Analysis of the potential contribution to energy and climate neutrality from Danish technology within the global wastewater sector

A comparative assessment

Report
Project No 11827675

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Prepared for Danish Water Industries Federation – a part of the Confederation of Danish Industry
Represented on behalf of Vandvisionen

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Prepared for the Danish Water Industries Federation – a part of the Confederation of Danish Industry
Represented by Mr. Mads Helleberg Dorff

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Summary

To date, the wastewater treatment sector is responsible for 1% of the electricity use and 3% of greenhouse gas emissions worldwide. Urgent actions are therefore deemed necessary to reduce the energy and carbon footprint and thus increase the sustainability of the sector. As a pioneering country in this context, Denmark can offer multi-decade expertise as well as reliable solutions and technologies to increase the energy efficiency of treatment facilities, achieving energy-positive operation, and minimize direct greenhouse gas emissions. The Danish experience shows that 70% improvement in energy efficiency can be achieved through digitalization and process optimization, with very attractive return of investment.

This report presents an evaluation of current status of the wastewater treatment sector at city-wide scale (Krakow, Valencia, and Chicago), regional (Europe) and global scale, and estimates the benefits achievable from implementing leading Danish technologies and solutions in terms of energy savings, cost savings and avoided CO_2e emissions. The goal to be realized, based on the Danish experience, is to achieve 140% energy neutral operation, reduce direct emissions of N_2O by 50% and uncontrolled CH_4 emissions by 80%, and implement heat pumps to exploit the heat recovery potential from treated wastewater.

The findings from the study highlight that transferring the Danish experience in energy optimization and reduction of direct GHG emissions in other contexts:

- can contribute to reducing a city's CO_2 footprint by 1% to 2%, corresponding to avoided CO_2e emissions up to 235,000 tCO_2e/y in large cities (with more than 1 million inhabitants).
- can reduce operational CO_2e emissions from the European wastewater treatment sector by more than 50% while providing for cost savings of up to 2.3 billion EUR per year.
- can reduce the total CO_2e emissions from the global wastewater treatment sector by up to 20%, while providing energy savings of more than 200 TWh/y and cost savings of up to 200 billion EUR per year.
- can support the achievement of Sustainable Development Goal 6.3 (50% reduction of the amount of untreated wastewater by 2030) in a climate-friendly way by avoiding up to 100,000,000 tCO_2e/y as compared to implementation of conventional technologies and solutions
- can provide global energy savings from existing and new wastewater treatment facilities (in fulfilment of Sustainable Development Goal 6.3) up to 350 TWh/y in total, which corresponds to the current electricity production from coal in Europe. Furthermore, avoided CO_2e emissions from existing and new treatment facilities amount to up to 300,000,000 tCO_2e/y, corresponding to 7 times the CO_2 footprint of Denmark in 2020 and 14 times the CO_2 footprint to be achieved in 2030.

In addition to this, heat recovery from wastewater using heat pumps shows highly promising results and can contribute to satisfying more than 20% of the residential heat demand in cities with a district heating network. Overall, heat recovered from effluents can potentially constitute 10-15% of the European and global residential heat demand if surplus heat can be delivered to the district net. At European level, implementation of heat pumps in areas already served by a district heating network can significantly reduce CO_2e emission of the wastewater sector. While their implementation is dependent on the possibility of

reusing the recovered heat, heat pumps have the potential to support the transition of the wastewater treatment sector to climate neutrality, while representing a reliable solution to promote energy efficiency, grid stability, and energy independence.

1 Introduction

1.1 Background

Energy and heat

The water sector is responsible for using 4% of the total electricity generated globally, a considerable part of which (25%) is consumed in the operation of wastewater treatment plants (WWTPs) (IEA, 2016; IEA, 2018). WWTPs are among the largest energy consumers in municipalities, contributing to 20% of the energy use (C-FOOT-CTRL, 20219). Increasing electricity prices, limitations in the energy supply due to the present geo-political situation and the contribution of energy use to the indirect carbon footprint are strong drivers for improving the energy efficiency of WWTPs.

Denmark is a pioneering country in the context of energy efficiency of WWTPs and is widely acknowledged as a reference both in Europe and globally for achieving energy-neutral and energy-positive operation. This is the result of decades of experience gathered from the use of technologies and operational solutions to improve the energy footprint. The potential shown by heat recovery from wastewater effluents is expected to further enhance the energy recovery from WWTPs. In this way, WWTPs can become an important part of a city's energy network and thereby further expand the sustainability goals already set by UN (Rambøll et al., 2019).

GHG emissions

Direct greenhouse gas (GHG) emissions, such as N_2O and CH_4, from wastewater treatment processes are also strong contributors to the carbon footprint of WWTPs. Regulatory targets recently set in Denmark for direct GHG emissions have resulted in the development and implementation of technologies and solutions for monitoring and reducing these emissions. While this is still a major challenge, it has strengthened the position of Denmark towards climate neutrality in the water sector.

Overall, the use of Danish technologies and solutions has shown the potential in contributing to increasing the sustainability of the wastewater sector globally, which currently contributes to 3% of the total GHG emissions (IEA, 2018). An estimation of the benefits achievable from the adoption of the Danish model require an evaluation of the current status of WWTPs. The present report addresses this question and provides an assessment of the status of WWTPs at local (city-wide), regional and global scale as well as of the benefits to be obtained from the implementation of Danish technologies and solutions with respect to increased energy efficiency, reduced GHG emissions and costs.

1.2 Objectives of the study

The overall goals of the present study are to (i) evaluate the current status of energy efficiency and GHG emissions at local, regional and global scale in comparison with the status in Denmark, and (ii) estimate the improvements in energy efficiency, GHG emissions and costs that can be achieved by implementing documented Danish best practices and technologies and solutions in other geographical contexts.

The results of the assessment are to be regarded as estimates. While it is acknowledged that the implementation of specific technologies and solutions may be required to achieve the estimated improvements, it is beyond the scope of the study to provide an assessment of technical feasibility of such implementation and to review and discuss data availability methodologies for the determination of relevant indicators used in the analysis.

The assessment performed in this study includes:

1) A description of Danish benchmark with respect to energy efficiency (including heat recovery) and GHG emission reduction, including quantified results achieved in 2021

2) An estimate of the benefits in terms of avoided CO_2e emissions to be achieved by implementing the Danish benchmark in other geographical contexts:
   - at city-wide scale (Krakow, Valencia, Chicago),
   - at regional scale (Europe),
   - at global scale.

   Total avoided CO_2e emissions include the reduction in Scope 1 emissions (N_2O from bioprocesses, and CH_4 emissions from sludge and biogas management), Scope 2 emissions (indirect energy-related emissions, including emissions avoided by utilizing effluent heat by heat pumps), and Scope 3 emissions (N_2O from effluent discharge to recipients).
   While other factors may contribute to the carbon footprint of WWTPs (Figure 1.1), this study focused on energy, N_2O and CH_4 as they have been acknowledged as the top three contributors to the carbon footprint of WWTPs (Parravicini et al., 2020).

3) An estimate of the benefits in terms of avoided CO_2e emissions to be achieved by implementing the Danish benchmark at global scale, as opposed to conventional approaches, when fulfilling Sustainable Development Goal 6.3 (50% reduction of untreated wastewater by 2030).

The outcome of the assessment will be used to showcase the potential of Danish technologies and solutions in contributing to the green transition of the water sector globally and thus enhance their adoption outside Denmark. The assessment can also contribute to stimulating a discussion about interventions to be prioritized and information to be acquired, based on the Danish experience, to reduce the energy and carbon footprint of the wastewater sector in a local, regional, and global context.

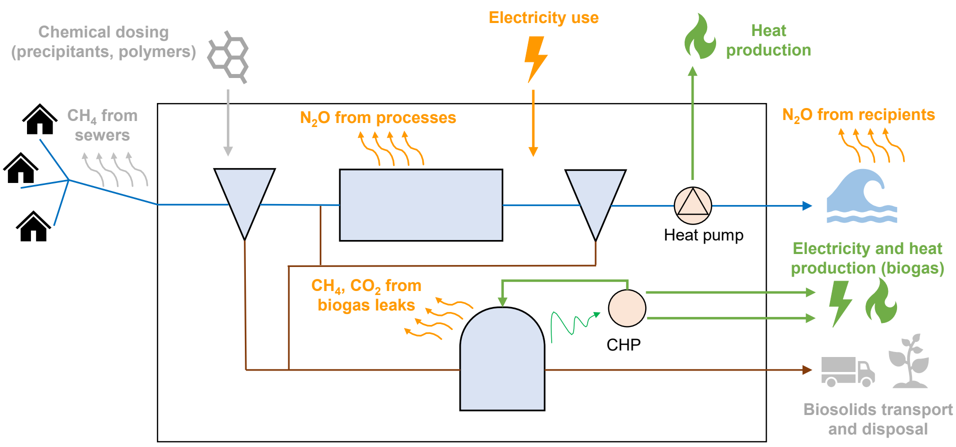


Figure 1.1 Overview of contributors to the carbon footprint of WWTPs: accounted contributors (orange), contributors to avoided CO2e emissions (green), neglected contributors (grey).

2 Data reconciliation and calculation methodology for comparative analysis

In order to evaluate the potential benefits from the use of Danish technologies and solutions locally and globally, a calculation model was established to estimate improvements in terms of increased energy efficiency, avoided CO_2-e emissions and reduced costs. Input data requirements for the calculation estimation of the benefits have been accordingly defined, focusing on relevant indicators of energy generation mix, CO_2 emissions, wastewater treatment and energy and heat prices.

The calculation model was designed to estimate the potential benefits at different scales:

- At city-wide level for Krakow (Poland), Valencia (Spain) and Chicago (Illinois, United States).
- At regional and global level, for the European Union and the entire world.

The rationale for the selection of the three city-wide examples was to cover a range of:

- Mix of sources for electricity and heat generation, and related CO_2 intensity.
- Operational conditions for wastewater treatment plants (m^3/capita generated, energy efficiency).
- Different district heating implementation levels.

When describing the status of wastewater treatment in selected locations, the actual treatment facilities serving the local areas was considered. For the initial comparative analysis presented in this case, it was considered to focus on the status of WWTPs having similar size to Marselisborg, due to the known impact of facility of size on the extent of energy use (ENERWATER, 2015). The estimated improvements for one WWTP were then extrapolated to the entire city.

With respect to energy efficiency, indicators of specific use and production were given as kWh/m^3 and kWh/PE/y. The second indicator (if available) is to be preferred, given that normalization by the treated wastewater volume may be affected by spatial variations in per capita wastewater generation, infiltration, and inflow contribution.

For the regional (EU) and global analysis, average indicators in terms of energy mix, CO_2 intensity, wastewater treatment status and energy prices were considered. In addition to the average scenario, worst-case and best-case scenarios were evaluated to determine a range (minimum-maximum) of the potential benefits to be achieved from the use of Danish technologies and solutions.

The information and data collected are summarized in Table 2.1. The table provides a summary of the minimum data required for the comparative assessment in other cases.

