	T_{diff} [K]	Heat pump (exhaust) air temperature drop.	9
3	Q [m^3/h]	Ventilation flow (average)	n/a
4	ρ [kg/m^3]	Medium density	1.2
5	c [kJ/kg·K]	Specific heat of medium	1.01
6	t_{month} [h]	Number of hours in the month considered	730

The default value for T_{diff} is based on the Bunhill case study (Mildenstein, Durup Thomsen, & Kennedy, 2014). Those values that are expected to vary greatly (being dependent on local circumstances, both climatically and relating to the specificities of the subway system), should be user provided, and are therefore marked as n/a.

Data processing

None required.

Algorithm

$$E_{heat} = \rho c \times Q \times T_{diff} / (3.6 * 10^3) \qquad [kWh]$$

Where E_{heat} is the (monthly) available thermal energy [kWh].

This calculation needs to be run twelve times, once for each month. The sum is the annual potential.

Application and validation / case study

Data on a single subway ventilation shaft was considered. Preliminary research on the underlying energy balance suggests that for larger networks the amount of heat exhausted may differ significantly in different areas of the network, as there is a relation to usage intensity. The possibility of providing a spatial mapping method without requiring each ventilation shaft to be individually monitored is being investigated, but will be dependent on access to other detailed datasets.

Exhausted airflow mechanical ventilation (Q) 500 m^3/h **Algorithm:** $E_{heat} = (T_{diff}) \times Q \times 1.2 \times t_{month} / (3.6 * 10^3)$ [kWh]

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Extractable Thermal power [kW]	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50 kW
Extractable Thermal energy per month [kWh/mo]	1116	1008	1116	1080	1116	1080	1116	1116	1080	1116	1080	1116	1095 kWh/mo
Extractable Thermal energy year [kWh/yr]													**13,140 kWh/yr**

Table 5: Example calculation for extracting heat from exhausted air with a heat pump from subway networks

For the Bunhill district heating system, heat from a ventilation shaft of the London Underground is recovered with a heat pump (Figure 9). The temperature of the exhausted air is between 18 and 28 ^{o}C (Figure 10) and cooled to 10-18 ^{o}C to produce heat up to 80 ^{o}C. The average temperature drop is 9K (from 23 to 14^{o}C). The airflow is about 30 m^3/s. The amount of heat that is extracted from the exhausted air is in this situation 3600 x 30 x 9 x 1,2 / 3600 = 324 kW. It was calculated that the heat pump has an average COP of 3 (Figure 11).

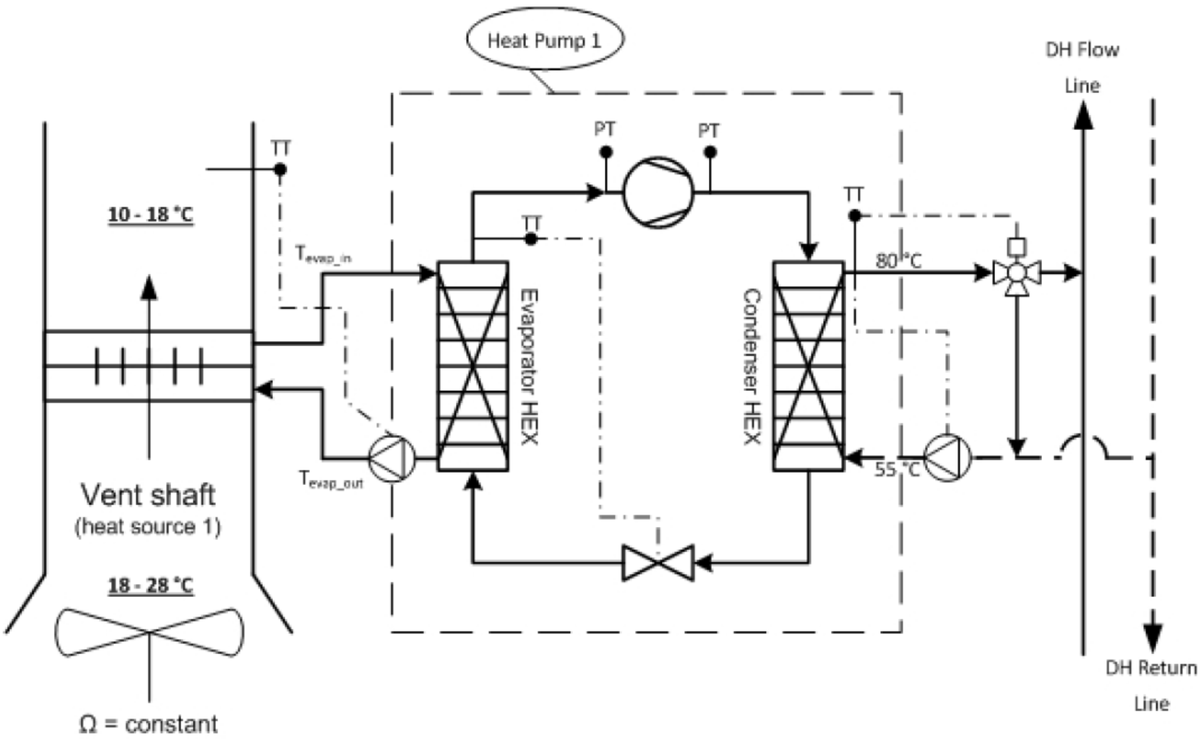

Figure 9: system layout of Bunhill source 1 heat pump (Mildenstein, Durup Thomsen, & Kennedy, 2014) (reproduced with kind permission from Ramboll District Energy)

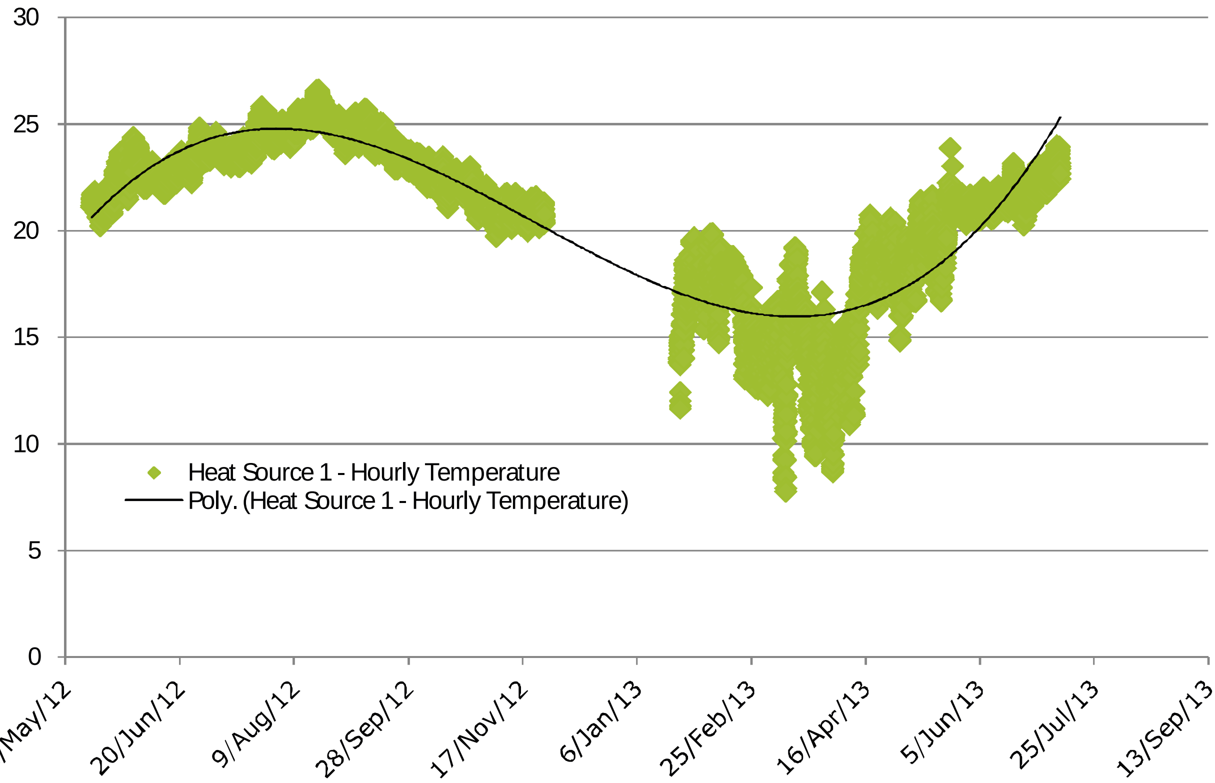

Figure 10: London Underground exhaust vent air temperature in Bunhill (Mildenstein, Durup Thomsen, & Kennedy, 2014) (reproduced with kind permission from Ramboll District Energy)

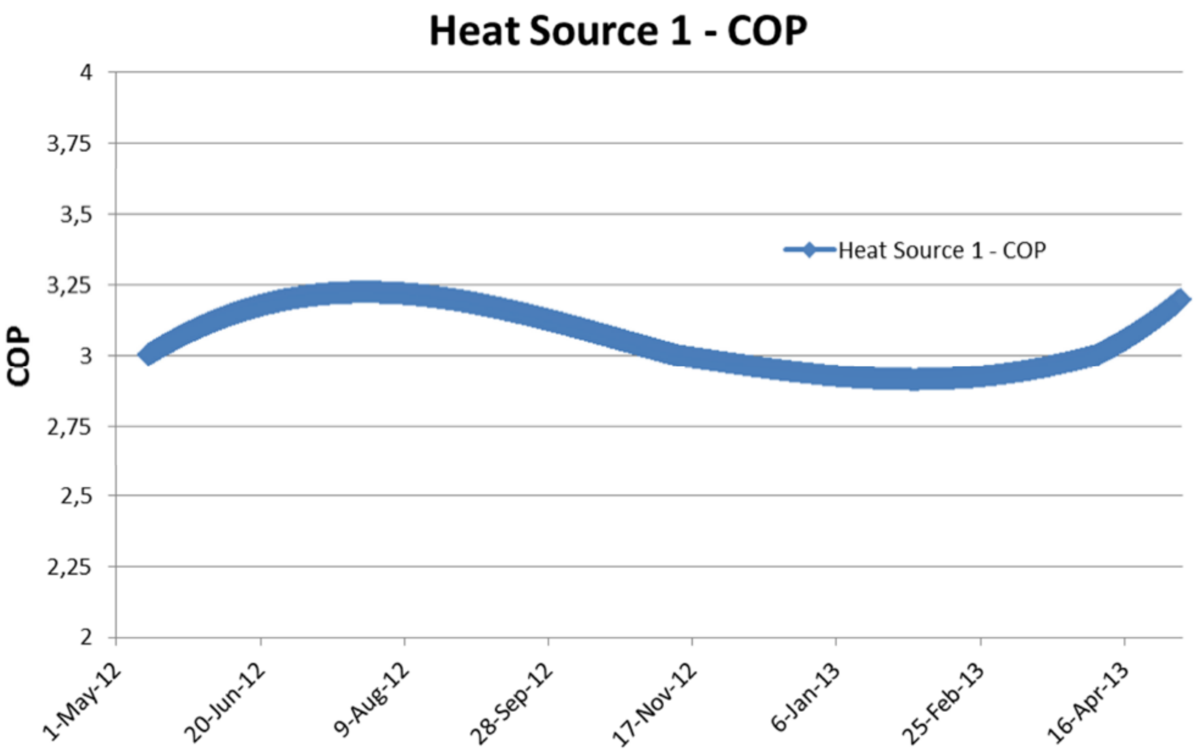

Figure 11: COP of Bunhill Heat Source 1 heat pump on an hourly basis (Mildenstein, Durup Thomsen, & Kennedy, 2014) (reproduced with kind permission from Ramboll District Energy)

2.3 Extracting heat from indoor car park ventilation exhaust air

The algorithm for subway networks exhaust air can also be used to calculate the exhausted air ventilation heat potential of indoor (multi storey) car parks which feature mechanical ventilation. The geometry variable here is the floor area (if this is not known, an estimate can be made using the garage footprint and the number of floors).

The European Union specifies maximums to air quality related indicators (Priemus & Schutte-Postma, 2009). Dutch parking garage norm NEN 2443 (NEN, 2013) therefore specifies a ventilation rate of 3 litres per second per m^2, which translates to 10.8 $m^3/m^2/h$:

$$Q = 3 / 10^3 \times 3600 \qquad [m^3/m^2/h]$$

The heat pump (exhaust) air temperature drop [T_{diff}] for indoor car parks is set at 7K.