Table 2.1 Summary of information and data collected [measurement units]

Group	Type of information / data
Energy mix	Electricity generation mix (regional if available, country-wide) [%] Heat generation mix (regional if available, country-wide) [%]
CO_2 footprint	CO_2 emissions for electricity and heat generation [$MtCO_2$] CO_2 intensity for electricity and heat generation [$kgCO_2$ / kWh]
Population	Person equivalents served by wastewater treatment in the city, region or globally [PE]
Wastewater treatment	Capacity [PE] Inlet load [PE] Loading degree [%] Inlet flow [m^3/y] N removal efficiency [%] Fraction of wastewater discharged to sensitive recipients [%] Electricity consumption [kWh/m^3, kWh/PE/y] Electricity production [kWh/m^3, kWh/PE/y] Energy neutrality [%] Excess heat production from biogas [kWh/m^3, kWh/PE/y] Average effluent temperature [˚C] Emission factor for N_2O in bioprocesses [$kgN_2O\text{-}N/kgN_{influent}$] N_2O emission factor for effluents [$kgN_2O\text{-}N /kgN_{effluent}$] Fraction of produced CH_4 in biogas leaked to the atmosphere [%]
District heating (only for local assessment)	Is district heating already implemented in the location? Total heat demand (city-wide) [TWh/y] Residential heat demand (city-wide) [TWh/y] Share of heat demand provided by heat district heating (city-wide) [%]
Energy prices (including network costs and taxes)	Electricity price for industries [EUR/kWh] Heat price for residential use [EUR/kWh]

In the present report, a distinction is considered between energy efficiency and energy neutrality. The following definitions are proposed:

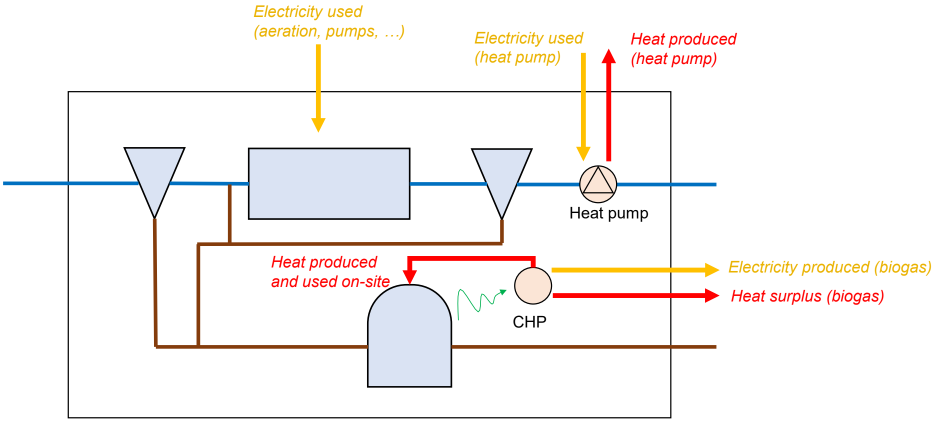
Energy efficiency is the objective to be achieved by reducing the energy (electricity) consumption in a WWTP, independently of the energy production capabilities. In the scope of this report, a WWTP is energy efficient when it can reduce its energy use until complying with the Danish benchmark.

Energy neutrality is the objective to be achieved by reducing the energy (electricity, heat) consumption in a WWTP and at the same time increase the energy (electricity, heat) production. In the scope of this report, the energy neutrality is an indicator that can be quantified by taking into input and output fluxes of electricity and heat from and to the external world, considering the WWTP as the system assessment. Therefore, the calculation of the energy neutrality neglects on-site energy reuse and considers the following terms as in agreement with DANVAs definition (DANVA, 2020):

- for electricity: input (consumption) and output (production) from and to the grid

- for heat: only the surplus (heat recovered from biogas, minus heat used for heating of digesters)

- for heat pumps: input (electricity used) and output (heat produced and sent to the district heating network)



Energy neutrality is thus calculated, when considering electricity and in the absence of heat pump installations, as:

Energy neutrality = Electricity produced / Electricity used

According to this definition:

- A *0% energy neutral WWTP* has a certain electricity consumption, but does not produce electricity
- A *100% energy neutral WWTP* produce the same amount of electricity that it consumes (and thus can also be referred to as **self-sufficient**)
- A *150% energy neutral WWTP* produces 50% more electricity that it consumes (and thus can also be referred to as **energy positive**)

Energy neutrality can also be extended to consider the entire energy balance, i.e., also heat surplus form biogas and heat pumps, being calculated as

Energy neutrality = (Electricity produced + Heat surplus + Heat produced from heat pumps) / (Electricity used in WWTP + Electricity used by heat pumps)

2.1 The Danish benchmark

2.1.1 WWTP optimisation

Marselisborg WWTP has achieved the status of being energy self-sufficient and even energy positive (Lynggaard-Jensen et al., 2017). Traditionally, WWTP operation is considered an energy intensive process. Looking at data from Europe and globally, energy neutrality above 80% is rarely reported (ENERWATER, 2015; see also Tables 2.3 and 2.4). Marselisborg has achieved the goals of a positive energy production using biogas from anaerobic digesters while reducing energy use (e.g., for aeration). In addition, feasibility studies to achieve energy savings and increase energy production has led to action plans resulting in an overall energy reduction of 26% as well as increasing the production with 66% with 2005 as benchmark.

The main steps in the process of achieving net energy production has been:

- Process optimisation with sensor based real time control of the plant (digitalisation and automation of the operation).
- Upgrading and optimisation of hardware (blowers, mixers, pumps, biogas engine, etc.).
- Implementation of new process (mainstream simultaneous nitrification-denitrification, side stream DEMON).

Around 70% of the optimisation has been achieved by digitalisation steps and better process control (Lynggaard-Jensen et al., 2017). These WWTP improvements does not require large investments in equipment resulting in very attractive ROI of <1 year.

While differences exist among WWTPs, and actions to achieve net energy production will depend on the plant in question, it is assumed in the present study that energy optimisation is possible for any WWTP in Europe, as Marselisborg is not an exception in any of the reported conditions and parameters (Lynggaard-Jensen et al., 2017). Nevertheless, achievement of energy positive operation requires the possibility of delivering electricity to the energy grid. Local restrictions may affect this option. Strategies to become more energy efficient by reduce energy consumption are therefore equally important and according to International Energy Agency, the greatest savings will be from a global reduction in energy consumption (IEA, 2022).

The performance indicators obtained at Marselisborg WWTP have been used as benchmark for the achievement of energy positive operation. Operating conditions and energy efficiency indicators (consumption and production) has been reported using monitored data from 2021 (Table 2.2).

Table 2.2 **Summary of information about Marselisborg WWTP and energy efficiency indicators measured during 2021.**

Indicator	Value
Capacity	220,000 PE
Inlet load	166,667 PE
Loading degree	75.8 %
Inlet flow	10,463,860 m^3/y
Electricity consumption	0.32 kWh/m^3 19.9 kWh/PE/y
Electricity production	0.45 kWh/m^3 28.3 kWh/PE/y
Excess heat production from biogas	0.21 kWh/m^3 13.4 kWh/PE/y
Energy neutrality	142.1% (electricity only) 209.5% (electricity and heat surplus from biogas)
Effluent temperature	16.3 °C

2.1.2 GHG emissions

Wastewater collection and treatment is a sizable contributor to the overall greenhouse gas (GHG) emissions globally (Ye and Porro, 2022). Nitrous oxide (N_2O) emissions contribute to around 42% to the CO_2 footprint of Danish WWTPs, highlighting the importance of control strategies targeted on N_2O mitigations measures. Large variation in N_2O emissions from WWTPs has been reported, due to e.g., the impact of process configuration, seasonal variations in operating conditions, unstable operation, and abrupt changes in inlet load.

The CO_2e reduction potential from wastewater operation is still in its early stages of understanding. Projects recently conducted in Denmark (e.g., VARGA) have shown that the potential for reducing N_2O emissions is around 30-65% for mainstream biological processes, 90% for secondary settlers and 50% for sidestream processes (Unisense, 2020). Overall, a 50% reduction potential is expected to be obtained in Denmark through the implementation of online monitoring and advanced real-time control strategies. For the assessment conducted in this report, a 50% mitigation was therefore considered (Table 2.5).

Emissions of methane (CH_4) are less well characterized in WWTPs. Recent efforts have been made to monitor plant wide CH_4 emissions in Nordic WWTPs (Delre, 2018). Fugitive emissions of CH_4 produced in sewers and uncontrolled CH_4 emissions from biogas generated during anaerobic sludge stabilization are the main sources. CH_4 emissions can be reduced with improved operation of anaerobic digesters and sludge management. Based on the comparison of Danish emission factors (Thomsen, 2016) with standard figures for uncontrolled CH_4 emissions, a mitigation target of 80% was considered (Table 2.5).

2.1.3 District heat systems and heat pumps

District heating systems have been in operation since the late 1870s, mostly in densely occupied areas with high and consistent heat demand. Many buildings and industrial sites rely on district heating, ranging from large urban networks in Beijing, Seoul, Milan, Copenhagen, and Stockholm to smaller networks such as university and medical campuses in USA (IEA, 2021b).

One of the main strengths of district heating systems is their capacity to integrate several energy sources, including waste heat and renewables. Despite this, in 2020 nearly 90% of heat globally was produced from fossil fuels (IEA, 2021b). Renewables are being integrated into the district heating generation mix. However, data from 2020 has showed that only 8% of energy inputs for district heat production comes from renewable energy.

Globally, district heating supplies 8.5% of the sectors heat consumption, a share that has remained relatively constant since 2000, even though floor area has increased by 65% at the same time (IEA, 2021b). Although the global average share is low, district heat does cover a high portion of the heat delivered in buildings in some European countries, such as Denmark and Sweden (>45%) as well as Russia (~45%) and China (~15%).

Heat pumps installed at WWTPs produce green energy by using the thermal energy content of the effluent wastewater. The treated wastewater is an energy source as it typically has higher temperature than recipient water (freshwater or marine) and air. For heat pumps to be rentable, they require coupling to the district heat system as they need a receiver of the surplus heat. Additionally, installation of large heat pumps requires room, time, and often up-front finances as the return of investment can be relatively high (up to 7 years excluding governmental funding; C. Risborg, private communication). The return of investment can vary significant from plant to plant. High effluent volumes and temperature can contribute to lower the price as well as reuse of buildings for heat pump installation.

If local factors allow for it, heat pumps can be a supplementary technology which can help WWTPs become energy positive. However, for the technology to provide energy positive results, heat pumps need to be coupled to the local district heating system. Local legislation and absence of a district heating system may hinder cross sector coupling and coupling to the district heat system. Therefore, heat pumps are not an optimisation option for all treatment plants. When conditions favour the installation of heat pumps, this technology can contribute to the overall energy recovery of a WWTP and make it energy positive. The technology generally results in net energy production higher than 150% (C. Risborg, private communication).

2.2 Data reconciliation for alternative scenarios

2.2.1 Data collection for city-wide assessment: Krakow (Poland), Valencia (Spain), Chicago (US)

The calculation model was initial designed and used for the city-wide assessment for selected locations. Information and data are listed in Table 2.1 and were collected to estimate benefits from the implementation of the Danish benchmark in the selected locations. Data for Krakow (Poland), Valencia (Spain) and Chicago (US) were collected from selected literature sources, based on the following criteria and assumptions:

- *Energy mix*: national data (Spain, Poland) and regional data (Illinois) were considered
- *CO_2 intensity*: national data (Spain, Poland) and regional data (Illinois) were considered. Reported CO_2 intensity for electricity and heat generation were preferred over calculated values. If available, different specific CO_2 intensity for electricity generation and for heat generation were considered.
- *Energy prices*: national data (Spain, Poland) and regional data (Illinois) were considered. If specific local conditions existed (e.g., the presence of a district heating network), heat prices for the specific city were considered. In case no specific data for heat prices were available, the price of natural gas was used, or it was assumed that the heat price was 50% of the electricity price.
- *Wastewater treatment*: if available, information on all the WWTPs serving the selected cities was collected, with subsequent prioritization of data from WWTPs of a size similar to Marselisborg. In case effluent temperature data were not available for the prioritized WWTP, measurements from a WWTP in the same region were considered. It was assumed that no excess heat production was achieved in the selected WWTPs,
- *District heating*: Effluent flow and temperature from the selected WWTPs was considered.