The available thermal energy from exhausted air of indoor parking garages is therefore:

$$E_{heat} = T_{diff} \times Q \times 1.2 \times t_{month} / (3.6 * 10^{3}) \qquad [kWh]$$

Application and validation / case study

Floor area indoor car parking [A]	2,000	m^2	**Algorithm:** E_{heat} = 7 x Q x 1.2 x t_{month} / (3.6 *10^3) [kWh]
Airflow mechanical ventilation (Q)	21,600	m^3/h	Q = A x 3 / 10^3 * 3600 [m^3/h]

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Extractable Thermal power [kW]	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67 kW
Extractable Thermal energy per month [kWh/mo]	3,472	3136	3472	3360	3472	3360	3472	3472	3360	3472	3360	3472	3407 kWh/mo
Extractable Thermal energy year [kWh/yr]													**40,880 kWh/yr**

Table 6: Example calculation for extracting heat from exhausted air with a heat pump from car park ventilation

3 Residual heat from cooling processes

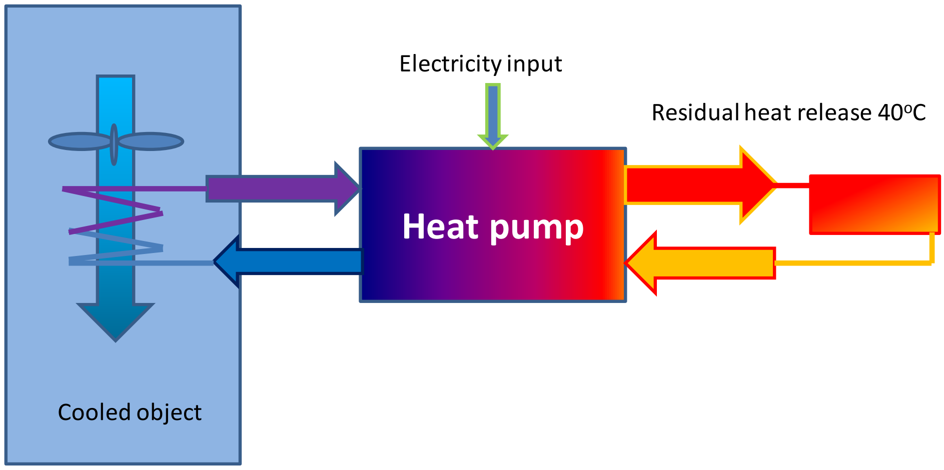

Figure 12: residual heat from cooling processes, principle. Note that the heat pump in the figure is part of the existing cooling process, so in the context of the mapping module this still considered 'theoretical' potential.

This section considers residual heat coming from existing cooling processes present in the study area. These usually involve the exhaust heat from heat pumps used for cooling. The COP mentioned in this section therefore refers to the COP of the primary heat pump to convert electricity consumption to cool and the residual heat production, rather than the COP of a heat pump to convert this relatively low temperature exhaust heat to a higher level.

The temperature of this exhaust heat is around 40°C and can be used directly for low temperature room heating. Fluctuation is relatively limited, owing to either the very large amount of heat that needs to be cooled away (data centres and refrigerated storage facilities) or the reference temperature for the refrigeration units being that of the indoor environment rather than ambient (supermarkets).

A common issue with these sources is that for some categories the locations of individual facilities are known, but not necessarily the data indicative of residual heat potential. There are two main reasons for this. Firstly, the vast majority will be below the 50MW capacity that would require them to do LCP (Large Combustion Plants) Directive reporting. Secondly, these facilities also tend to have electricity as the main energy source (carrier) for cooling, which (apart from in some cases water vapour and on-site emergency diesel generators) does not result in on site emissions, therefore also not making them visible on the LCP map. If no national or local data sources are available, data acquisition is therefore necessary.

The parameters required are however limited, and should therefore not require much effort to retrieve. In most cases the surface area or the volume are sufficient to reach an indication, in some cases a category needs to be defined (for example in the case of refrigerated storage). Default values can always be bypassed if more precise figures are known (for example electricity consumption, or even the exact share of that used by the cooling installations).

3.1 Data centres

Related H/C demand: Heating
Level of detail: installation

Residual heat from cooling processes is often released in the air with cooling towers by evaporation, natural draft or induced draft. It is also possible to transmit this heat to a fluid that can be used for (low temperature) heating purposes.

Required support maps

Map	Mapped variable [unit]	Data specification	Default maps
1	A [m^2] and if available, PwD [kW/m^2]	Location, size and power density of data centres	NL: https://www.dutchdatacenters.nl/map/
2	ED [kWh/yr]	Alternatively: Location and annual electricity demand of data centres	n/a

Required data

Data	Variable [unit]	Data specification	Default values
1	A [m^2]	Data center floor area	n/a
2	CPwD [W/m^2]	Cooling Power density	1000
3	FSU [%]	Floor Space Utilisation	50
4	LL [%]	Load Level	45
5	COP [n]	Coefficient of Performance of the cooling system	5

Algorithm

$$E_{heat} = A \times PwD \times FSU \times LL \times (1 + (1 / COP)) \times t_{month} \qquad [kWh]$$

For data centres using traditional chillers, the seasonal variations in cooling exhaust temperature are limited, therefore a static calculation method can be used. However, if a datacentre additionally uses (seasonal) free (air) cooling, this variation will be significantly larger and monthly calculation steps would be required. As mentioned, the COP in this calculation refers to the existing cooling system that produces the heat, rather than that of a secondary heat pump that would use this heat as input.

Data processing

Although literature mostly refers to power density, the spatial source found for Dutch data centres provides a total power P for the datacentre. In this case it would need to be divided by the floor area (A) before being fed into the algorithm.

It is also possible to calculate with the total annual electricity demand of the data centre. The estimation is that 90% of this electricity is converted into heat that has to be removed by the chillers. The algorithm for the extractable thermal heat (per month) is:

$$E_{heat} = ED \times 0.9 / 12 \qquad [kWh/mo]$$

Data	Variable [unit]	Data specification	Default values
1	ED [kWh/yr]	Annual electricity demand	n/a

Application and validation / case study

The temperature of the residual heat is about 40 ^{o}C for compression cooling machines (heat pumps) for producing temperatures of 5 ^{o}C. These chillers are most often used for cooling data centres and buildings. The cooling needed for data centres is about 1 kW/m^2 floor space. Office buildings have an average cooling capacity of 0,1-0,2 kW/ m^2 floor space, so there is quit some residual heat to recover in data centres. The COP of these compression cooling machines is around 5 and the potential of this residual heat is the cooling power including the used electric energy for these heat pumps. Per kWh cooling there is 1 + 1/5 = 1,2 kWh of residual heat with a temperature of around 40^{o}C (RVO, 2015). Although the average cooling capacity for data centres is 1 kW/m2 floor area (Afman, van Grinsven, & de Buck, Energiebesparing door best beschikbare technieken voor koeling van serverruimtes, 2014) it is not always fully in use. The average utilization rate and degree of load is 50, resp. 45% (Afman, 2014) so the total heat production power from cooling is:

50% x 45% x (1+1/5) = 0,27 kW / m^2 floor area.

The heat production / month = 30 days x 24 hours x 0,27 kW = 194 kWh / month / m^2 floor area.

The residual heat exhaust from cooling data centres doesn't fluctuate much over the months unless the datacenter partially makes use of free cooling (especially in the cold season). In that case the residual heat from cooling will be less.

Datacentre floor area [A]	10	m^2	**Algorithm:** $E_{heat} = A \times PD \times FSU \times LL \times (1 + 1/COP) \times t_{month}$ [kWh]
Cooling power density [PD]	1000	W/m^2	(default value for NL = 1000 W)
Floor space utilisation [FSU]	50	%	(default value for NL = 50%)
Load Level [LL]	45	%	(default value for NL = 45%)
Coefficient of performance of the cooling system	5	[COP]	default COP for cooling = 5

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Extractable Thermal power [kW]	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.70 kW
Extractable Thermal energy per month [kWh/mo]	2009	1814	2009	1944	2009	1944	2009	2009	1944	2009	1944	2009	1971 kWh/mo
Extractable Thermal energy year [kWh/yr]													**23,652 kWh/yr**

Table 7: Example calculation for extracting heat from exhausted air from data centres

If the exact electricity usage of the data centre is known, the calculation becomes very straightforward, as displayed in Table 8.

Yearly electricity demand [ED] 5000 kWh/yr **Algorithm:** E_{heat} = ED x 0.9 /12 [kWh/mnth]

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total	
Extractable Thermal power [kW]	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	kW
Extractable Thermal energy per month [kWh/mo]	382	345	382	370	382	370	382	382	370	382	370	382	375	kWh/mo
Extractable Thermal energy year [kWh/yr]													**4,500**	**kWh/yr**

Table 8: Example calculation for extracting heat from exhausted air from data centres, based on electricity usage

3.2 Supermarkets

Related H/C demand: Heating
Level of detail: installation

Most of the electricity demand of supermarkets is used for product cooling. These figures can therefore be used to estimate residual heat production.

Required support maps

Map	Mapped variable [unit]	Data specification	Default maps
1	Floor area [m^2]	Supermarket net ground floor area	n/a

Required data

Data	Variable [unit]	Data specification	Default values
1	A [m^2]	Supermarket net ground floor area	n/a
2	E_{PC} [$kWh/m^2/yr$]	Annual electricity demand for product cooling	246
3	COP	Coefficient of performance of the cooling system	Average COP = 3 (2 for freezing and 4 for cooling)

Data processing

Where location and surface are concerned, care should be taken that the geodata source refers to actual supermarket rather than offices, warehouses and other assets run by the same company.
As supermarkets are rarely multi storey, the net ground floor area derived from the footprint of the building (or buildings) that each individual supermarket occupies, should be a sufficient approximation.

If none of this data is publicly available, the fastest route will be an inquiry on location, square meterage and (if available) electricity consumption of local supermarkets with the regional offices of their parent companies.

In terms of energy, this map layer specifically relates to cooling equipment within a controlled indoor environment. The ‘ambient’ (or offset) temperature for the installations involved is therefore usually near room temperature (as opposed to outdoor temperature). Because of the relative homogeneity of supermarkets (their floor size being the major variable), a default value for residual heat potential has therefore been used. If more detailed figures on the types of cooling equipment, their share of the building’s electricity usage and the COPs involved are available, these should be used instead.

Algorithm

$$E_{heat} = A \times E_{PC} / 8760 \times (COP + 1) \times t_{month} \quad [kWh]$$

Application and validation/case study

The average electricity demand for product cooling in the Dutch supermarkets is 246 kWh electricity per year /m^2 floor area (Meijer & Verweij, 2009). Depending on the cooling temperature the COP will be between 2 (for freezing) and 4 (for cooling). The average COP is set to 3 (van den Bovenkamp, 2016) which means there is a residual heat potential of:

(3 +1) x 246 kWh = 984 kWh / year / m^2 floor-area of the supermarket

During the different months of the year there won’t be much difference. At this moment the residual heat from cooling in most supermarkets is transmitted to the outside air. It is also possible to transmit this residual heat of 30-40^{o}C to a liquid and use it for heating processes.
General information on energy demand for cooling in refrigerated storage facilities is not found yet but can be calculated in the same way as done with product cooling in supermarkets. The average electricity demand for cooling per m^2 floor area is needed as well as the average COP. Depending on the cooling-temperature, the average COP will be between 2 and 4.

It is also possible to calculate with the total annual electricity demand of the supermarket [ED]. In the Netherlands 65% of the annual electricity demand is for product cooling (Meijer & Verweij, 2009). With an average COP for product cooling and freezing of 3, the algorithm for the monthly extractable heat is;

$$E_{heat} = ED \times 0.65 \times 3 / 12 \quad [kWh/mo]$$

Supermarket net ground floor area [A]	10	m^2	**Algorithm:** $E_{heat} = A \times PC / 8760 \times (COP + 1) \times t_{month}$ [kWh]
Electricity demand for product cooling [PC]	246	kWh/yr/m^2	(default value for NL = 246 kWh/yr/m2)
Coefficient of performance of the cooling system	3	[COP]	Average COP = 3 (2 for freezing and 4 for cooling)

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Extractable Thermal power [kW]	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12 kW
Extractable Thermal energy per month [kWh/mo]	836	755	836	809	836	809	836	836	809	836	809	836	820 kWh/mo
Extractable Thermal energy year [kWh/yr]													**9,840 kWh/yr**

Table 9: Example calculation for extracting heat from exhausted air from supermarkets

As with data centres, if the electricity usage of each supermarket is known the calculation becomes more straightforward, as displayed in Table 10.

Yearly electricity demand [ED] 5000 kWh/yr **Algorithm:** E_{heat} = ED x 0.65 x 3 / 12 [kWh/mnth]

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Extractable Thermal power [kW]	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11 kW
Extractable Thermal energy per month [kWh/mo]	828	748	828	801	828	801	828	828	801	828	801	828	813 kWh/mo
Extractable Thermal energy year [kWh/yr]													**9,750 kWh/yr**

Table 10: Example calculation for extracting heat from exhausted air from supermarkets, based on electricity usage

3.3 Refrigerated storage facilities

Related H/C demand: Heating
Level of detail: installation

Almost all electricity demand at refrigerated storage facilities is directly related to product cooling. This data can therefore be used to estimate residual heat production. The algorithm used is mostly identical to the supermarket layer. The main differences are in the input data and default values. There are two main categories of refrigerated storage, cooling and freezing. These come with different COPs, default values have been provided for both categories. Because actual energy usage will strongly be influenced by the energy efficiency and usage of each facility (Vermeeren, Verwoerd, & Lobregt, 2000), it is recommended to use the electricity based calculation if this source data is available.

Note that for theoretical potential a single calculation step is sufficient. Contrary to supermarkets, where the environment in which refrigeration takes place is essentially room temperature and therefore constant over the year, refrigerated storage facilities may have their insulated walls directly border the outdoor environment and will therefore likely experience some fluctuation in their heat output over a year. Data on this however may not always be available, therefore the baseline is provided using annual calculation.

Required support maps

Map	Mapped variable [unit]	Data specification	Default maps
1	A [m^2]	Location and size of refrigerated storage facilities	n/a

Required data

Data	Variable [unit]	Data specification	Default values

1	V [m^3]	Refrigerated storage facility volume	A x 3
2	E_{PC} [kWh/m^3]	Annual electricity demand for cooling/freezing	100
3	COP	Coefficient of performance of the cooling system	Average COP = 3 (2 for freezing and 4 for cooling)

It is assumed that the height of the refrigerated storage facilities is 3m. The volume will therefore be 3 x A [m^3].

Data processing

Because refrigerated storage facilities can vary significantly, both in floor area and height, the volume is used as a variable. If the energy usage is known per m^2, the second algorithm should be used.

Algorithm

$$E_{heat} = A \times 3 \times E_{PC} / 8760 \times (COP + 1) \times t_{month} \quad [kWh]$$

It is also possible to calculate with the total annual electricity demand of refrigerated storage facilities [ED]. It is assumed that 90% of the electricity demand is used for the chillers. With an average COP for product cooling and freezing of 3, the algorithm for the monthly extractable heat is:

$$E_{heat} = ED \times 0.9 \times COP / 12 \quad [kWh/mo]$$

Application and validation / case study

Table 11 shows an example calculation based on geometry, Table 12 shows a calculation based on electricity usage.

Refrigerated storage facility floor area [A]	30	m2	**Algorithm:** $E_{heat} = A \times 3 \times PC / 8760 \times (COP + 1) \times t_{month}$ [kWh]
Electricity demand for cooling/freezing [PC]	100	$kWh/yr/m^3$	(default value for NL for freezing = 100 kWh/yr/m3)
Coefficient of performance of the cooling system	4	[COP]	Average COP = 3 (2 for freezing and 4 for cooling)

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Extractable Thermal power [kW]	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14 kW
Extractable Thermal energy per month [kWh/mo]	3822	3452	3822	3699	3822	3699	3822	3822	3699	3822	3699	3822	3750 kWh/mo
Extractable Thermal energy year [kWh/yr]													**45,000 kWh/yr**

Table 11: Example calculation for extracting heat from exhausted air from refrigerated storage facilities

Yearly electricity demand [ED]	5000	kWh/yr	**Algorithm:** $E_{heat} = ED \times 0.9 \times COP / 12$ [kWh/mnth]
Coefficient of performance of the cooling system	4	[COP]	Average COP = 3 (2 for freezing and 4 for cooling)

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Extractable Thermal power [kW]	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05 kW
Extractable Thermal energy per month [kWh/mo]	1529	1381	1529	1479	1529	1479	1529	1529	1479	1529	1479	1529	1500 kWh/mo
Extractable Thermal energy year [kWh/yr]													**18,000 kWh/yr**

Table 12: Example calculation for extracting heat from exhausted air from refrigerated storage facilities, based on electricity usage

4 Heat from sewage systems

Heat from sewage systems can be extracted in the sewer system itself as well as at the sewage treatment plants. Theoretical heat can be extracted to the point the sewage water will freeze. The minimal temperature is set to 2 ^{o}C. The temperature of the sewage is fluctuating during the year and is also effected by the amount of rain/melting water that is drained in the sewer system.
The available thermal energy is depending on:

- The average temperature (T_{sew}) of the sewage per month
- Minimal sewage temperature (T_{min}): (2 ^{o}C is the minimum)
- The flow of the sewage in m^3/hour (Q)

The available potential can then be calculated with:

$$E_{heat} = (T_{sew} - T_{min}) \times Q \times 4200 / 3600 \qquad [kW]$$

Heat from the sewage system can be extracted in the building (e.g. shower drain heat exchanger), in the sewer system itself and at the sewage treatment plant (influent and effluent). The temperature in the sewage system shouldn't decrease too much which can be harmful for the purifying process. Keep the temperature drop on 1-2K, unless there is enough distance between the extraction point and the sewage treatment plant (Kluck, van den Bulk, Flameling, & de Brauw, 2011). In this case (T_{sw}- T_{min}) will be between 1 and 2K.

	Recovery in building (as raw wastewater)		Recovery in wastewater sewer system (as raw wastewater)		Recovery in the sewage treatment plant (from treated wastewater)

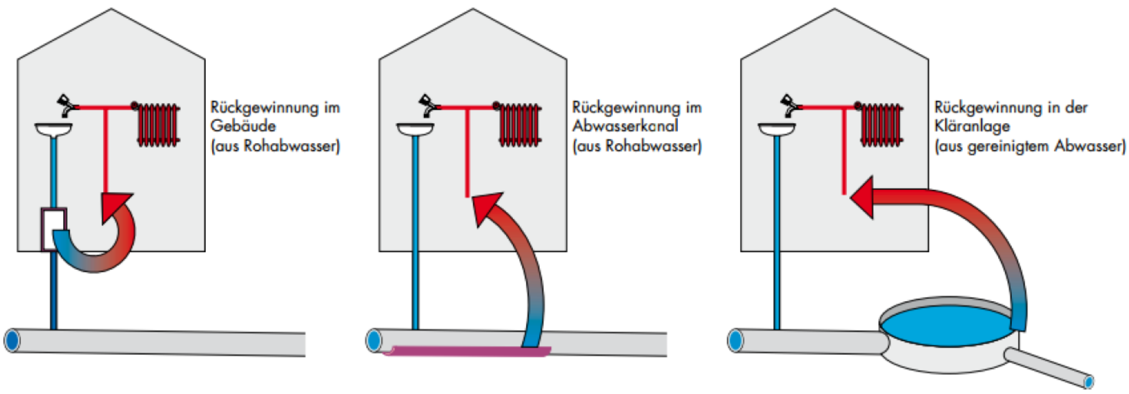

Figure 13: types of sewage heat recovery (Eawag, 2009) (reproduced with kind permission from Eawag)

When extracting heat at a sewage treatment plant, there are larger flow rates and when extracting at the effluent-side (instead of the influent side), the minimal outflow temperature can narrow 2 ^{o}C. For these reasons there is more heat to extract at the treatment plants than in the sewer system itself. The capacity of these waste water treatment plants usually the associated actual usage figure (load_entering_wwtp) are represented in in population equivalents (p.e.).

1 p.e. means that 1 person resident in a normal house is expected to produce 200 l of sewage flow per day. This can be used as an indicator of the flow rate in the sewage treatment plant.

To determine the location and p.e. of sewage treatment plants the following map can be used: https://www.eea.europa.eu/themes/water/water-pollution/uwwtd/interactive-maps/urban-waste-water-treatment-maps

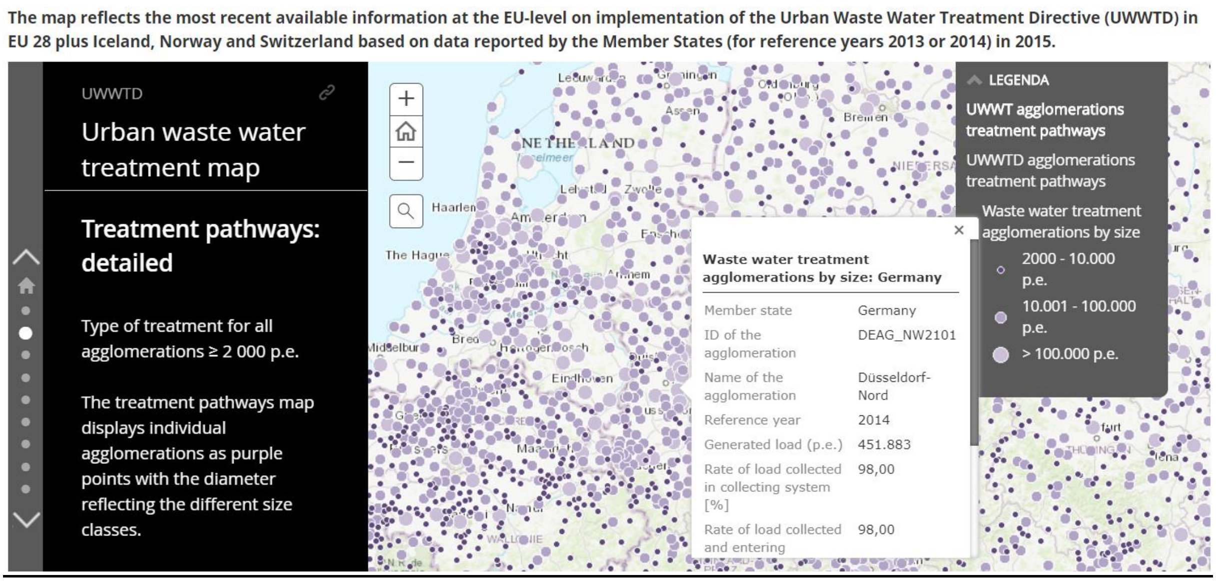

Figure 14: Urban waste water treatment map (EEA, 2017)

For the local sewer system the same indicator can be used, counting the houses connected to the system and using an average occupation for every house. The temperature in the sewer system itself doesn’t differ much from the temperature of the influent of the sewage treatment plant (see Figure 15).