Information from the three locations, which was used in the comparative assessment, is summarized in Table 2.3.

Table 2.3 Summary of information and data collected for Krakow (Poland), Valencia (Spain) and Chicago (IL, US)

Group	Type of information / data	Krakow (Poland) *[reference]*	Valencia (Spain) *[reference]*	Chicago (US) *[reference]*
Energy mix	Electricity generation mix	70% coal 11% natural gas 10% wind 5% biofuels/biomass 2% hydro 1% oil [IEA, 2020a]	27% natural gas 23% nuclear 22% wind 13% hydro 6% solar 6% geothermal 4% oil 2% coal 2% biofuels/biomass 1% waste [IEA, 2020b]	53% nuclear 26% coal 12% natural gas 8% wind [US EIA, 2020a]
	Heat generation mix	80% coal 10% natural gas 7% biofuels 2% waste 1% oil [IEA, 2020a]	N/A	78% natural gas 9% biofuels 5% coal 4% oil 4% waste [IEA, 2020c]
CO_2 footprint	CO_2 intensity of electricity generation	0.647 $kgCO_2$ / kWh [EEA, 2020]	0.198 $kgCO_2$ / kWh [IEA, 2020b]	0.273 $kgCO_2$ / kWh [US EIA, 2020b]
	CO_2 intensity for heat generation	0.590 $kgCO_2$ / kWh [IEA, 2020a; calculated]	0.198 $kgCO_2$ / kWh [IEA, 2020b]	0.372 $kgCO_2$ / kWh [IEA, 2020; calculated]
Population	Total inlet load from all WWTPs serving the city	1,300,335 PE [EEA, 2016]	3,056,824 PE [EEA, 2016]	4,500,000 PE [Kunetz, 2011]
Wastewater treatment	Name of the WWTP	Kujawy	Cuenca del Carraixet	John E. Egan
	Capacity	373,000 PE [EEA, 2016]	186,666 [EEA, 2016]	160,000 [MWRD, 2019]
	Inlet load	300,051 PE [EEA, 2016]	239,677 [EEA, 2016]	266,667 [MWRD, 2019]
	Loading degree	76%	128%	60%
	Inlet flow	20,281,000 m^3/y [EEA, 2016]	13,368,008 m^3/y [EEA, 2016]	41450240 m^3/y [MWRD, 2019]
	N removal efficiency	90% [EEA, 2016]	81% [EEA, 2016]	50% [Zhang et al., 2006]
	Electricity consumption	0.36 kWh/m^3 24.4 kWh/PE/y [Luszczek, 2017]	0.40 kWh/m^3 22.3 kWh/PE/y [Mezquita et al., 2009]	0.47 kWh/m^3 122.4 kWh/PE/y [Kunetz, 2011]
	Electricity production	0.16 kWh/m^3 11.0 kWh/PE/y [Luszczek, 2017]	0.11 kWh/m^3 6.14 kWh/PE/y [Mezquita et al., 2009]	0.05 kWh/m^3 [assumed] 13.0 kWh/PE/y [assumed]
	Energy neutrality	45.2%	27.5%	21.2%
	Excess heat production	0 kWh/m^3 0 kWh/PE/y [assumed]	0 kWh/m^3 0 kWh/PE/y [assumed]	0 kWh/m^3 0 kWh/PE/y [assumed]
	Average effluent temperature	12.8˚C [Kowalik and Bak-Patyna, 2021]	20.2˚C [Zornoza et al., 2016]	17.2˚C [Oskouie et al., 2008]
	Discharge to sensitive recipients (city-wide)	0% [EEA, 2016]	91% [EEA, 2016]	0% [assumed]
District heating	Is full-scale district heating implemented?	Yes	No	No (district cooling only)
	Total heat demand	4.2 TWh/y [Halaj et al., 2021]		
	Residential heat demand	2.5 TWh/y [Halaj et al., 2021]		
	Demand share provided by district heating	65% [Halaj et al., 2021]		
Energy prices	Electricity price for industries	0.12 EUR/kWh [Eurostat, 2021a][1]	0.14 EUR/kWh [Eurostat, 2021a][1]	0.06 EUR/kWh [US EIA, 2021][2]
	Heat price for residential use	0.05 EUR/kWh [MPEC, 2022][3]	0.08 EUR/kWh [Eurostat, 2021b][4]	0.03 EUR/kWh [calculated][5]

[1]Price for industrial facilities class ID, consuming 2,000-19,999 MWh/y, including network costs, taxes and fees; [2]Price for industries; 3Price for Krakow heat providing utility MPEC; [4]Price for natural gas, non-household users; [5]Assumed equal to 50% of electricity price

2.2.2 Data collection for regional (EU) and global assessment

For the estimate of potential benefits achievable at regional and global level, information and data listed in Table 2.1 were collected for Europe and the entire world. Information and data (Table 2.4) describe an average scenario for Europe and globally and was accordingly used in the comparative assessment. Where possible, data from European Union (EU-27 or EU-28) were collected to characterize the European scenario.

Due to limited knowledge and data availability from many areas of the world as well as the expected variability of energy use and production in WWTPs, four scenarios were considered (with different current status and final objectives):

- **Scenario 1:**
    - *Europe*: WWTPs are on average 50% energy neutral, and can all be optimized to the Danish benchmark
    - *Worlds*: WWTPs are on average 20% energy neutral, and can all be optimized to the Danish benchmark

- **Scenario 2:**
    - *Europe*: WWTPs are on average 25% energy neutral, and can all be optimized to the Danish benchmark
    - *Worlds*: WWTPs are on average 10% energy neutral, and can all be optimized to the Danish benchmark

- **Scenario 3:**
    - *Europe*: WWTPs are on average 0% energy neutral (i.e., do not produce any energy), and can all be optimized to the Danish benchmark
    - *Worlds*: WWTPs are on average 0% energy neutral (i.e., do not produce any energy), and can all be optimized to the Danish benchmark

- **Scenario 4:**
    - *Europe*: WWTPs are on average 25% energy neutral. Half them can be optimized to the Danish benchmark, while the other half can be optimized to 50% of the Danish benchmark.
    - *Worlds*: WWTPs are on average 10% energy neutral, Half them can be optimized to the Danish benchmark, while the other half can be optimized to 50% of the Danish benchmark.

In the absence of specific data for heat prices, the price of natural gas was considered (Europe) or it was assumed that the heat price was 50% of the electricity price (global).

Table 2.4 Summary of information and data collected for Europe (EU-27) and the entire world

Group	Type of information / data	Europe *[reference]*	Global *[reference]*
Energy mix	Electricity generation mix	23% nuclear 21% natural gas 18% coal 16% hydro 11% wind 4% biofuels/biomass 4% solar 1% waste 1% oil 1% geothermal [IEA, 2019a]	
	Heat generation mix	43% natural gas 20% coal 19% biofuels 9% waste 3% oil 1% geothermal 6% other [IEA, 2019a]	
CO_2 footprint	CO_2 intensity of electricity generation	0.231 $kgCO_2$ / kWh [EEA, 2020]	0.475 $kgCO_2$ / kWh [IEA, 2018]
	CO_2 intensity for heat generation	0.253 $kgCO_2$ / kWh [IEA, 2019a]	0.475 $kgCO_2$ / kWh [IEA, 2018]
Wastewater treatment	Total inlet load from all WWTPs in the region	585,300,00 PE [Macedo et al., 2022][1]	4,341,680,000 PE [calculated][2]
	Fraction of generated wastewater being safely treated	82% [EEA, 2021]	56% [UN Habitat and WHO, 2021][2]
	Inlet flow	42,726,900,000 m^3/y [calculated][3]	316,942,640,000 m^3/y [calculated][3]
	N removal efficiency	60% [calculated][4]	20% [calculated][5]
	Electricity consumption	0.50 kWh/m^3 36.5 kWh/PE/y [ENERWATER, 2015]	0.72 kWh/m^3 52.3 kWh/PE/y[6] [calculated]
	Electricity production	0.25 kWh/m^3 [Scen 1] 0.13 kWh/m^3 [Scen 2] 0.00 kWh/m^3 [Scen 3] 0.13 kWh/m^3 [Scen 4]	0.14 kWh/m^3 [Scen 1] 0.07 kWh/m^3 [Scen 2] 0.00 kWh/m^3 [Scen 3] 0.07 kWh/m^3 [Scen 4]
	Energy neutrality	50% [Scen 1] 25% [Scen 2] 0% [Scen 3] 25% [Scen 4]	20% [Scen 1] 10% [Scen 2] 0% [Scen 3] 10% [Scen 4]
	Excess heat production	0 kWh/m^3 0 kWh/PE/y [assumed]	0 kWh/m^3 0 kWh/PE/y [assumed]
	Average effluent temperature	15.0°C [assumed]	15.0°C [assumed]
	Discharge to sensitive recipients	48% [Preisner et al., 2020]	30% [assumed]
District heating	Is full-scale district heating already implemented?	Yes	
	Total heat demand	6,100 TWh/y [Heat Roadmap Europe, 2017]	
	Residential heat demand	2,800 TWh/y [Heat Roadmap Europe, 2017]	26,028 TWh/y [IEA, 2021a]
	Demand share provided by district heating	20% [Lund, 2014]	
Energy prices	Electricity price for industries	0.15 EUR/kWh [Eurostat, 2021a][7]	0.12 EUR/kWh [Global Petrol Prices, 2021]
	Heat price for residential use	0.07 EUR/kWh [Eurostat, 2021b][8]	0.06 EUR/kWh [assumed][9]

[1]Includes wastewater generated from households and industries, entering municipal WWTPs; [2]Only households, where 1 person = 1 PE; [3]Calculated assuming 0.2 m^3/PE/d; [4]Calculated assuming 80% N removal efficiency and 75% of PE in Europe covered by WWTPs with N removal (Parravicini et al., 2022); [5]Calculated assuming 80% N removal efficiency and 25% of PE in the world covered by WWTPs with N removal, based on extrapolations from 2010 to 2050 (van Puijenbroek et al., 2019); [6]Calculated considering electricity consumption in the water sector is 4% of the global electricity use (909 TWh/y, 2020), 25% of which is being used for wastewater treatment (IEA, 2016; IEA, 2021); [7]Price for industrial facilities class ID, consuming 2,000-19,999 MWh/y, including network costs, taxes and fees; [8]Price for natural gas, non-household users; [9]Assumed equal to 50% of electricity price

2.2.3 GHG emissions

As GHG emissions are typically not measured routinely in WWTPs, a calculation methodology was established to estimate (i) current GHG emissions based on existing standard methodologies and (ii) their potential reduction based on the application of Danish technologies and solutions. Specific focus was given to nitrous oxide (N_2O) emissions from biological processes and effluents and fugitive methane (CH_4) emissions resulting from leakage of biogas produced during anaerobic digestion. Parameters used in the calculation of avoided emissions are summarized in Table 2.5.