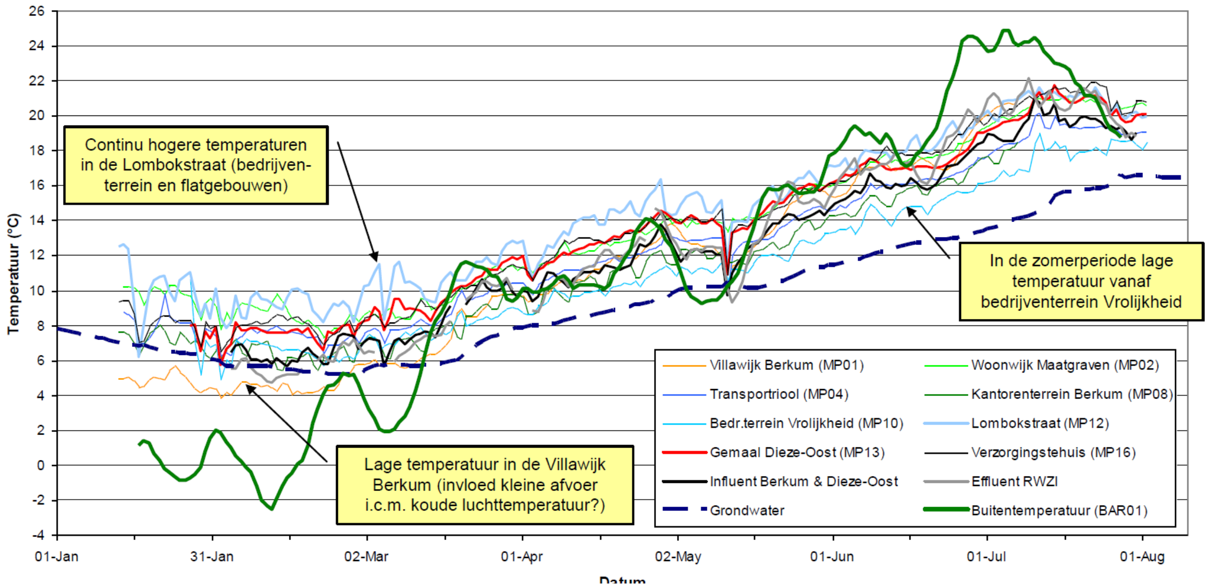

Figure 15: daily average temperatures of sewage, ambient air and ground water (Kluck, van den Bulk, Flameling, & de Brauw, 2011) (reproduced with kind permission from Stowa)

4.1 Sewage network (basic approach)

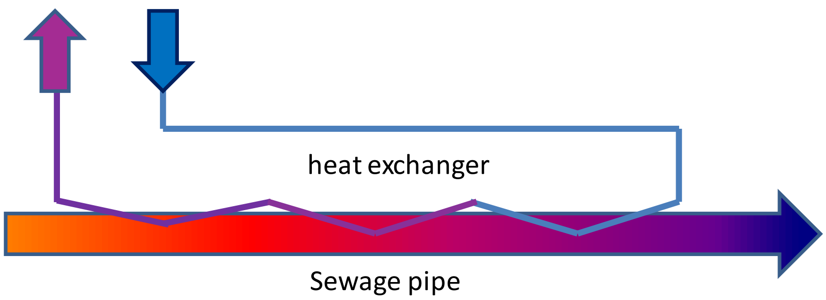

Figure 16: residual heat from sewage pipes, principle

Related H/C demand: Space heating, temperature levels
Level of detail: area

The basic approach considers the sewage production per capita, using population density to calculate heat potential. Although on average the connectedness of the EU population to sewage disposal (either individual or collective) is very high, there are differences on the national level, and between urban and rural areas. Relevant for this potential is the percentage of the population that uses a collective pipe system for sewage disposal, usually (albeit not always) connected to a wastewater treatment plant.

Required support maps

Map	Mapped variable [unit]	Data specification	Default maps
1	Population density [PD][inhabitants/ha]	Number of people per area	http://cidportal.jrc.ec.europa.eu/ftp/jrc-opendata/GHSL/GHS_POP_GPW4_GLOBE_R2015A/GHS_POP_GPW42015_GLOBE_R2015A_54009_250/V1-0/ dataset description: http://data.jrc.ec.europa.eu/dataset/jrc-ghsl-ghs_pop_gpw4_globe_r2015a

Required data

Data	Variable [unit]	Data specification	Default values
1	T_{sew} [°C]	Monthly average sewage temperature (12 values per year). The influent temperature of the receiving sewage treatment plant may be a good representative.	User required
2	T_{cool} [°C]	Max cool down temperature. User specified, 2 °C will be the maximum realistic delta T.	2
3	P [kg/m^3]	Density of medium (i.e. sewage / water)	1000
4	C [J/kg/K]	Heat capacity of medium (i.e. sewage / water)	4.2
5	p.e. [l/day]	Population equivalent: volume (in liters) of sewage generated per capita per day. EEA figure applicable to all of Europe, user may specify more precise data.	200
6	t_{month} [h]	Number of hours in the month considered	730
7	CON [-]	Share of the population in the area connected to the sewage network (usually 100% or “1” in urban areas).	1*

*In most urban areas this will probably be 100%. However, national averages show that coverage may sometimes be less (WHO, 2018).

In practice the maximum cooling temperature of sewage water in sewage pipes does not exceed the 2K. For this reason this 2K can be assumed to be a fixed value. For calculating the monthly extractable heat, it is not necessary to know the monthly average sewage temperature. These temperatures are necessary to determine the COP of the heat pump that extracts the heat from the sewer system.

Data processing

Population Equivalent is commonly reported in liters per person per day, the algorithm has been adapted to accept this and is converted to m^3/h by dividing these 200 l by 24 h and 1000 l. When multiplying this number with the amount of people in the area that is connected to the sewer system, the flow of the sewage can be calculated in m^3/hour (Q):

$$Q = A \times PD \times p.e. / 24 / 1000$$

Where:

- A = Area connected to the sewage system [ha]
- PD = Population density [inhabitants / ha]
- p.e. = Population Equivalent (1 p.e. = 200 liters/day)

Algorithm

$$E_{heat} = 2 \times Q \times 4200 \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

Application and validation / case study

Area connected to the sewer system [A] 2 ha.
Population Density [PD] 50 inhabitants/ha

Algorithm: $E_{heat} = 2 \times A \times PD \times 200 / 24 / 1000 \times 4200 \times t_{month} / (3.6 * 10^3)$ [k\

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total	
T_{sw} = Average temperature of the sewage [°C]	5.7	5.7	8.2	11.6	13.2	17.5	20.9	20.9	17.5	13.2	11.6	8.2	12.85	°C
Extractable Thermal power [kW]	2	2	2	2	2	2	2	2	2	2	2	2	2	kW
Extractable Thermal energy per month [kWh/mo]	1,447	1,307	1,447	1,400	1,447	1,400	1,447	1,447	1,400	1,447	1,400	1,447	1,419	kWh/mo
Extractable Thermal energy year [kWh/yr]													**17,033**	**kWh/yr**

Table 13: Example calculation for extracting heat from exhausted air from sewage networks (basic approach)

4.2 Waste Water Treatment Plants (WWTPs)

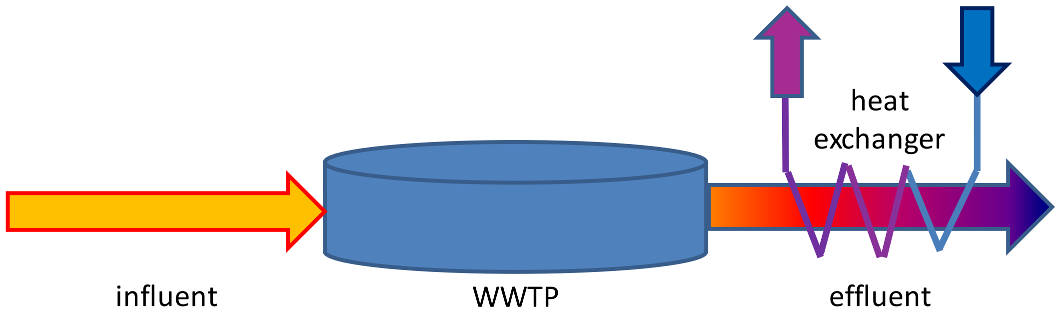

Figure 17: residual heat from WWTP effluent, principle

Related H/C demand: Space heating, temperature levels
Level of detail: area

There are nearly 40.000 WWTP facilities in the European Union, due to their function usually close to populated areas. Because of the internal treatment processes that add heat to the wastewater, WWTP effluent has an increased temperature compared to the surface water it releases into. This therefore makes it interesting as a source medium for heat pumps.

Required support maps

Map	Mapped variable [unit]	Data specification	Default maps
1	Sewage treatment plant locations		https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-5
2	Sewage treatment plant, number of p.e. treated annually [p.e./yr]	uwwLoadEnteringUWWTP: Number of person equivalents treated (note: actual use, not capacity). If not available, use 73% of uwwCapacity (based on known uwwCapacity and uwwLoadEnteringUWWTP in the UWWTP database)	EEA – Urban Waste Water Treatment Map: https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-5
3	Effluent of waste water treatment plants	Flow of the effluent of the waste water treatment plant	EEA – Waste water treatment plants http://www.eea.europa.eu/themes/water/water-pollution/uwwtd/interactive-maps/urban-waste-water-treatment-maps-1

Required data

Data	Variable [unit]	Data specification	Default values
1	T_{sew} = Sewage network temperature [°C]	Monthly average effluent temperature (12 values per year). The influent temperature of the receiving sewage treatment plant may be a good representative.	User required
2	Max cooling temperature [°C]	User specified, 2 °C will be the maximum realistic delta T.	2
3	Heat capacity [J/kg/K]	Heat capacity of sewage	4.2
4	Person equivalent [l/day]	EEA figure applicable to all of Europe, user may specify more precise data	200

Data processing

- To determine the flow that is leaving the waste water treatment plant, the load entering the plant can be considered. If there is data of the load entering the waste water treatment plant in Population Equivalent [PE =200 liters/day], this input should be used, otherwise a default value of 67% of the capacity of the treatment plant can be used.
- The flow (Q) is calculated in m^3/hour:
- Q = PE x 200 / 24 / 1000
- PE = Population Equivalent [1 PE = 200 liters/day]

Algorithm

$$E_{heat} = \rho \times Q \times C \times (T_{sew} - T_{cool}) \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

Application and validation / case study

Knowledge institute STOWA did research on the sewage system of the municipality Zwolle (NL) to indicate how much heat can be extracted from the local sewage system. They investigated mixed sewer systems, rainwater systems and the improved separated systems for residential, office and industrial areas.

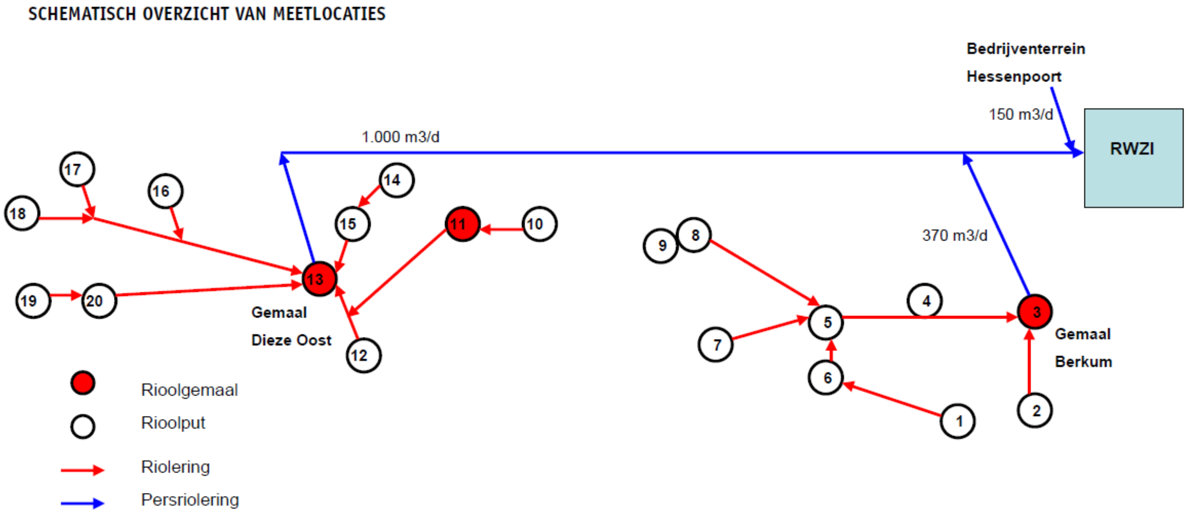

Figure 18: overview of measurement locations (Kluck, van den Bulk, Flameling, & de Brauw, 2011) (reproduced with kind permission from Stowa)

The temperatures in the same months do not differ a lot between themselves. During the months of the year, the temperatures of the sewage change and so does the potential of heat that can be extracted. Using the flow and temperatures of the effluent in the table of Table 15, the maximum heat that can be extracted (E_{heat}) when cooling the effluent to 2 °C can be calculated, by using the following algorithm:

$$E_{heat} = (T_{sw} - T_{min}) \times V \times 4200 / 3600 \qquad [kW]$$

Capacity of the waste water treatment plant	1000	PE	**OR**	Load entering the waste water treatment [ ] PE
Q = PE x 200 / 24 / 1000	5.58	m^3/hour		**Algorithm:** $E_{heat} = \rho \times Q \times C \times (T_{sew} - T_{cool}) \times t_{month} / (3.6 * 10^3)$ [kWh]
Minimum sewage temperature [T_{min}]	2	°C		

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
Teff = Average effluent temperature [°C]	5.7	5.7	8.2	11.6	13.2	17.5	20.9	20.9	17.5	13.2	11.6	8.2	12.85 °C
Temperature difference [K]	3.7	3.7	6.2	9.6	11.2	15.5	18.9	18.9	15.5	11.2	9.6	6.2	11 K
Extractable Thermal power [kW]	24	24	40	63	73	101	123	123	101	73	63	40	71 kW
Extractable Thermal energy per month [MWh/mo]	18	16	30	45	54	73	92	92	73	54	45	30	52 MWh/mo
Extractable Thermal energy year [MWh/yr]													**621 MWh/yr**

Table 14: Example calculation for extracting heat from sewage treatment plant effluent

Code	Naam meetlocatie	DWA (m3/dag)	Januari (°C)	Februari (°C)	Maart (°C)	April (°C)	Mei (°C)	Juni (°C)	Juli (°C)
BAR01	Buitenlucht		0,1	1,3	7,0	11,3	12,5	19,6	22,4
21GL0010	Grondwater		6,9	5,5	6,2	8,6	10,4	12,1	
MP09	Kantorenterrein Berkum	N.v.t.	5,0	4,7	6,2	9,1	11,1	14,2	16,2
MP10	Bedrijventerrein Vrolijkheid	10	7,3	6,5	7,8	10,0	11,7	14,6	17,7
MP11	Bedrijventerrein Vrolijkheid	10	5,7	5,2	7,0	10,3	12,4	16,1	19,5
MP12	Lombokstraat (bedrijventerrein)	420	10,0	9,1	10,8	13,8	15,2	18,2	20,8
MP13	Gemaal Dieze-Oost	1.000	7,5	7,5	9,6	12,6	14,4	17,2	20,3
MP14	Flatgebouw Pieter Steynstraat	10	6,9	6,6	9,6	13,6	15,2	18,5	21,4
MP15	Flatgebouw Pieter Steynstraat	10	6,4	6,7	7,9	12,9	14,5	18,2	21,1
MP16	Verzorgingstehuis	85	8,2	7,9	9,5	12,7	14,4	17,8	20,9
MP18	Flatgebouw Hornstraat	3	5,7	5,8	8,8	12,1	13,6		
MP19	Sporthal Stilo	Onbekend	5,4	4,7	6,8	10,2	12,0	15,3	17,8
MP20	Sporthal Stilo	Onbekend	6,1	6,0	8,0	11,1	13,3	16,4	18,9
	Industrie He ssenpoort *	150	-	5,7	7,1	9,8	11,6	14,7	17,5
	Aanvoer Berkum en D-O	1.400	-	6,4	8,2	11,2	12,8	16,2	19,1
	Influent rwzi	1.400	-	6,1	7,7	11,2	12,8	15,2	-
	Effluent rwzi	1.550	-	5,7	8,2	11,6	13,2	17,5	20,9
Gemiddeld			7,1	6,6	8,3	11,5	13,3	16,4	19,4

Table 15: Average monthly sewage temperatures (Kluck, van den Bulk, Flameling, & de Brauw, 2011) (reproduced with kind permission from Stowa)

5 Heat and cold from surface water bodies

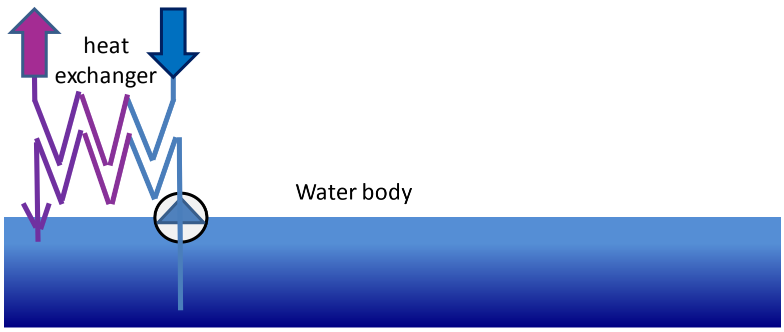

Figure 19: heat and cold from surface water, principle

There are various ways in which lakes, rivers and seas can be used for both heating and cooling. Cold can be extracted with a heat pump or by free cooling (with heat exchanger). Heat can be extracted with a heat pump. Because most cold is there in the heating season when most heat is needed and most heat is there in the cooling season when most cold is needed, heat and cold storage is necessary to make effective use of the cold and heat potential of water bodies.

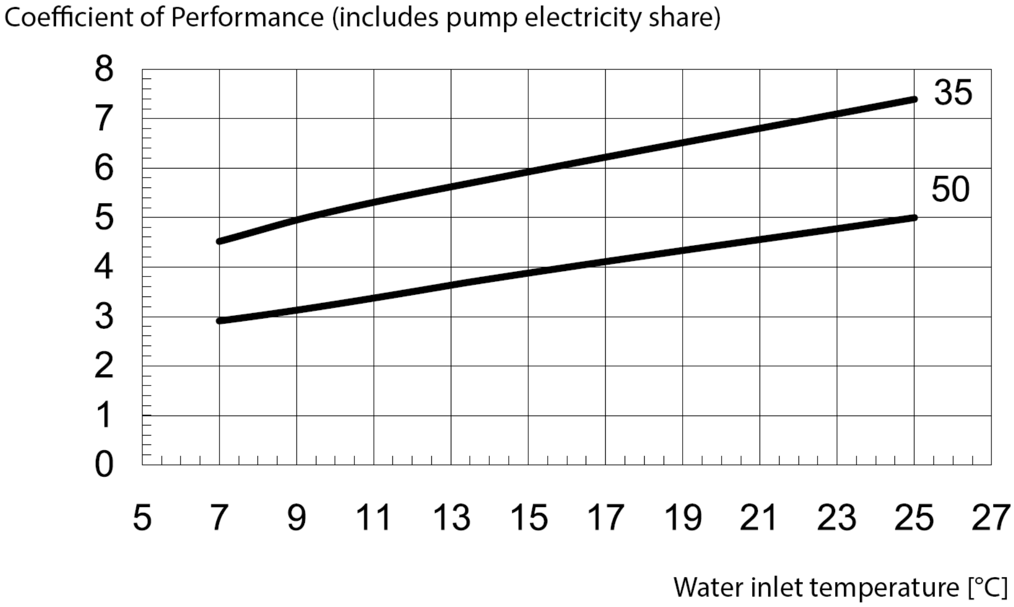

Figure 20: Heat pump COP using water of different temperatures as a source for different system temperatures. [for Dimplex WI 9ME water/water heat pump]. (Dimplex, 2008) (reproduced with kind permission from Dimplex GmbH)

Required support maps

Map	Mapped variable [unit]	Data specification	Default maps
1	Geometry [-]	Coast line	OpenStreetMap
2	T_{in} [°C]	Average monthly water temperature (12 values)	ftp://podaac-ftp.jpl.nasa.gov/allData/modis/L3/aqua/11um/v2014.0/4km/monthly/2017/ - the *_SST_*.nc files (named by day number range, so 20170012017031 means january), variable 'sst' Documentation: ftp://podaac-ftp.jpl.nasa.gov/allData/modis/L3/docs/modis_sst.html
3	specialisedZoneType [-]	EU water framework directive – aquatic habitat maps	http://water.discomap.eea.europa.eu/arcgis/services/Water/WFDSurfacewater_Dyna_WGS84/MapServer/WMSServer - WFD surface water - WFD surface water – Ecological status or potential of water bodies – Water body ecological status or potential – River / Lake / Transitional Water / Coastal water * Documentation: http://icm.eionet.europa.eu/schemas/dir200060ec/resources
3	Aquatic habitat type [-]	EU water framework directive – aquatic habitat maps	Updated datasets (these will be combined into the WFD2016 dataset later in 2018): cr.eionet.europa.eu (query – click for full url) – EU28 national datasets on protected areas (a few are restricted) Documentation: http://cdr.eionet.europa.eu/help/WFD/WFD_521_2016/GISGuidance/Clarification%20note%20protected%20areas.pdf

* The WFD dataset is unusual in that some water body data is projected as points, presumably equating monitoring stations. These points would have to be associated with topography, i.e. a check if there are points on the WFD map placed inside the surface water body geometry, as defined by the topographical source.

Required data

Data	Variable [unit]	Data specification	Default values
1	T_{aq} [°C]	Average monthly water temperature	(map)
2	T_{max} [°C]	Maximum absolute temperature (based on habitat type)	(map)
3	K_{max}	Maximum temperature difference (based on habitat type)	(map)
4	Q [m^3/h]	Water flow of installation (average)	100
5	ρ [kg/m^3]	Medium density	1000
6	C [kJ/kg·K]	Specific heat of medium	4.2
7	t_{month} [h]	Number of hours in the month considered	730

The maximum heat or cold (E in kWh) that can be extracted from a water body depends on the temperature difference (K) and the volume flow of the water (Q in m^3/hour):

$$E = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

The maximum flow is different for the different types of water bodies. For seas there is no limit for the volume of water, whereas for rivers it depends on the flow rate. For lakes there is almost no flow, therefore the effective volume of the lake determines the thermal potential.

5.1 General environmental restrictions concerning temperatures

As river water cooling effectively amounts to warming up the body of water used, environmental restrictions apply (Fremouw M. (., 2015). EU directive 2006/44/EC (*"on the quality of fresh waters needing protection or improvement in order to support fish life"*) provides maximum downstream temperature increases for three groups of aquatic species:

1. +1.5K max or 21.5 °C total for salmonid habitats
2. +3K max or 28°C total for cyprinid habitats
3. +2K max or 25 °C total for shellfish habitats.

Furthermore, the temperature delta at the exhaust itself may be no more than +7K, or 30°C total. According to Deltares, the maximum cooling of the water is -6K and the maximum warming is +3K (de Boer, Scholten, Boderie, & Pothof, 2015).

Determining the maximum potential in an area therefore requires answering three basic questions:

1. Geometry: What are the type and dimensions of the body of water under consideration?
    a. Lakes: heat capacity plays a role, therefore the surface size needs to be known, whereas for rivers the flow is the most important (for example the monthly average).
    b. Seas, rivers and other very large bodies of water: because of size and/or flow their thermal capacity is enormous, therefore only the nozzle exhaust temperature is important.

2. Is the body of water part of a habitat for one of the aquatic species defined in the EU water directive? This will define the maximum temperature for an exhaust nozzle, as well as the maximum that body of water may be warmed up. This could be one of these categories as definied in the attribute 'specialisedZoneType' in the WFD dataset:
    a. 'freshwaterFishDesignatedWater' (corresponding to cyprinids, group 2)
    b. 'shellfishDesignatedWater' (corresponding to group 3)
    c. Salmonid designated waters (corresponding to group 1) do not appear to be reported in the WFD2010 map, therefore it is recommended that the user provides this data themselves. Salmon spawn inland in a number of European rivers that flow into the Atlantic Ocean, North Sea and Baltic Sea.

3. What is the natural temperature for the body of water during a year? This does not only provide the offset against which the cooling capacity of an individual intake can be calculated, but is also important in calculating the maximum allowed capacity according to the EU water directive.

When using heat pumps for heating and water bodies are the source for the heat pump, the temperature of the water bodies decreases. According to Deltares, the maximum cooling of water bodies is -6K (K_{min}) and there is a limit for freezing, set to 2^{o}C (T_{min}) (de Boer, Scholten, Boderie, & Pothof, 2015). The water temperature for those months considered part of the charging period needs to be known (T_{aq}) to indicate by how many degrees it can be cooled down (K).

This temperature can be determined as follows:

$$K = (-K_{min} + (-T_{min})+(T_{aq} + K_{min}))$$

5.2 Determining the flow rate

Rivers

If no measured data is provided, the average flow rate of the river in m^3/h (Q) can be approximated by multiplying the average depth (d) and width (w) of the river in meters by the average speed (v) in meters per hour:

$$Q = d \times w \times v \qquad [m^3/h]$$

Lakes

For lakes, the volume of water that can be cooled can be estimated by considering the surface of the water (A) in m^2, multiplied by the "effective" depth (d) in meters. The default value for the depth can be set at 2 meters, although this will vary greatly so it should be user configurable.
It should be noted that lakes with very large in- and outflow will behave more like rivers in regard to the thermal balance, and therefore have significantly higher heating/cooling capacity. For this section, 'lakes' refer to water bodies with relatively little (or no) in- and outflow compared to their surface area.

The volume of water is divided by the hours of the cooling season. Because the length of the cooling season depends on climate and building, the amount of hours (h) is set at a default value of 4392 hours (the months April till September).

$$Q = A \times d / h \qquad [m^3/h]$$

For those months belonging to the 'active' season, an estimate can now be made how much heat can be extracted from the water body with a heat pump:

$$E_{heat} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

Application and validation / case study

In the district Duindorp in The Hague (NL), seawater from the harbour of Vlissingen is used as a source for heat pumps, providing 780 apartments with heat for space heating and domestic hot water. The heat capacity of the sea is essentially infinite, but the temperature of the seawater changes. During the cooling season the seawater is used for (high temperature) 'free cooling' mode (i.e. directly with a heat exchanger, see Figure 21).