For N_2O, emissions from bioprocesses and residual N in effluent (from both treated and untreated wastewater) were calculated using standard emission factors provided by IPCC (2019). With respect to bioprocess N_2O emissions, a standardized and simplified calculation approach was adopted, although wide variability of emissions has been reported as a function of WWTP configurations and operational conditions. Parravicini et al. (2022) and de Haas and Andrews (2022) have recently suggested lower N_2O emission factors than IPCC recommendations in consideration of e.g., the positive effect of complete N removal on N_2O emissions. Recent WWTP monitoring campaigns conducted in Denmark have reported emission factors of 0.025 $kgN_2O\text{-}N/kgN_{inlet}$ (Unisense, 2020) and 0.0084 $kgN_2O\text{-}N/kgN_{inlet}$ (MUDP, 2020), showing that IPCC emission factors might either underestimate or overestimate actual emissions. We believe that, at the present state, there is insufficient evidence for extrapolating the Danish emission factors to other countries, hence a standard factor of 0.016 $kgN_2O\text{-}N/kgN_{inlet}$ was considered. With respect to N_2O emissions from residual N in effluents, the recommended emission factors of 0.005 $kgN_2O\text{-}N/kgN_{effluent}$ and 0.019 $kgN2O\text{-}N/kgN_{effluent}$ were considered for discharges to non-sensitive and eutrophic recipients, respectively.

As to CH_4, it was considered that the main source of emissions is uncontrolled leakages of biogas produced during anaerobic digestion, in agreement with IPCC (2019). A simplified approach was considered also in this case, assuming all biogas produced is used on-site for energy production. This approach does not consider emissions from sludge storage, dewatering, biogas processing units, for which a standardized approach does not yet exist (Brotto and Lake, 2022). Furthermore, while it is well known that emissions of CH_4 produced in sewers occur also in other parts of a WWTP, these emissions were considered out of the scope of the present study, given that emission factors are not available (Brotto and Lake, 2022) and their minimization is a currently unresolved challenge (Parravicini et al., 2022). Based on reported evidence from typical digester operation (Delre, 2018) and emission factors from IPCC (2019), it was assumed that 5% of produced biogas volumes escape without being utilized. An emission reduction target of uncontrolled leakages down to 1% was considered, in agreement with current state-of-the-art biogas capture technologies (Parravicini et al., 2022) and with Danish guidelines (Thomsen, 2016).

Table 2.5 Summary of parameters used for the quantification of N_2O and CH_4 emissions and their potential reduction.

GHG	Type of information / data	Value used *[reference]*
N_2O	Inlet N per PE	9 gN/PE [Parravicini et al., 2022]
	Emission factor (bioprocesses)	0.016 $kgN_2O\text{-}N/kgN_{inlet}$
	Emission factor (untreated and treated effluent)	0.005 $kgN_2O\text{-}N/kgN_{effluent}$ 0.019 $kgN_2O\text{-}N/kgN_{effluent}$ for eutrophic, low oxygen recipients [IPCC, 2019]
	Global warming potential (100 years)	273 [IPCC, 2022]
	Reduction of N_2O emissions achievable using Danish technologies and solutions	50% [Unisense, 2020]
CH_4	Energy recovery potential from biogas	1 kWh/m^3 [assumed]
	Methane content in biogas	60% v/v (40% v/v CO_2) [assumed]
	Global warming potential (100 years)	27.9 [IPCC, 2022]
	Typical biogas leak (fraction of produced biogas)	5% [IPCC, 2019]
	Achievable biogas leak (fraction of produced biogas)	1% [Thomsen, 2016]

2.2.4 Heat recovery from effluents and biogas

Heat pumps can be placed at many locations in collection systems and WWTPs. For simplicity, we have only assessed the potential by placing them at the effluent of the treatment plant. The energy potential depends on the temperature drop of effluent after energy recovery, which again depends on the heat exchange potential of the equipment, on seasonal variations of the effluent temperature and on the type of recipient, to which the effluent is discharged. When considering this, an average temperature decreases of 10°C was assumed as a result of heat extraction from wastewater effluent.

The heat embedded in wastewater depends upon its temperature and flow rate. The content of available heat for recovery from wastewater can be calculated using the heat transfer equation:

$$q = m\, c_p\, \Delta T \qquad (1)$$

where q is the recovered heat content per unit time [kJ/d or kWh/d], m is the mass flow rate of wastewater [kg/d], c_p is its specific heat capacity [4.18 kJ/kg/C°], and ΔT is the temperature change of wastewater due to heat recovery [C°]. As per Equation (1), a higher flow rate and temperature of wastewater results in a higher potential for heat recovery.

The heat potential *Hp* [kWh/d] is then calculated as:

$$Hp = (-COP\ Q) / (1-COP) \qquad (2)$$

where *COP* is the coefficient of performance. For the analysis in this report, we used COP = 3.3 and a Lorentz efficiency = 57%. The later gives an indication of the deviation of the actual COP from the theoretical COP. For the calculation of the actual COP, influx and reflux temperatures of the central district system are also accounted for. For the analysis, we assumed 80 C° and 50 °C, respectively. A heat loss from the equipment of 10% is assumed.

The energy consumption required for the heat pump [kWh/d] is calculated as

$$Energy\ consumption = Hp - q \quad (3)$$

The heat recovery potential from heat pumps, $HRP_{HeatPumps}$ [kWh/d], has energy consumption and heat loss subtracted.

$$HRP_{HeatPumps} = Hp - 1.1\ Energy\ consumption \quad (4)$$

where the factor 1.1 includes the assumed heat losses (10%).

In addition to heat pumps, heat is also utilised from biogas production at Marselisborg WWTP. The biogas from anaerobic digester is treated in activated carbon filters before the biogas is used in three Combined Heat and Power units (CHP) with high power and heat efficiencies. Currently, excess heat is produced, which is sent to the district heating network. The specific heat recovery potential, HRP_{Biogas} [kWh/PE/y], resulting from excess heat production from biogas, is calculated as:

$$HRP_{Biogas} = (Heat\ production - Heat\ consumption)\ /\ Inlet\ load \quad (5)$$

where Heat production from biogas and Heat consumption for digester heating [kWh/d] are extracted from measured data from Marselisborg for 2021 and the inlet load [PE] is as reported in Table 2.2.

2.2.5 Contribution to SDG 6.3

The Sustainable Development Goal 6.3 states that "*By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally*". The present study aimed at quantifying improvements in energy efficiency, cost efficiency and carbon footprint that could be obtained if Danish technologies and solutions are employed as opposed to conventional treatment in new wastewater treatment plants built to achieve this goal.

In this context, it was of great importance to find updated evidence on the current status of wastewater treatment and sanitation. It has been recently hypothesized that 80% of the wastewater produced worldwide is not safely treated (IEA, 2018). This estimate has been challenged, and a study by UN has recently proposed that only 44% of household wastewater and 30% of industrial wastewater is not safely treated (UN Habitat and WHO, 2021). Considering that the more recent estimate for household wastewater was based on findings from 128 countries, it was considered as the reference value in the calculation model.

Therefore, the comparative analysis was performed considering the present status of wastewater treatment worldwide (56% of wastewater produced is safely treated) and the objective outlined in SDG 6.3 (78% of wastewater produced is safely treated). When calculating the number of people served, population projections for 2030 (8.5 billion; UN, 2015) were considered. Industrial wastewater was not considered in the evaluation, as the treated fraction was estimated based on numbers provided only by 14 countries, challenging the extrapolation to the entire world. Information and data used for the evaluation is summarized in Table 2.6.

Table 2.5 Summary of parameters used for the comparative analysis of conventional treatment and Danish best practice technologies and solutions in fulfilling SDG6.3.

Group	Type of information / data	Conventional treatment *[reference]*	Danish benchmark *[reference]*
Wastewater load	World population currently with wastewater treatment	4,341,680,000 [UN Habitat and WHO, 2021] [1]	4,341,680,000 [UN Habitat and WHO, 2021][1]
	Wastewater flow currently treated	316,942,640,000 m^3/y [calculated][2]	316,942,640,000 m^3/y [calculated][2]
	World population in 2030	8,500,000,000 [UN, 2015][1]	8,500,000,000 [UN, 2015][1]
	World population with wastewater treatment in 2030 (SDG 6.3)	6,630,000,000 [calculated][3]	6,630,000,000 [calculated][3]
	Wastewater flow to be treated in 2030 (SDG 6.3)	483,990,000,000 m^3/y [calculated][2]	483,990,000,000 m^3/y [calculated][2]
	World population with new wastewater treatment in 2020-2030	2,288,320,000	2,288,320,000
	Wastewater flow to be newly treated in 2020-2030 (SDG 6.3)	167,047,360,000 m^3/y [calculated][2]	167,047,360,000 m^3/y [calculated][2]
Wastewater treatment	Electricity consumption	0.72 kWh/m^3 52.3 kWh/PE/y [calculated]	0.32 kWh/m^3 19.9 kWh/PE/y
	Electricity consumption	0.14 kWh/m^3 [Scen 1] 0.07 kWh/m^3 [Scen 2] 0.00 kWh/m^3 [Scen 3]	0.45 kWh/m^3 28.3 kWh/PE/y
	N removal efficiency	70%	90% [EEA, 2016]

[1]Asssuming 1 person = 1 PE; [2]Assuming 0.2 m^3/PE/d; [3]Calculated by considering halving of untreated wastewater from 44% to 22%, in agreement with SDG 6.3

2.3 Calculation methodology

The benefits from the implementation of Danish technologies and solutions were estimated by considering the existing status of wastewater treatment at city-wide, regional and global level (Table 2.3-2.4) and improvements to be achieved by:

- implementing energy efficiency objectives set in the Marselisborg benchmark (Table 2.2).
- implementing heat recovery from wastewater effluents using heat pumps and increase heat recovery from biogas as in the Marselisborg benchmark.
- reducing N_2O and CH_4 emissions.

The estimated benefits were expressed in terms of electricity savings, cost savings and avoided CO_2e emissions saved by implementing the three actions above.

The equations below provide a description of the key indicators estimated in the assessment (for the definitions and values of parameters, please refer to Tables 2.1-2.6).

Electricity savings in WWTPs

*Electricity savings = (Energy consumption$_{current}$ – Energy consumption$_{Marselisborg}$) + (Energy production$_{Marselisborg}$ – Energy production$_{current}$) * Inlet load* (6)

where Energy production and consumption in [kWh/PE/y], Inlet load in [PE], Electricity savings in [kWh/y]

*Avoided CO_2e emissions for electricity = CO_2 intensity of electricity generation * Electricity savings / 1000* (7)

where CO_2 intensity in [kgCO_2/kWh], Avoided CO_2 in [tCO_2/y]

*Cost savings for electricity = Electricity price * Electricity savings* (8)

where Electricity price in [EUR/kWh], Costs savings in [EUR/y]

Heat recovery in WWTPs

Heat recovery = Heat recovery$_{HeatPumps}$ + Heat production$_{Biogas}$ (9)

where Heat recovery$_{HeatPumps}$ = HRP$_{HeatPumps}$ [kWh/y] as per Equation (4), Heat production$_{Biogas}$ [kWh/y] = HRP$_{Biogas}$ * Inlet load [PE]

*Avoided CO_2e emissions for heat = CO_2 intensity of heat generation * Heat recovered* (10)

where CO_2 intensity in [kgCO_2/kWh], Avoided CO_2 in [tCO_2/y]

*Cost savings for heat = Heat price * Heat savings * 1000* (11)

where Heat price in [EUR/kWh], Costs savings in [EUR/y]

Fraction of heat demand satisfied by heat recovery = Heat recovery / Residential heat demand (12)

where Residential heat demand in [TWh/y], Fraction of heat demand in [%]

GHG reduction

*N_2O emission reduction = (Inlet N per PE * Inlet load * Emission factor$_{bioprocesses}$ + Inlet N per PE * Inlet load * (1 – N removal efficiency) * Emission factor$_{effluent}$) * 44/28 * Emission reduction target / 1000 * 365* (13)

where Inlet N per PE in [gN/PE/d], Inlet load in [PE], 44/28 in [gN_2O-N/gN], N removal efficiency in [%], Emission factor in [gN_2O-N/gN_{inlet}], Emission reduction target in [%], N_2O emission reduction in [kgN_2O/y]