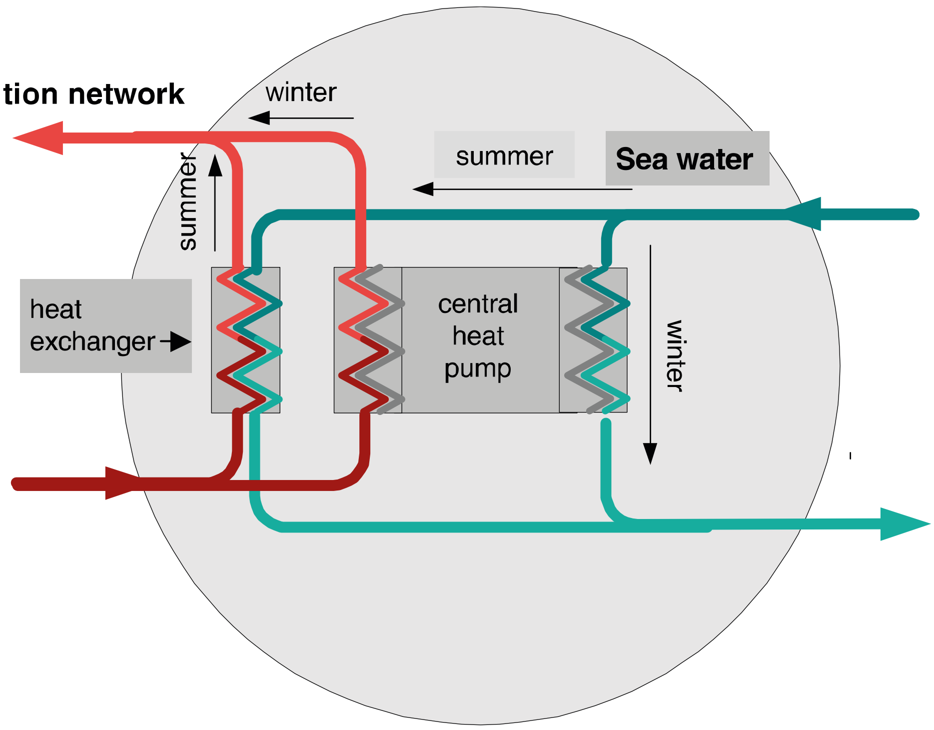

Figure 21: seawater heating and cooling using a heat pump (Deerns, 2016) (reproduced with kind permission from Deerns B.V.)

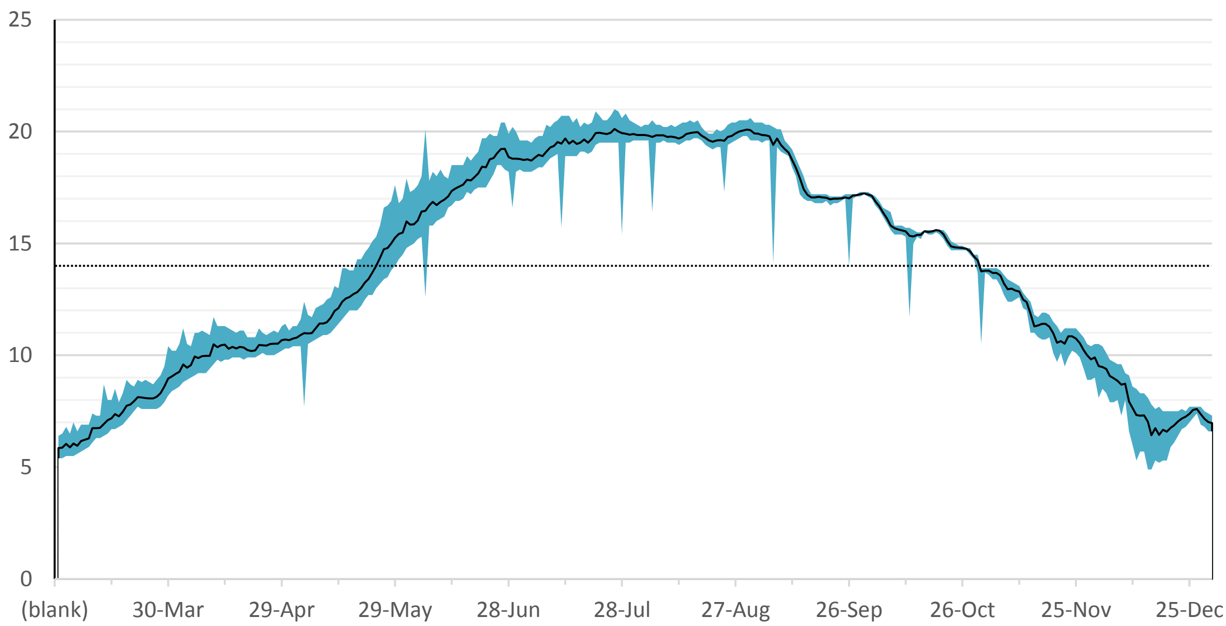

Figure 22: water temperature bandwidth at Hoek van Holland (based on data from Rijkswaterstaat Waterinfo (Rijkswaterstaat, 2018))

Figure 22 is an example of the water temperature fluctuations throughout a year in the Nieuwe Waterweg, a canal stretching from Hoek van Holland to Rotterdam (NL) as recorded by Rijkswaterstaat. The temperature is recorded every 10 minutes, with a 0.1 degree accuracy. In the graph above, for each day the average temperature was determined, represented by the continuous

black line. The blue area is the bandwidth between the minimum and maximum temperatures recorded on that day. The temperature spikes are probably measurement errors (these are single 10 minute values that significantly deviate from their next day neighbours). Furthermore, data for January and February was not available.
The year round average is 14.0 °C, as represented by the dotted black line. From a demand perspective, this shows that both heat and cold supply potential are available from surface water, but mostly off-season. In the summer period (June-July-August) there is almost no power for free cooling (water temperature is over 20°C). A reversible heat pump can be used to cool in this period.

In case of Duindorp, which has its seawater extraction point in the harbour of Scheveningen (with slightly lower summer temperatures), the local temperature can be used to calculate how much seawater is needed for the amount of heat required. When there is not enough heat available for extraction, the flow can be increased. The next estimation is made with the temperatures of the seawater in Scheveningen harbour.

Minimum seawater temperature [T_{min}]*	2	°C	**Algorithm:** $E_{heat} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3)$ [kWh]
Seawater flow (Q)	100	m^3/h	$K = (-K_{min} + (-T_{min}) + (T_{aq} + K_{min}))$ $K_{min} = -6K$

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average sea water temperature [°C]	7.0	6.0	6.5	8.0	12.0	14.5	17.0	18.0	17.0	14.5	11.0	8.5	11.67 °C
Temperature difference [K]	5.0	4.0	4.5	6.0	10.0	12.5	15.0	16.0	15.0	12.5	9.0	6.5	10 K
Extractable Thermal power [kW]	583	467	525	700	1,167	1,458	1,750	1,867	1,750	1,458	1,050	758	1127.78 kW
Extractable Thermal energy per month [MWh/mo]	434	314	391	504	868	1,050	1,302	1,389	1,260	1,085	756	564	826 MWh/mo
Extractable Thermal energy year [MWh/yr]													**9,916 MWh/yr**

Table 16: Example calculation for extracting heat from seawater with a heat pump

5.3 Using water bodies for cooling

Extracting cold from seawater (coast lines) with a heat pump

Using water bodies for cooling results in a water temperature increase. For seawater, the only limit is the temperature delta at the exhaust itself. This is not allowed to be no more than +7K (K_{max}), or 30°C (T_{max}) total. The temperature of the water body per month (T_{aq}) is also required to determine how much of a temperature increase (K) of the seawater is allowed:

$$K = \text{IF } (T_{max} - T_{aq}) > K_{max} \text{ THEN } K_{max} \text{ ELSE } (T_{max} - T_{aq})$$

The cold that can be extracted from water bodies is:

$$E_{cool} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3) \quad [kWh]$$

Because there is almost no upper limit for the flow, the cooling capacity can be increased by increasing the flow.

Maximum outlet temperature (T_{max})*	30	°C
Seawater flow (V)	100	m^3/h
Maximum temperature lift (K_{max})*	7	K

Algorithm: $E_{cooling} = K \times Q \times 4200 \times t_{month} / (3.6 *10^3)$ [kWh]

$K = IF\ (T_{max} - T_{aq}) > K_{max}\ THEN\ K_{max}\ ELSE\ (T_{max} - T_a)$

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average sea water temperature [°C]	7.0	6.0	6.5	8.0	12.0	14.5	17.0	18.0	17.0	14.5	11.0	8.5	11.67 °C
Temperature difference [K]	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7 K
Extractable Thermal power [kW]	-817	-817	-817	-817	-817	-817	-817	-817	-817	-817	-817	-817	-816.67 kW
Extractable Thermal energy per month [MWh/mo]	-608	-549	-608	-588	-608	-588	-608	-608	-588	-608	-588	-608	-596 MWh/mo
Extractable Thermal energy year [MWh/yr]													**-7,154 MWh/yr**

Table 17: Example calculation for extracting cold from seawater with a heat pump

Extracting cold from rivers and lakes with a heat pump

When using water bodies like rivers and lakes for cooling, the water temperature increases. As mentioned before, there are some restrictions to both the maximum temperature of the water (T_{max}) and the temperature lift (K_{max}) compared to the natural situation, based on the aquatic species.

It is therefore important to know which aquatic species are living in the water to determine the maximum temperature (T_{max}) and the maximum lift (K_{max}).

$$K = IF\ (T_{max} - T_{aq}) > K_{max}\ THEN\ K_{max}\ ELSE\ (T_{max} - T_{aq})$$

The cold that can be extracted from the river or lake is calculated with:

$$E_{cool} = K \times V \times 4200 \times t_{month} / (3.6 *10^3) \quad [kWh]$$

The average flow rate for rivers and lakes is estimated in the same way as mentioned before:

For rivers: $V = d \times w \times v$ $[m^3/h]$

For lakes: $V = A \times d / h$ $[m^3/h]$

The following calculation is based on temperature levels of the river Maas in Rotterdam. The flow is set on 100 m^3/h because no exact figures were available.

Water flow (Q)*	100	m^3/h
Maximum outlet temperature (T_{maxout})**	25	°C
Maximal temperature lift (K_{max})***	2	K

Algorithm: $E_{cooling} = K \times Q \times 4200 \times t_{month} / (3.6 *10^3)$ [kWh]

$K = IF\ (T_{maxout} - T_{aq} > K_{max}\ THEN\ K_{max}\ ELSE\ T_{maxout} - T_{aq})$

$IF\ (T_{aq} > T_{maxin}\ THEN\ K = 0\ ELSE\ K = -K)$

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average river water temperature [°C]	4.5	6.0	8.0	12.0	17.0	20.0	22.0	23.0	19.0	14.0	10.0	6.5	13.50 °C
Temperature difference [K]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2 K
Extractable Thermal power [kW]	-233	-233	-233	-233	-233	-233	-233	-233	-233	-233	-233	-233	-233.33 kW
Extractable Thermal energy per month [MWh/mo]	-174	-157	-174	-168	-174	-168	-174	-174	-168	-174	-168	-174	-170 MWh/mo
Extractable Thermal energy year [MWh/yr]													**-2,044 MWh/yr**

Table 18: Example calculation for extracting cold from the Maas river with a heat pump