For the contribution to SDG 6.3, N_2O emission reduction by reducing the amount of untreated wastewater were also considered:

*N_2O emission reduction$_{Untreated}$ = Inlet N per PE * (Inlet load$_{Untreated,2020}$ – Inlet load$_{Untreated,2030}$) * 44/28 / 1000 * 365* (15)

where Inlet load in [PE]

*Avoided CO_2e emissions for N_2O reduction = Global warming potential of N_2O * N_2O emission reduction / 1000* (16) where Global warming potential in [$kgCO_2e/kgN_2O$], Avoided CO_2e emissions in [tCO_2e/y]

*CH_4 emission reduction = CH_4 production in biogas * (Biogas leak$_{current}$ – Biogas leak$_{target}$)* *(17)*

where CH_4 production and emission reduction in [$kgCH_4/d$], Biogas leak in [%]

*Avoided CO_2e emissions for CH_4 reduction = Global warming potential of CH_4 * CH_4 emission reduction / 1000* *(18)*

where Global warming potential in [$kgCO_2e/kgCH_4$], Avoided CO_2e emissions in [tCO_2e/y]

Avoided CO_2e emissions for GHG reduction = Avoided CO_2e emissions for CH_4 reduction + Avoided CO_2e emissions for CH_4 reduction *(19)*

where Avoided CO_2e emissions in [tCO_2e/y]

Total savings

Total avoided CO_2e emissions = Avoided CO_2e emissions for electricity + Avoided CO_2e emissions for heat + Avoided CO_2e emissions for N_2O reduction + Avoided CO_2e emissions for CH_4 reduction *(20)*

where Total avoided CO_2 emissions in [tCO_2/y]

Total cost savings = Cost savings for electricity + Cost savings for heat *(21)*

where Total costs savings in [EUR/y]

3 Comparative analysis

3.1 Current status assessment

3.1.1 Krakow (Poland)

Energy mix

70% of Poland's energy supply is based on coal (IEA, 2020a). As much as 87% of the coal burned by all EU households is used in Polish households (Forum Energii, 2019), and 47% of Polish households heat their homes with solid fuels. This is contributing to local smog problems and an expenditure of 30 billion EUR per year is used to treat smog-related diseases. Poland is taking significant steps to transform its energy system and is one of the fastest-growing European markets for rooftop solar. The government has introduced an ambitious offshore wind program and nuclear power is a critical part of Poland's energy strategy. The country's first reactor is planned by 2033 and a total of six nuclear plants by 2040 are set to cover an estimated 16% of the energy generation. The government has actively worked to reduce reliance on natural gas from Russia. Poland has succeeded in reducing Russia's share of gas imports from 90% in 2010 to 55% in 2021 despite an increase in gas demand during the same period. However, natural gas use needs to be reduced over time for Poland to meet its long-term decarbonisation goals. Despite Poland's notable success in clean energy and energy security, it remains heavily reliant on fossil fuels and considerable work needs to be done across all sectors to meet the country's targets for increasing the share of renewables and reducing emissions

WWTP operation

Means are taken in Poland to make WWTPs energy neutral and even energy producing. Kujawy WWTP was selected as a representative WWTP for the city of Krakow, having a similar size to Marselisborg WWTP. Kujawy has undergone several energy optimisation projects and is achieving 45% energy neutrality (Luszczek, 2017). Other WWTPs in the vicinity of Krakow have reportedly undertaken extensive energy optimisation. As an example, Rzeszow WWTP has achieved 84% energy neutrality (Masłon, 2017). As a result, Krakow has the lowest energy consumption (0.36 kWh/m^3) of the compared cities, which is only slightly higher than that reported from the benchmark treatment plant Marselisborg. (0.32 kWh/m^3). Energy production, while still being far from the Marselisborg goal (0,16 kWh/m^3 compared to a benchmark of 0.45 kWh/m^3), is, results in energy neutrality of 45%, which by far is the highest reported for the three compared cities.

District heating

Poland has one of the best developed district heating systems in Europe, comprising approximately 21,400 km network (Forum Energii, 2019). Krakow is Poland's second largest city in terms of inhabitants, which results in a high demand for energy. The city has approximately a 900 km long district heating network largely based on coal. In Poland, 80% of the heat generation is based on coal, resulting in a yearly emission of 43,6 Mt CO_2, which represent as much as 16% of the national emissions (Table 2.1). Despite being one of Europe's most well-developed district heating systems, around 80% of heating companies in Poland (responsible for production of 38% of district heating) are classified as inefficient. Modernisation goals for the heating sector are needed in the perspective of 2030 and to develop mechanisms to support their implementation and business models that introduce changes. The well-developed district heating system in Poland provide great potential for heat pumps at treatment plants, even though modernisation is needed to achieve the full potential.

3.1.2 Valencia

Energy mix

Energy transition is at the forefront of Spain's energy and climate change policies. As part of this transition, Spain has since 2015 closed all its coal mines. This has heavily influenced the energy mix, whereby coal currently contributes to only 3% of the total energy supply. However, fossil fuels, including natural gas and oil, are still dominating the total energy mix of Spain (69%). The current Spanish framework for energy and climate is based on the 2050 objectives of national climate neutrality, 100% renewable energy in the electricity mix and 97% renewable energy in the total energy mix. There is substantial development in the areas of renewable energy, energy efficiency, electrification, and renewable hydrogen.

WWTP operation

In many parts of Spain, there is a strong focus on water reuse from WWTPs to e.g., respond to drought situations, to gain an alternative resource to achieve a good status of groundwater bodies, and to improve the status of surface water bodies by reducing the volume of treated wastewater discharged into the environment. The main destination of reclaimed water is agriculture. Areas with the greatest volumes reused are located in the regions of Júcar and Segura (Ferrero Polo, 2018; Monreal, 2015). Valencia is part of the Júcar river basin and Cuenca del Carraixet WWTP is one of the plants serving the city and was selected as the plant most similar to Marselisborg WWTP). Approximately 28% of the treated wastewater at Cuenca del Carraixet is reused for irrigation (EPSAR, 2015). In order to be compliant with effluent quality when considering reuse of wastewater for irrigation, tertiary treatment is often implemented at WWTPs, which can lead to increase in energy consumption. For the WWTPs serving the city of Valencia, this is reflected in the energy consumption reported. Pinedo WWTP reuses 18% of the treated water (EPSAR, 2016; IAA, 2016; JCJLM, 2016) and has the lowest energy consumption with 14 kWh/PE/y, which is similar to Marselisborg WWTP. Conversely, other WWTPs such as Quart–Benager and Cuenca del Carraixet reuse 100% and 28% of the treated water and consume 30.8 kWh/PE/y and 22.3 kWh/PE/y, respectively (EPSAR, 2016; IAA, 2016; JCJLM, 2016).

When considering energy production, there is significant optimisation potential for Valencia, whereby Cuenca del Carraixet WWTP produces 76% less energy than Marselisborg (Murgui Mezquita et al., 2009). The energy neutrality is 28%, in line with typical levels for the Valencian Community (EPSAR, 2011). This leaves a large gap to full energy neutrality (100%), with energy production being the main negative contributor to the large difference.

District heating

In Spain, some local district heating projects are implemented. In 2019, 426 networks have been identified, of which 414 were censored. The majority of networks (374) are designed to provide heat, 36 networks can provide both cold and heat, and just 4 networks are designed exclusively for cold (Balboa-Fernandez et al., 2020) In the Valencian Community, 2.2% of the heat is distributed in district heating system. 37% of heating is generated by renewable energy (Balboa-Fernandez et al., 2020). The waste heat of industrial origin has a low potential for use in centralized systems, such as urban heat and cooling networks, because the distances between thermal power plants and consumption centres are too large. Overall, the potential for heat pumps in Spain can be exploited in a limited number of areas and the system needs expansion to gain the full potential of the technology.

3.1.3 Chicago

Energy mix

Chicago is the largest city in the state Illinois, USA. It has 2.7 million inhabitants (9.6 million considering the metropolitan area) and is the third largest city in the US. Illinois is the fifth-largest energy-consuming state in the nation and its industrial sector, which includes petroleum refining, coal mining, and agriculture, uses the most energy of any end-use sector in the US (US EIA, 2021). Considering state data, 35% of the total energy mix supply is from fossil fuels. Nuclear energy is largely contributing to the energy mix supply with 53.3% of the total energy demand. In recent history, nuclear power has accounted for roughly a fifth of US electricity generation (IEA, 2019b). However, competition from low-cost natural gas and renewables, combined with mounting costs for nuclear plant upgrades has changed this picture. Some states are introducing measures to help nuclear generators stay in the market by valuing their contribution to low-carbon electricity generation in the form of zero-emission credits (ZECs). This has been applied in Illinois and has prevented the closure of two nuclear plants, which positively affects the energy mix supply.

WWTP operation

Compared to the other selected cities, Chicago has reported the highest energy consumption of 122 kWh/PE/y, being considerable higher than 20 kWh/PE/y, 24 kWh/PE/y, and 22 kWh/PE/y for Marselisborg, Krakow, and Valencia, respectively. As to energy production, Chicago produces less than half the energy of Marselisborg (13 kWh/PE/y as compared 28 kWh/PE/y). When considering the energy production per m^3 of influent, Chicago has the lowest energy production of the compared locations, which is highly influenced by the higher wastewater inflow compared to the other locations.

Several successful energy optimisations projects have been accomplished in the US (Daw et al., 2012). However, numerous factors influence the level of energy efficiency and neutrality. Legislation makes it difficult for WWTPs to deliver electricity to the grid. Permits often come with binding clauses for a minimum energy supply, which can result in fines if this supply is not met. Furthermore, strict legislation on carbon footprint emissions from digesters prevent WWTPs to be interested in surplus energy production. Therefore, few WWTPs are interested in implementing energy production strategies. Treatment processes differs from many places in Europe and several aspects (e.g., high per capita wastewater generation) result in elevated energy consumption. Additional, WWTPs are heavily reliant on project fundings for large scale optimisation projects to take place. National policies have been fundamental in driving the energy optimisation evolution in Europe and their influence can be needed as a driver to put treatment plants in the US on the energy positive side.

District heating

District heating in the United States is being implemented but not at the pace or in the extent it is in Europe or China. The district heating systems are typically located on university or college campuses, hospital or research campuses, military bases and airports, or areas of dense building settings, such as central business districts of larger municipalities. Larger US cities with downtown district energy systems include New York, Boston, Philadelphia, San Francisco, Denver, Minneapolis (US EIA, 2020c). As of 2012, a total of 660 district energy systems were operating in the United States, covering 510 km2 floor space (US EIA, 2018).

District cooling systems are currently in operation in several urban environments (e.g., Atlantic City, Chicago, Denver, Huston Phoenix, Portland, Ore, St. Paul, Minn) (HPAC, 2013). They were developed during the mid- to late 1990s, when chillers often were in high-rise penthouses and consequently were extremely expensive and difficult to replace. District heating is making its way into the American market. However, slow development and local factors are negatively influencing the potentials for heat pumps.

3.1.4 Europe

Due to the variability in terms of energy efficiency and neutrality, the comparative assessment for Europe considered four alternative scenarios

- Energy neutrality of 50% as starting point (Scenario 1)
- Energy neutrality of 25% as starting point (Scenario 2 and 4)
- Energy neutrality of 0% as starting point (Scenario 3)

Scenarios 1-3 assume that all WWTPs can be energy optimised with Marselisborg as benchmark, and therefore can be considered ideal. Scenario 4 realistically assumes that 50% of WWTPs optimised with Marselisborg as benchmark, while the remaining WWTPs can only achieve 50% of the savings. This roughly corresponds to that all larger treatment plants in Europe can be optimised according to Marselisborg standards, while the remaining smaller plants only can achieve 50% of the savings.

Energy mix

When considering all of Europe the energy mix consists of 39% fossil fuels, while renewables supply 31% of the energy mix. Nuclear power provides most to the energy mix (23%) followed by natural gas (21% and coal (18%). In Europe coal phase-out policies has been applied and as a result renewables have been replacing the energy supply. However, the gas crisis has created a paradigm shift in EU's electricity transition where renewables are replacing fossil gas instead. More than 52% of the renewable energy is replacing fossil gas while only 7% coal is replaced (EMBER, 2022).

The coal proportion of the energy mix has been decreasing with 29% a year from 2017-2019. Due to the gas crisis the decline has only been 3% in the subsequent years (EMBER, 2022). Therefore, EU power sector emissions has declined less than half the rate required for global warming of 1,5 °C (IPCC, 2018). Limiting global temperature rise to 1,5 °C and avoiding the worst impacts of the climate crisis, will require power sector emissions to reach zero by 2035. This requires that the power sector emissions decline at an average annual rate of 6% per year.

WWTP operation

Compared to the European cities in the analysis, Europe as a whole has the highest energy consumption (37 kWh/PE (Europe), 20 kWh/PE (Marselisborg), 24 kWh/PE (Krakow), 22 kWh/PE Valencia). Only Chicago in USA has a higher energy consumption (20 kWh/PE). In the analysed scenarios we assume 50% (scenario 1 + 4), 25% (scenario 2) and 0% (scenario 3) energy production in Europe. This results in an energy production of 18 kWh/PE, 9 kWh/PE and 0 kWh/PE respectively.

Large variation in countries economy and focus on modernisation, digitalisation, and optimisation of WWTPs results in large variation in energy consumption and production within the region. Local and European legislation, such as the water Framework Directive 2000/60/EU and Energy Efficiency Directive 2012/27/EU, has promoted cost and resource-efficiency of WWTPs in Europe and several WWTPs across Europe are striving to be energy self-sufficient and even energy productive.

District heating

Europe is together with China and Russia responsible for more than 90% of the global district heat production (IEA, 2021b). Europe leads in the use of renewables for district heating, accounting for most global solar thermal and geothermal use and 75% of bioenergy-based production.

Modernisation of existing networks to reduce losses and inefficiencies and to enable the shift to new-generation district heating systems are project aims for some of the projects funded by EU Horizon 2020 programme. The projects KeepWarm and REWARDHeat aims to accelerate the modernisation of district heating systems in Europe. The grants that support these projects are one of the effects from policies in Europe which support greater district heating penetrations others include e.g., polluter and carbon taxes, energy and heating strategies, the integration of district heating into energy standards for buildings (IEA, 2021b).

The political focus on district heating in Europe has resulted in Europe being among the lead runners when it comes to a well-established heat net. While Europe is well advanced when it comes to district heating, large areas still exists where district heating are not present, or the heat demand is too low for such a system to payoff.

3.1.5 Global assessment and fulfilment of SDG 6.3

Due to the variability in terms of energy efficiency and neutrality, the comparative assessment for the entire world considered four alternative scenarios

- Energy neutrality of 20% as starting point (Scenario 1)
- Energy neutrality of 10% as starting point (Scenario 2 and 4)
- Energy neutrality of 0% as starting point (Scenario 3)

Scenarios 1-3 assume that all WWTPs can be energy optimised with Marselisborg as benchmark, and therefore can be considered ideal. Scenario 4 realistically assumes that 50% of WWTPs optimised with Marselisborg as benchmark, while the remaining WWTPs can only achieve 50% of the savings.

For the fulfilment of the sustainable development goal 6.3, three scenarios were considered

- Energy neutrality of 20% as conventional treatment (Scenario 1)
- Energy neutrality of 10% as conventional treatment (Scenario 2)
- Energy neutrality of 0% as conventional treatment (Scenario 3)

The potential benefits obtained when treating by 2030 the additional 22% of currently untreated wastewater were evaluated according to the Danish benchmark, as opposed to the assumed state of the art in terms of conventional treatment.

Energy mix

Fossil fuels consists of around 80% of the global energy mix. In the prognosis for 2050 liquid, gaseous and solid fuels of varying types will continue to make a major contribution to the global energy mix (IEA, 2021). Fossil fuels remain the main energy source for electricity in many countries such as India, South Africa, Japan, China, and Australia, which highly influence the carbon footprint of the global energy mix, which is more than double that of Europe (0,48 kg CO_2e/kWh and 0,23 kg CO_2e/kWh, respectively.

WWTP operation

In many places of the world wastewater are not being treated. Only 56% of the generated wastewater are safely treated (UN Habitat and WHO, 2021). Of these treatment plants the general energy consumption is estimated to be 52 kWh/PE/y compared to 20 kWh/PE/y, 24 kWh/PE/y, 22 kWh/PE/y, 122 kWh/PE/y, 37 kWh/PE/y for Krakow, Valencia, Chicago, and Europe respectively. Only Chicago has a higher energy consumption, which can partly be an effect of the associated high per capita wastewater genration (>0.5 m^3/d).

In the analysed scenarios we assume 20% (scenario 1 + 4), 10% (scenario 2) and 0% (scenario 3) energy production in the world. This results in an energy production of 11 kWh/PE, 5 kWh/PE and 0 kWh/PE respectively.

Again, large variation in countries economy and strategy on modernisation, digitalisation, and optimisation of WWTPs results in large regional and local variation in energy consumption and production within the world. Not all countries have the infrastructure to collect and facilitate safe cleaning of the wastewater, resulting in around 44% of the wastewater produced are discharged uncleaned to the environment. Large potentials exist globally for both energy efficiency and neutrality.

District heating

Russia and China are together with Europe responsible for more than 90% of the district heat production (IEA, 2021b). In many areas of the world, an extensive district heating system are completely lacking. Leaving little potential for heat pumps in those parts.

3.2 Results of the comparative analysis and estimates of potential benefits

The following paragraphs summarize the results of the comparative assessment and the potential benefits in terms of energy efficiency and neutrality, heat recovery and carbon footprint reduction to be achieved when implementing the Danish benchmark at city-wide, regional, and global scale. A comprehensive summary of the results of the assessment can be found in Table 3.1 and 3.2.

The assessment will be presented following a stepwise approach. In the first place, we will present benefits from the implementation of measures for increased energy efficiency/neutrality and reduction of direct GHG emissions, which are applicable independently of the local infrastructure situation. Benefits from the implementation of heat recovery using heat pumps will be subsequently presented and discussed, highlighting the potential of this technology while considering the need of a district heating infrastructure to be realized.

3.2.1 City-wide assessment (Krakow, Valencia, Chicago)

Figure 3.1 presents the estimated avoided CO_2e emissions from the implementation of measures for increased energy efficiency (reduced electricity consumption), increased energy neutrality (increased energy production) according to the Danish benchmark at city-wide scale and reduction of direct GHG emissions as discussed in section 2.1.2.

Energy efficiency

Savings from increased energy efficiency were estimated to be 5,900–461,000 MWh/y. When normalized for the population equivalents served in the three cities, major differences can be observed for Krakow and Valencia (2.4–4.5 kWh/PE/y) as compared to Chicago (102.5 kWh/PE/y). Due to the large deviation from the Danish benchmark, considerable savings can thus be obtained for Chicago. It is noted that higher specific energy consumption in the US can be associated to high per capita wastewater generation (above 0.5 m^3/d), which can be decreased by implementing relevant source minimization strategies. When considering the local electricity price, these savings translate into yearly cost savings of 704,000 (Krakow) to 52,000,000 (Chicago) (Table 3.1). In terms of carbon footprint, reduction of energy use can contribute to reducing CO_2e emissions by 3,800 (Krakow), 1,460 (Valencia) and 126,999 (Chicago) tCO_2e/y (Figure 3.1). As a result of the higher CO_2 intensity of the Polish electricity generation mix, 1 kWh of electricity saved in Krakow leads to roughly 3-fold higher CO_2e reductions as compared to Valencia and Chicago.

Energy neutrality

Additional savings from increased energy neutrality were estimated to be 22,400–69,000 MWh/y. Lower variability between cities is shown in this case (15.3–22.1 kWh/PE/y). Overall, energy optimization of WWTPs with combined reduction in electricity use and increased electricity production can contribute to avoided CO_2e emissions in the range of 15,000–145,000 t/y (Figure 3.1) and cost savings in the range of 3.3–60.5 million EUR/y.

Direct GHG reduction

Minimization of direct GHG emissions (N_2O and CH_4) was estimated to potentially result in a CO_2 footprint reduction of 22,200 (Krakow), 51,900 (Valencia) and 90,800 (Chicago) tCO_2e/y (Figure 3.1).

When considering the energy optimization and direct emission reduction, combined, the respective contribution is dependent on the local conditions. At city-wide scale, energy optimization and reduction of direct GHG emissions can contribute to reducting the city's CO_2 footprint by 1% (Krakow; Climate KIC, 2021) to 2% (Valencia; Lorenzo-Saez et al., 2022).

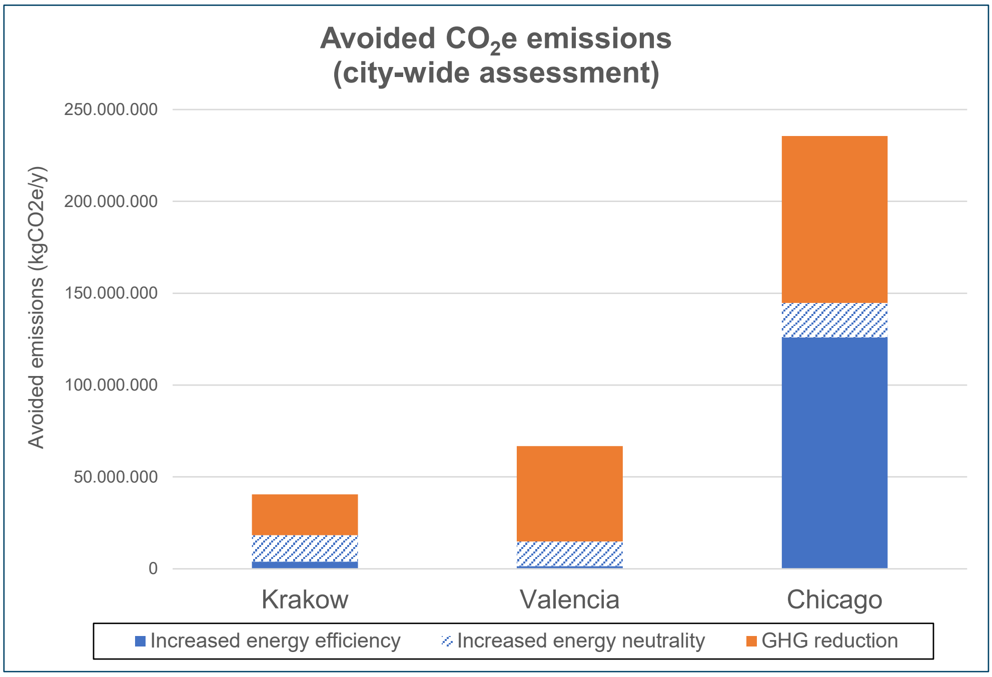


Figure 3.1 **Estimated reduction in CO_2 emissions achievable in Krakow, Valencia and Chicago upon implementation of the Danish benchmark.**

Heat recovery

Heat recovery through implementation of heat pumps in WWTP effluents and use of surplus heat from biogas can contribute to the production of 650,000 to 14,200,000 MWh/y of heat to be potentially sent to the district heating network. Considerable heat recovery potential is shown especially for Chicago (3,155 kWh/PE/y) because of the high specific wastewater generation (0.71 $m^3/PE/d$). As presented in Figure 3.2, heat recovery is a significantly (5 to 20-fold) higher contributor to the reduction of CO_2e emissions from WWTPs, as compared to energy optimization and reduction of direct GHG emissions.