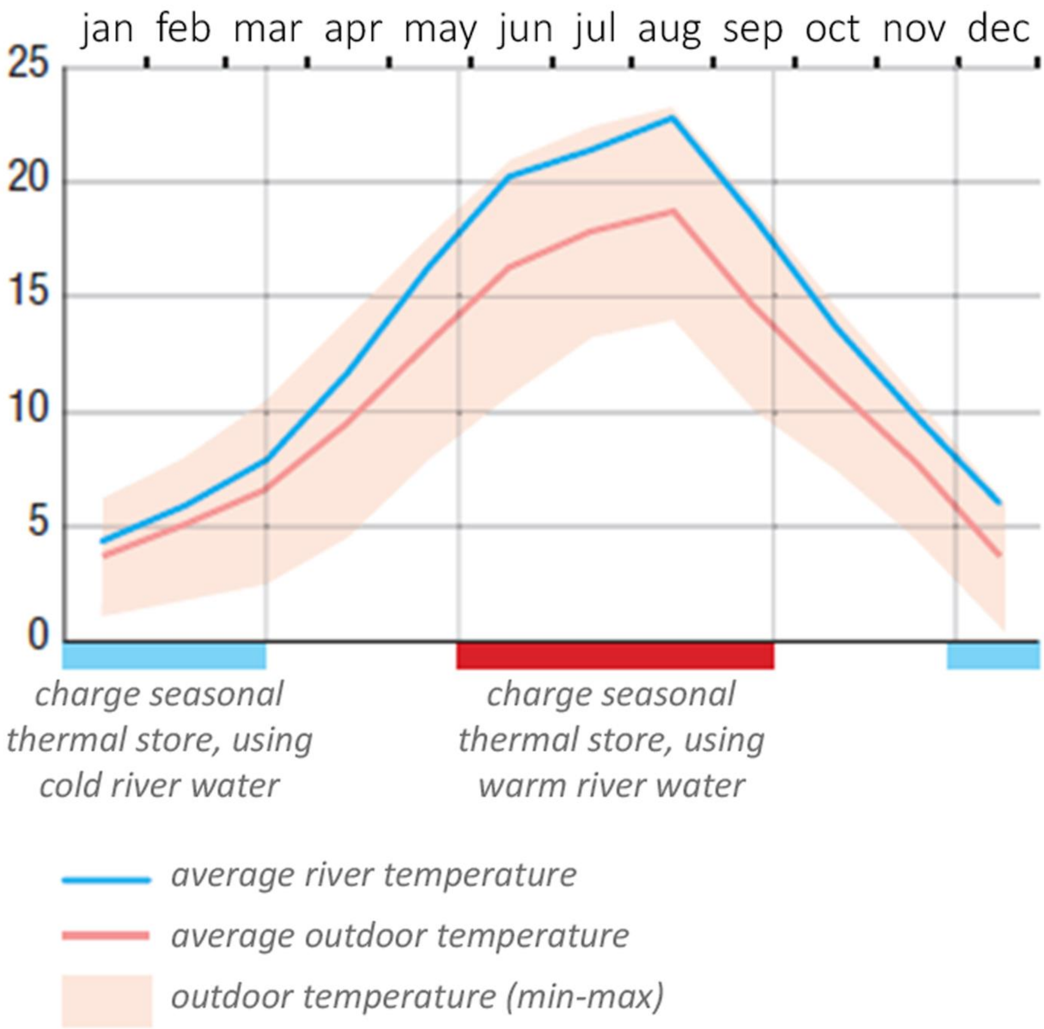

Figure 23: river water heating and cooling at the Maastoren in Rotterdam (NL) (Schwandt Infographic (commissioned by Techniplan), 2009) (reproduced with kind permission from Techniplan B.V.)

Extracting cold from rivers and lakes by free cooling

These water bodies can also be used for free cooling (without a heat pump). To estimate how much cooling is provided by the water bodies the same restrictions for the temperature of the water can be used, that apply to cooling with a heat pump. The maximum temperature of the water inlet ($T_{max,in}$) can be set to 17°C, based on the fact that there is almost no cooling capacity left for high-temperature-cooling of buildings when the temperature is over 17°C. This will be in the months when there is the greatest need for cooling. For this reason free cooling is often combined with heat and cold storage (BTES or ATES).

The maximum outlet temperature for the free cooling of buildings will not exceed 25°C and for certain aquatic species it is not allowed to have a temperature that is above 21,5 °C. For this reason the maximum outlet temperature (T_{maxout}) is set to 21 °C. The maximum cooling power will be dependent on the difference between the water temperature (T_{aq}) and the outlet temperature (K) with a maximum increase of 1,5, 2 or 3K (K_{max}), depending on the group aquatic species.

$$K = IF\ (T_{max,in} - T_a) > K_{max}\ THEN\ K_{max}\ ELSE\ (T_{max,in} - T_{aq})$$
$$K = 0\ IF\ T_{aq} > 17^oC$$

The Flow (Q) for rivers and lakes is determined as mentioned before.

The cold that can be extracted from the river or lake by free cooling is calculated with:

$$E_{cooling} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

Water flow (Q)*	100	m^3/h
Maximum inlet temperature (T_{maxin})**	18	°C
Maximum outlet temperature (T_{maxout})***	21	°C
Maximum temperature lift (K_{max})****	2	K

Algorithm: $E_{cooling}$ = K x Q x 4200 x t_{month} / (3.6 *10^3) [kWh]
K = IF (T_{maxin} - T_{aq}) > K_{max} THEN K_{max} ELSE (T_{max} - T_{aq})
IF (T_{aq} > T_{maxin} THEN K = 0 ELSE K = -K)

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average river water temperature [°C]	4.5	6.0	8.0	12.0	17.0	20.0	22.0	23.0	19.0	14.0	10.0	6.5	13.50 °C
Temperature difference [K]	2.0	2.0	2.0	2.0	2.0	1.0	-1.0	-2.0	2.0	2.0	2.0	2.0	1 K
Usable temperatures < max	2.0	2.0	2.0	2.0	2.0	0.0	0.0	0.0	0.0	2.0	2.0	2.0	
Extractable thermal power [kW]	-233	-233	-233	-233	-233	0	0	0	0	-233	-233	-233	-155.56 kW
Extractable thermal energy per month [MWh/mo]	-174	-157	-174	-168	-174	0	0	0	0	-174	-168	-174	-113 MWh/mo
Extractable thermal energy year [MWh/yr]													**-1,361 MWh/yr**

Table 19: Example calculation for extracting cold from rivers and lakes by free cooling

Extracting cold from seawater by free cooling

For seawater there is no limit for the flow. The maximum outlet temperature for seawater is 30°C and the maximum lift is 7K (K_{max}). For free cooling of buildings, the outlet temperature of 30°C is not reached. The only limit will be the maximum temperature lift of 7K and the temperature of the seawater when it is over 17°C.

$$K = 0\ IF\ T_a > 17^oC$$

$$K = IF\ (T_{max} - T_a) > K_{max}\ THEN\ K_{max}\ ELSE\ (T_{max} - T_a)$$

$$E_{cool} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

Maximum inlet temperature (T_{max})*	18	°C
Seawater flow (V)	100	m^3/h
Maximum temperature lift (Kmax)**	7	K

Algorithm: $E_{cooling}$ = K x Q x 4200 x t_{month} / (3.6 *10^3) [kWh]
K = IF (T_{max} - T_{aq}) > K_{max} THEN K_{max} ELSE (T_{max} - T_{aq})

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average sea water temperature [°C]	7.0	6.0	6.5	8.0	12.0	14.5	17.0	18.0	17.0	14.5	11.0	8.5	11.67 °C
Temperature difference [K]	7.0	7.0	7.0	7.0	6.0	3.5	1.0	0.0	1.0	3.5	7.0	7.0	5 K
Extractable thermal power [kW]	-817	-817	-817	-817	-700	-408	-117	0	-117	-408	-817	-817	-554.17 kW
Extractable thermal energy per month [MWh/mo]	-608	-549	-608	-588	-521	-294	-87	0	-84	-304	-588	-608	-403 MWh/mo
Extractable thermal energy year [MWh/yr]													**-4,837 MWh/yr**

Table 20: Example calculation for extracting cold from sea water by free cooling

5.4 Using water bodies for heating

Using water bodies for heating with a heat pump

When water bodies are used for heating with a heat pump the water body temperature cannot be decreased below 1oC because of freezing (which, apart from environmental consequences would also block the outlet). There may also be restrictions for the maximum temperature drop Kmax). For the potential calculation these are set to -6K.

The heat that can be extracted from water bodies (Eheat) with a heat pump is:

$$E_{heat} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3) \qquad [kWh]$$

Extracting heat from seawater (coast lines) with a heat pump

Similar to air sourced heat pumps, the heat sink used, the sea, has a very large capacity. The limitation in this case is the maximum temperature drop (K_{max}).

The temperature difference (K) will be:

$$K = (-K_{max} + (-T_{min}) + (Taq + Kmin))$$

Minimum seawater temperature [T_{min}]*	2	°C	**Algorithm:** $E_{heat} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3)$ [kWh]
Seawater flow (Q)	100	m^3/h	$K = (-K_{max} + (-T_{min}) + (T_{aq} + K_{min}))$ K_{max} = -6K

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average sea water temperature [°C]	7.0	6.0	6.5	8.0	12.0	14.5	17.0	18.0	17.0	14.5	11.0	8.5	11.67 °C
Temperature difference [K]	5.0	4.0	4.5	6.0	10.0	12.5	15.0	16.0	15.0	12.5	9.0	6.5	10 K
Extractable thermal power [kW]	583	467	525	700	1,167	1,458	1,750	1,867	1,750	1,458	1,050	758	1127.78 kW
Extractable thermal energy per month [MWh/mo]	434	314	391	504	868	1,050	1,302	1,389	1,260	1,085	756	564	826 MWh/mo
Extractable thermal energy year [MWh/yr]													**9,916 MWh/yr**

Table 21: Example calculation for extracting heat from sea water with a heat pump

Extracting heat from rivers with a heat pump

When there is no information about the water flow you may use the average speed (v) in meters/second, multiplied by the average depth (d) and width (w) of the river in meters:

$$Q_{river} = d \times w \times v \qquad [m^3/h]$$

Then there is a limitation for the maximum temperature drop (K_{max}) of the river water which should not exceed 6K (de Boer, Scholten, Boderie, & Pothof, 2015), and to be sure that the water wil not freeze, 2°C should be used as a minimum temperature (T_{min}).

The temperature difference (K) will be:

$$K = IF\ (T_{aq} - T_{min}) > K_{max}\ THEN\ K_{max}\ ELSE\ (T_{aq} - T_{min})$$

Water flow (Q)*	100	m³/h
Maximum temperature drop (K_{max})**	6	K
Minimum river water temperature [T_{min}]*	2	°C

Algorithm: $E_{heat} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3)$ [kWh]

$K = IF\ (T_{aq} - T_{min}) > K_{max}\ THEN\ K_{max}\ ELSE\ (T_{aq} - T_{min})$

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average river water temperature [°C]	4.5	6.0	8.0	12.0	17.0	20.0	22.0	23.0	19.0	14.0	10.0	6.5	13.50 °C
Temperature difference [K]	2.5	4.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	4.5	5 K
Extractable thermal power [kW]	292	467	700	700	700	700	700	700	700	700	700	525	631.94 kW
Extractable thermal energy per month [MWh/mo]	217	314	521	504	521	504	521	521	504	521	504	391	462 MWh/mo
Extractable thermal energy year [MWh/yr]													**5,541 MWh/yr**

Table 22: Example calculation for extracting cold from sea water by free cooling

Extracting heat from lakes with a heat pump

For lakes the same temperature limitations as applied as for rivers. Because there is almost no flow in a lake, the volume of water that can be cooled can be estimated by considering the surface of the water (A) in m², multiplied by the "effective" depth (d) in meters. The default value for the depth can be set at 2 meters, although this will vary greatly. The volume of water is divided by the hours of the heating season. Because the length of the heating season depends on climate and building, the amount of hours (h) is set at a default value of 4392 hours (the months October til March).

$$Q = A \times d / h \qquad [m^3/h]$$

It should be noted that lakes with very large in- and outflow will behave more like rivers in regard to the thermal balance, and therefore more heating/cooling capacity. For this section, 'lakes' refer to water bodies with relatively little (or no) in- and outflow compared to their surface area.
For those months belonging to the 'active' season, an estimate can now be made how much heat can be extracted from the water body with a heat pump:

Water flow (Q)*	100	m³/h
Maximum temperature drop (K_{max})**	6	K
Minimum river water temperature [T_{min}]*	2	°C

Algorithm: $E_{heat} = K \times Q \times 4200 \times t_{month} / (3.6 * 10^3)$ [kWh]

$K = IF\ (T_{aq} - T_{min}) > K_{max}\ THEN\ K_{max}\ ELSE\ (T_{aq} - T_{min})$

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	Average or total
T_{aq} = Average river water temperature [°C]	4.5	6.0	8.0	12.0	17.0	20.0	22.0	23.0	19.0	14.0	10.0	6.5	13.50 °C
Temperature difference [K]	2.5	4.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	4.5	5 K
Extractable thermal power [kW]	292	467	700	700	700	700	700	700	700	700	700	525	631.94 kW
Extractable thermal energy per month [MWh/mo]	217	314	521	504	521	504	521	521	504	521	504	391	462 MWh/mo
Extractable thermal energy year [MWh/yr]													**5,541 MWh/yr**

Table 23: Example calculation for extracting cold from sea water by free cooling

6 Technical potentials

As mentioned in the introduction, a distinction is made between theoretical and technical potentials. This distinction is based on system boundaries: especially with residual heat sources, heat pumps are usually part of the system that produces the heat and are therefore independent of the HC system that the user can design within the PLANHEAT tool.