To date, Krakow is the only city of three selected to have an extensive district heating network. Residential heat demand has been estimated to be 2.5 TWh/y, 65% of which is provided through district heating (Halaj et al., 2021). Heat recovered from heat pumps (0.65 TWh/y) can potentially satisfy 26% of the heat demand, representing a reliable and sustainable alternative to the use of fossil fuels. When considering Krakow's carbon footprint (5.5 million tCO_2/y; Climate KIC, 2021), energy optimization and direct GHG emission reduction in WWTPs together with heat recovery can reduce current emissions by 9%.

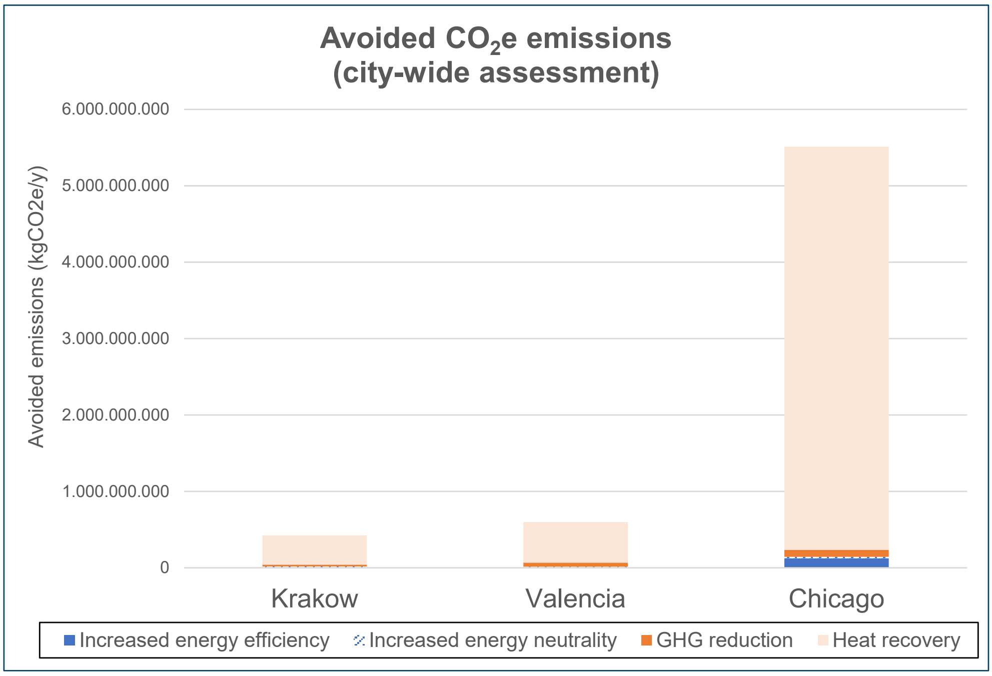


Figure 3.2 Estimated reduction in CO_2 emissions achievable in Krakow, Valencia and Chicago upon implementation of the Danish benchmark including heat recovery.

3.2.2 Regional assessment (Europe)

The assessment of the benefits to be achieved upon implementation of the Danish benchmark in a European context considered four alternative scenarios with different current state in terms of energy neutrality (50%, 25% and 0%) and goals to be achieved. While Scenarios 1, 2, 3 assume that the Danish benchmark can be implemented in all WWTPs in Europe, Scenario 4 sets the more realistic goal of implementing the Danish benchmark in 50% of the WWTPs (while the remaining WWTPs only achieves 50% of the potential savings from the Marselisborg benchmark).

Figure 3.3 presents the estimated avoided CO_2e emissions from the implementation of measures for increased energy efficiency and neutrality and reduction of direct GHG emissions at European scale.

Energy efficiency

Savings from increased energy efficiency were estimated to be 7,300,000–9,700,000 MWh/y, corresponding to 12–17 kWh/PE/y. This corresponded to a reduction in indirect CO_2e emissions of approximately 1,700,000–2,200,000 tCO_2e/y CO_2e emissions. When considering average European electricity prices, yearly savings of more than 1 billion EUR can be achieved.

Energy neutrality

Additional savings from increased energy neutrality were estimated to be 5,000,000–16,600,000 MWh/y (10.0–28.3 kWh/PE/y), with variability resulting from the initial assumption of energy neutrality. For WWTPs with no energy production (Scenario 3), savings from the implementation of energy production measures can reach up to 28.3 kWh/PE/y, corresponding to 4.2 EUR/PE/y.

Under more realistic assumptions (Scenario 4), energy optimization of WWTPs was estimated to achieve energy savings of 15,700,000 MWh/y, contributing to avoided CO_2e emissions of approximately 3,600,000 t/y and cost savings of around 2.3 billion EUR/y.

Direct GHG reduction

Reduction of direct GHG emissions from WWTPs was found to be a strong contributor, as compared to energy optimization, in avoided CO_2e emissions from WWTPs (from 8,400,000 to 14,500,000 tCO_2e/y). Reduction of N_2O emissions was the predominant contributor, providing for more than 60% of the total reduction in direct GHG emissions.

Overall, total CO_2e emissions (direct and energy-related) from WWTPs in Europe were estimated to be 23,800,000-25,600,000 tCO_2e/y, representing approximately 0.6-0.7% of total CO_2e emissions in Europe and being comparable to estimates of operational emissions provided by Parravicini et al. (2022). When neglecting the impact of carbon footprint from WWTP infrastructure (not considered in the present evaluation), the implementation of energy optimization measures and direct GHG emission reduction can reduce operational emissions by 54% (realistic scenario) up to 71% (ideal scenarios), therefore providing a significant contribution to reducing the carbon footprint of the European wastewater treatment sector.

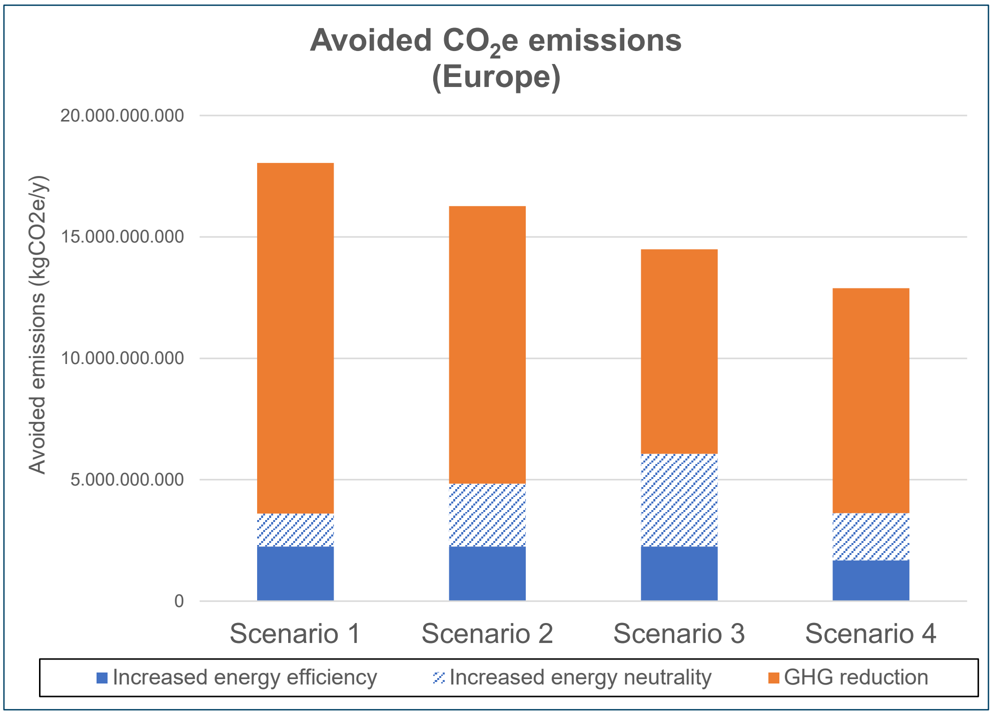


Figure 3.3 Estimated reduction in CO_2 emissions achievable in Europe upon implementation of the Danish benchmark.

Heat recovery

If implemented in a European context, heat recovery was estimated to contribute to the production of 317-423 TWh/y of heat, potentially satisfying 11-15% of the residential heat demand in Europe. As presented in Figure 3.4, heat recovery can potentially contribute to reducing CO_2e emissions by 80,000,000 (Scenario 4) up to 106,000,000 (Scenario 1, 2, 3) tCO_2e/y.

Implementing heat recovery from WWTPs can be considered feasible only in areas of Europe served by district heating, covering approximately 60,000,000 people (energypost.eu, 2022). In this context, avoided CO_2e emissions from energy optimization, direct GHG emission reduction and heat recovery combined amount to 21,100,000-29,000,000 tCO_2e/y. When considering the current estimated emissions from WWTPs in Europe, it can be concluded that the Danish benchmark can realistically help the European wastewater sector to achieve climate neutrality.

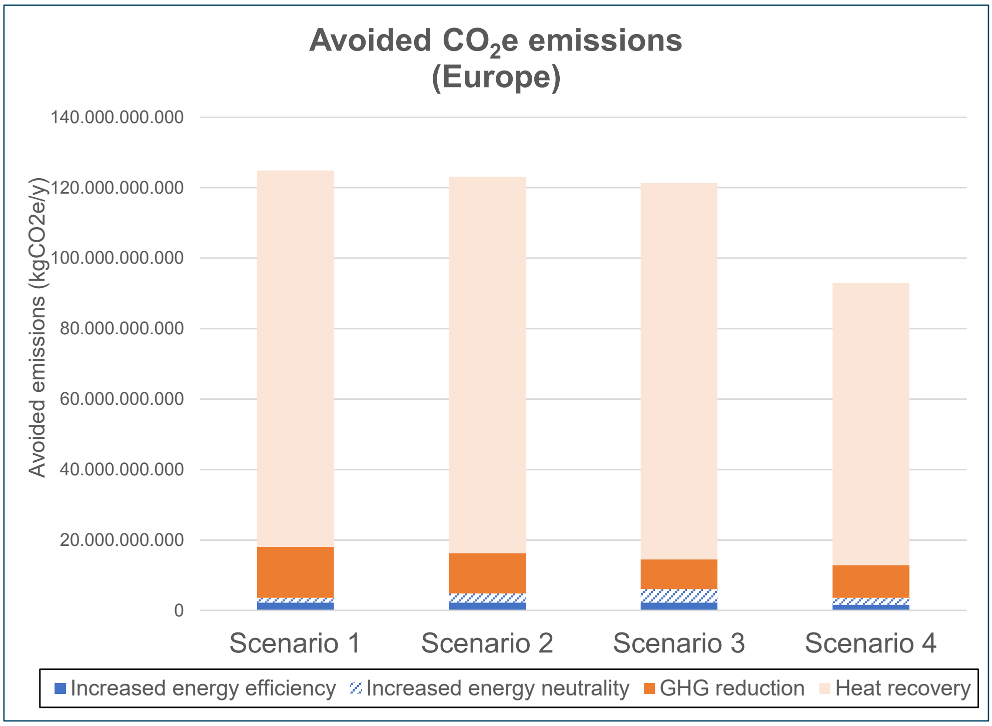


Figure 3.4 Estimated reduction in CO_2 emissions achievable in Europe upon implementation of the Danish benchmark including heat recovery.