Because showing theoretical maps to the user may result in misinterpretation of the supply potentials and overestimation of possibilities (because of Carnot efficiency and thermal storage requirements / limitations), a few simple calculation steps have been developed to approach a more realistic potential. This is particularly important for those unconventional sources that closely follow seasonal temperatures, and where the realistically available energy potentials are strongly dependent on the incorporation of thermal storage.

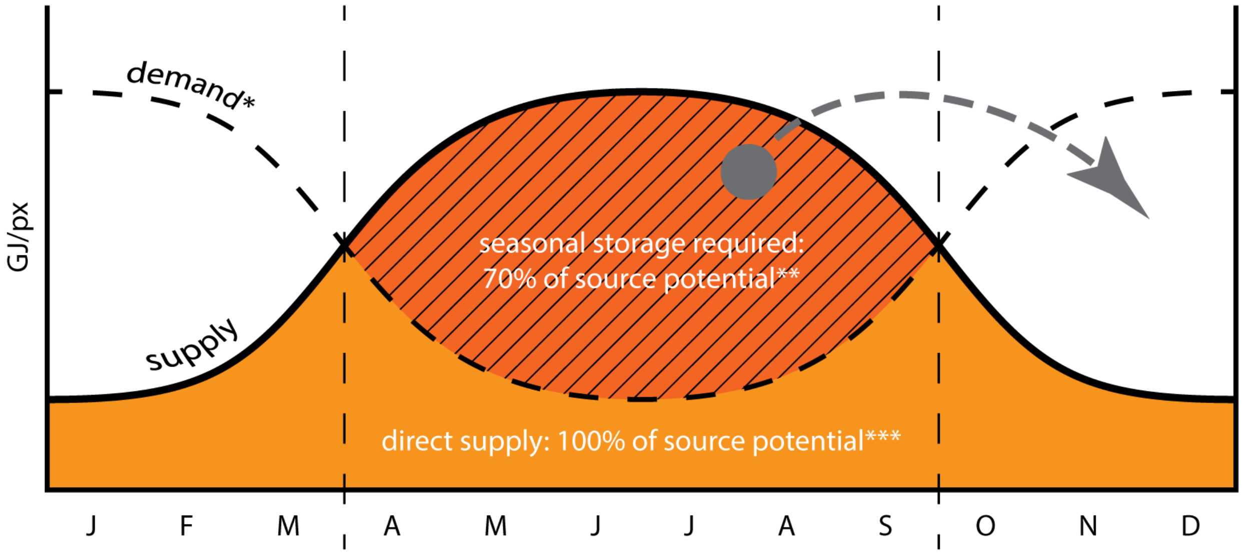

Figure 24: calculation method for intermittent low temperature thermal sources: direct vs stored energy

Figure 24 illustrates this issue for an intermittent low temperature heat source related to an inverse demand pattern.

Although a small share of the available heat supply can be used even in summer (due to a constant DHW demand throughout the year), the majority of heat demand will occur in the off season. Therefore, without a thermal store, only the part marked ‘direct supply’ will be used, the rest will be lost. Providing a storage facility (for example aquifer thermal storage in a suitable underground layer, common in the Netherlands) will allow the excess heat in summer to additionally be used in winter (minus thermal losses over time).

Even though water basins can also provide large scale seasonal storage (example: Vojens Fjernvarme in Denmark (Vojens Fjernvarme a.m.b.a., 2018)), these only tend to be economically feasible if the maximum temperature, and therefore the thermal energy charge, are as high as possible (for example up to 95 °C). As the output temperatures of the unconventional sources are significantly lower, the focus is therefore on Aquifer Thermal Energy Storage (ATES), Borehole

Thermal Energy Storage (BTES) and Cavern Thermal Energy Storage (CTES), which make use of the underground. Although ATES is cheaper than BTES for the same storage capacity (because only two wells need to be drilled, an 'open' system), a suitable aquifer has to be present, whereas BTES has few limitations. CTES is highly situational and requires the presence of underground cavities.
Fellow Horizon 2020 project ESTMAP provides information on the presence of ATES suitable aquifers, including this layer in the mapping module would facilitate planning (ESTMAP, 2018).

Map	Mapped variable [unit]	Data specification	Default maps
1	Presence of a suitable underground layer for ATES	Field 'reservoir_type_cd'(where the value equals 'AQUIFER')	http://www.estmap.eu/database.html

This temporal discrepancy of intermittent sources requires attention in the simulation module as well. If no thermal store is modelled, the share of these unconventional sources in the heat supply over a year will appear to be severely limited (represented by the light orange area at the bottom of Figure 24), even though their potential may be significantly higher if storage had been included.

To take the temporal fluctuation of intermittent heat sources into consideration in the simulation module of Planheat tool, the variation of the heat available as calculated by the algorithms provided will be taken into account using an adequate temporal resolution (from 1 hour to 1 month) depending on the amplitude of fluctuations over time.
Moreover the possibility to consider storage at building or district level provides the tool with the flexibility that is needed to best exploit these type of sources.

Because subsurface thermal capacities are not always available (and more capacity would effectively simply mean increasing the area used), for this technical potential seasonal storage has been simplified to 'available' or not, with a default seasonal thermal efficiency represented by a percentage.

The mapping module approach to approximate technical potential towards the user would consist of a small number of additional calculation steps and one extra data source: the local HDH / CDH per month (which NowCast is able to provide).
As mentioned earlier the mapping module considers annual potentials, however for fluctuating sources twelve monthly steps need to be calculated in order to arrive at the theoretical potential. The HDH (or CDH for cold sources) needs to be considered per month.

In order to determine the space heating season (in the figure above this translates to the exact locations of the vertical boundaries that define October-March as the heating season), the number of HDHs should be above 0 hours per month. For any month below this threshold, the potentially available heat will be reduced to 80% in order to approximate the combination of direct DHW demand and thermal storage losses.

For cold sources the same process is used, replacing HDH with CDH and omitting the DHW base load by using a 70% multiplier.
In both cases, if the thermal storage availability check fails, the supply in the off season will be either 10% in case of heat (representing the DHW load), and 0% in case of cold (this will be more than 0% in winter if non-residential cold applications are considered, however for PLANHEAT only housing and offices are factored in).

More investigation about how to integrate thermal storage in the PLANHEAT tool will be performed for the development of PLANNING and SIMULATION Module, also taking into account issues presented in this paragraph.
Nevertheless, as for mapping the solar source, the aim of the mapping module is to evaluate a potential at yearly basis that obviously cannot be 100% exploited (effectiveness of exploitation will be taken into account in simulation and planning module)

Here in the following a procedure to more effectively map the technical potential is proposed to be discussed and potentially included in Mapping Module (also considering future developments of Planning and Simulation tool in order to avoid overlap calculation).

Technical potential of heating sources

The following steps are defined for heating sources:

1. Is seasonal thermal storage available? i.e. ATES / BTES, as described above. Default value is 'yes'.
2. Which months belong to the heating season? The default setting could be from October to March, the exact length can be determined by finding the months with >0 HDH using NowCast.
3. The theoretical potential of those months belonging to the heating season are added up. These would not need seasonal storage and are therefore considered 100% usable.
4. The off-season months are also added up.
    a. If seasonal storage is available, 80% is considered directly and indirectly usable.
    b. If seasonal storage is not available, only 20%.
5. Adding up the on-season and off-season provides the technical potential of the unconventional source for heating.

Technical potential of cooling sources

The following steps are defined for cooling sources:

0. Is seasonal thermal storage available? i.e. ATES / BTES, as described above. Default value is 'yes'.

1. Which months belong to the cooling season? The default setting could be from May to September, the exact length can be determined by finding the months with >0 CDH using NowCast.

2. The theoretical potential of those months belonging to the cooling season are added up. These would not need seasonal storage and are therefore considered 100% usable.
3. The off-season months are also added up.
    a. If seasonal storage is available, 70% is considered indirectly usable.
    b. If seasonal storage is not available, 0% is considered indirectly usable.
4. Adding up the on-season and off-season provides the technical potential of the unconventional source for cooling.

These steps are defined in such a way that thermal demand does not need to be known on beforehand, therefore no output from the CMM or DMM would be required as input.

One important aspect to keep in mind is that PLANHEAT mainly caters to the residential sector on the demand side. If commercial and industrial activities are also included, there may be sufficient demand to still apply heat in summer (for example swimming pools in Northern Europe) and cold in winter (for example refrigeration and datacenters). Step 4 in both lists would in that case additionally include a check for local commercial and industrial cooling demand, which would translate to 100% of potential being considered usable.

It should be noted that this section is about determining *potential*: 'usable' does not necessarily mean the available thermal energy *will* be used, just that it is not already partially or fully discarded, because of either a complete lack of direct demand or seasonal storage availability.
In short: this is about determining which thermal energy could never be used.

Apart from the temporal aspects noted above, extracting energy from unconventional sources will also require some energy (mostly electricity), for example for fans for moving air, or pumps for moving liquid.
Furthermore, in most cases a heat pump will be involved in order to raise (or lower) the source temperature to the operating temperature. The amount of electricity for these depends on the temperature difference between these two. If both these temperatures are known, the seasonal COP of the heat pump can be determined by using the diagrams in Figure 6 and Figure 20. Both these aspects are considered part of the planning and simulation modules though.

7 Conclusions and recommendations

This document represents PLANHEAT deliverable D2.6, and documents the outcomes of a study into 'unconventional' sources, labeled as such within the project in order to distinguish them from the more widely known HC sources of solar thermal, biomass and geothermal heat (labeled 'conventional' sources and represented in deliverable D2.5), and industrial waste heat and cold (represented in deliverable D2.7).

LowEx sources

Unconventional sources, more commonly referred to as Low Exergy or LowEx sources (Schmidt & Kallert, 2018), are expected to find increasing importance in future HC systems.
Availability of conventional and industrial sources, now and particularly in the future, may not always be sufficient to fulfill local demand. In some cases there may be competition for surface use (solar thermal) or limited local availability (biomass, especially in urbanized regions), in other cases the original source of the residual heat may be fossil fuel based (industry) and therefore future availability may be less than expected.
Furthermore, a significant portion of the existing building stock can be upgraded to directly use low temperature heat and cold, and new buildings are often already suited for this due to efficiency requirements from the EPBD.

Unconventional sources are essentially the 'everything else' category, however commonalities were found, which allowed for a common approach to be formulated. This should make it possible to in the future apply these calculation methods to other sources as well.

Application within PLANHEAT

Although this deliverable is part of WP2 and primarily intended for the mapping module, the algorithms presented have been developed with the full PLANHEAT tool in mind. These should therefore also be usable in the planning and simulation modules, by using input data with a higher temporal resolution (i.e. hourly instead of monthly or yearly).

Because the end goal is a user friendly software tool both from an interface and software / input data requirement perspective, an ongoing discussion in many different areas is the level of complexity. More variables tailored to the location for example could mean more accurate results, but also requires more input and expertise from the user.
This applies to (temporal) calculation steps and higher spatial resolutions as well, which would have an effect on calculation time and required processing power, further multiplied by the number of supply potentials the user would like to study for their (municipal) area of interest.

An important aspect to be highlighted is the boundary crossing nature of these low temperature sources within the PLANHEAT tool, particularly to consider where to include a definition of H&C and storage technologies to evaluate an effective potential of these sources.
On one hand the user should not be asked to make technology choices in the mapping module (this is what the planning module is for), on the other hand some technologies (like heat pumps) are implied, and in other cases realistic potential may be affected by the presence or absence of certain technologies (for example seasonal thermal storage). Feedback towards the user on which percentage of theoretical potential is used, and which design change (for example introducing a seasonal thermal storage facility) would improve this, would be beneficial and approach has been here presented.
PLANHEAT integrated Tool development is currently ongoing (particularly for what it concerns Planning and simulation tool development): the exact implementation of these aspects will depend on considerations on the tool as a whole.

Due to the diverse nature of the components of the PLANHEAT tool and the parallel development of all the elements in them, this completed document should therefore be considered the state of the art of discussions and technical possibilities for unconventional sources at M21, the exact implementation of these algorithms will have to be carried out together with the partners responsible for the respective PLANHEAT software components.

Finally, experiences from, and interactions with both the PLANHEAT Validation Cities and the Training Cities that sign on during the project, will undoubtedly result in further refinements, which the authors warmly welcome. These will both find their way into the tool itself and the training materials, and will help current and future PLANHEAT users develop their HC plans.

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