3.2.3 Global assessment

Similar to the assessment for Europe, the implementation of the Danish benchmark in a global context considered four alternative scenarios with different current state in terms of energy neutrality (20%, 10% and 0%) and goals to be achieved, with Scenario 4 considering realistic implementation goals.

Figure 3.5 presents the estimated avoided CO_2e emissions from the implementation of measures for increased energy efficiency and neutrality and reduction of direct GHG emissions at European scale.

Energy efficiency

Savings from increased energy efficiency were estimated to be 123,000,000–141,000,000 MWh/y, corresponding to 28–32 kWh/PE/y. This can potentially result in a reduction of indirect CO_2e emissions by 58,000,000–67,000,000 tCO_2e/y.

Energy neutrality

Additional savings from increased energy neutrality were estimated to be 37,000,000–58,000,000 MWh/y (18–28 kWh/PE/y). Under realistic assumptions

(Scenario 4), energy optimization of WWTPs was estimated to achieve total energy savings of 202,000,000 MWh/y, contributing to avoided CO_2e emissions of approximately 96,000,000 t/y that correspond to 9% of the global emissions from the wastewater treatment sector.

Direct GHG reduction

Reduction of direct GHG emissions from WWTPs was estimated to contribute to avoided CO_2e emissions in the range 67,000,000–99,000,000 t/y. This contribution was comparable to what achieved by the energy optimization, corresponding to 7-10% of global emissions from the wastewater treatment sector.

When considering the reported carbon footprint of the wastewater treatment globally (1,000 MtCO_2e/y), the implementation of energy optimization measures and direct GHG emission reduction can reduce CO_2e emissions by 16-20% realistic scenario and ideal scenarios respectively).

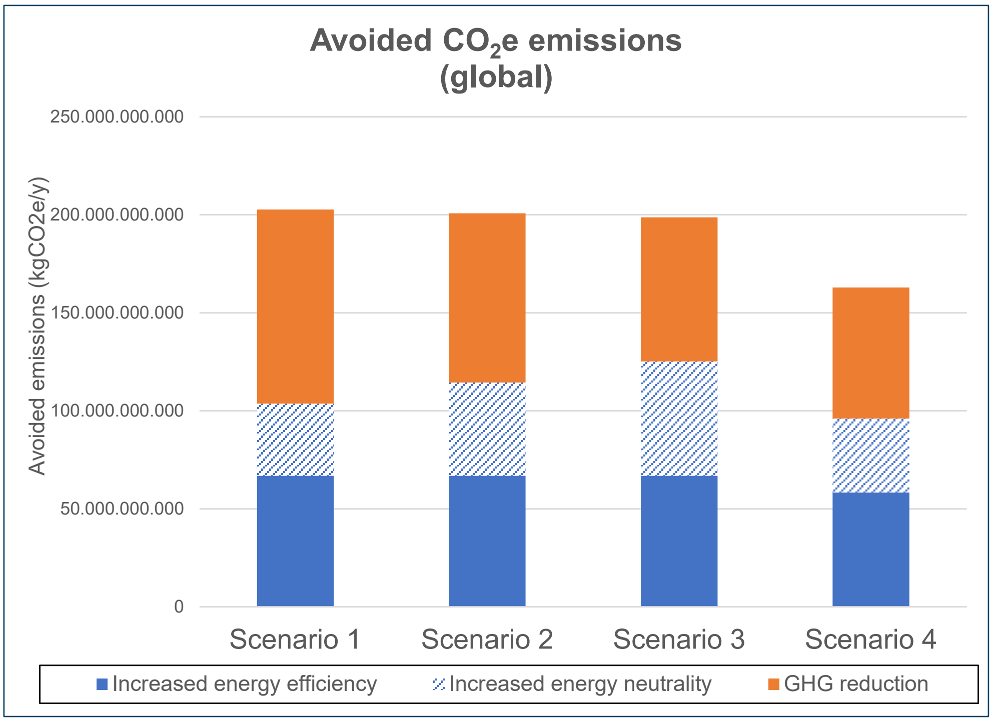


Figure 3.5 Estimated reduction in CO_2 emissions achievable globally upon implementation of the Danish benchmark.

Heat recovery

If implemented in a global context, heat recovery was estimated to contribute to the production of 2352-3136 TWh/y of heat, potentially satisfying 9-12% of the residential heat demand. Overall, heat recovery can potentially contribute to reducing CO_2e emissions by more than 1,000,000,000 tCO_2e/y (Figure 3.6).

On a global scale, 8.5% of the residential heat demand is currently satisfied by district heating (IEA, 2021b), corresponding to approximately 158 TWh/y (IEA, 2021a). Therefore, less than 10% of the total heat recovery potential estimated would be sufficient to fulfil the heat demand provided through district heating. Heat recovery can thus represent a potential source of heat in the growing district heating sectors worldwide.

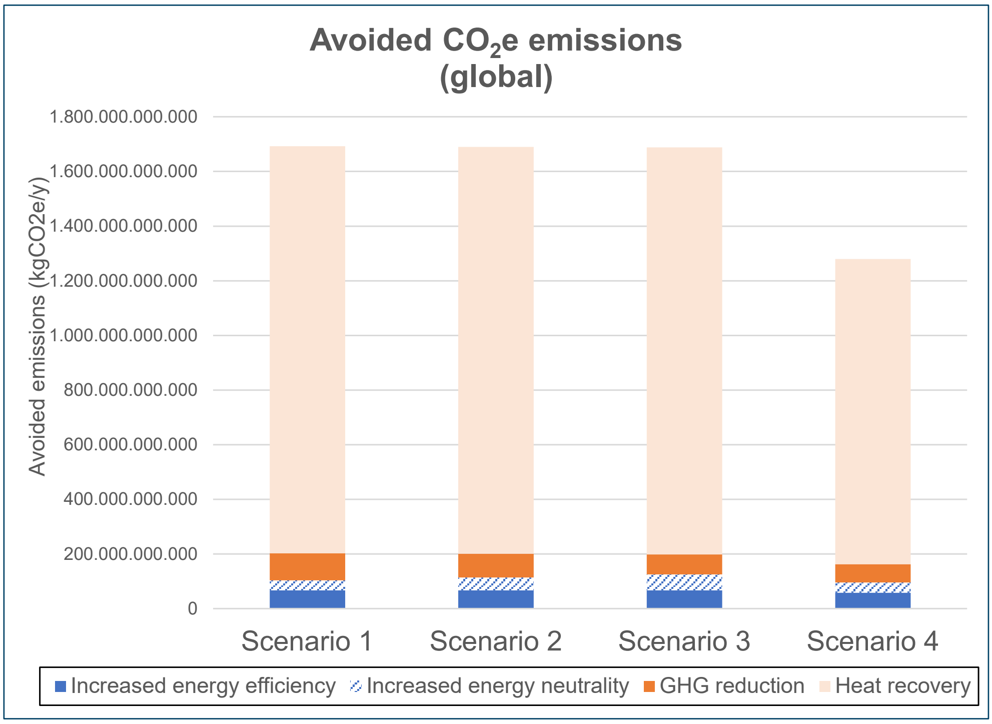


Figure 3.6 Estimated reduction in CO_2 emissions achievable globally upon implementation of the Danish benchmark including heat recovery.

3.2.4 Fulfilment of UN SDG 6.3

As of 2020, 56% of household wastewater undergoes safe wastewater treatment (UN Habitat and WHO, 2021). Fulfilment of SDG 6.3. requires a reduction of the untreated wastewater to half, thus resulting in 78% of household wastewater to undergo safe wastewater treatment by 2030. When considering population projections for 2030 (UN, 2015), this corresponds to 2.3 billion people to be newly served by wastewater treatment, amounting to approximately 484 million m^3/y of wastewater flow to be treated. In this context, we evaluated the potential benefits to be obtained when implementing new wastewater treatment in the period 2020-2030 accoridng to the Danish benchmark, as opposed to the current global state of the art.

Figure 3.7 summarizes the main results of the evaluation. There are no substantial differences among the three scenarios tested (i.e. state of the art assumed to be 20%, 10% and 0% energy neutral). Energy optimization combining reduced electricity consumption and increased energy production can potentially result in savings of 85,700,000 to 149,000,000 MWh/y, corresponding to avoided CO_2e emissions 41,000,000 to 71,000,000 tCO_2e/y.

Comparable carbon footprint reductions (26,000,000 to 39,000,000 tCO_2e/y) can be potentially achieved through minimization of direct GHG emissions, also as a result of reducing emissions from untreated wastewater.

Heat recovery potential from new WWTPs was estimated to be higher than 1 billion MWh/y, resulting in avoided CO_2e emissions up to 574,000,000 tCO_2e/y and being the largest contributor to the overall carbon footprint reduction. While the exploitation of this potential is dependent on the existence of a district heating network, its achievement can be facilitated by the existing focus on sustainability and by cross sector planning for sanitation and energy.

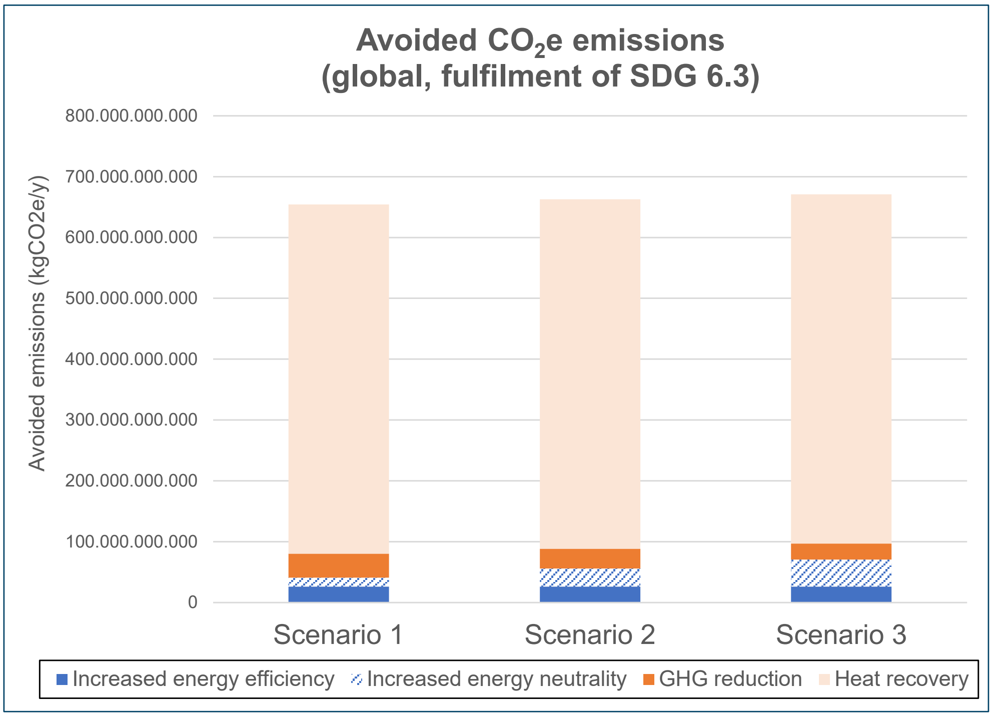


Figure 3.7 **Estimated reduction in CO_2 emissions achievable globally upon implementation of the Danish benchmark (including heat recovery) when fulfilling SDG 6.3.**

Table 3.1 Summary of results for city-wide, regional and global assessment of benefits related to energy savings, heat savings and avoided CO_2e emissions.

					Europe				Global			
		Krakow	**Valencia**	**Chicago**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Energy efficiency and neutrality	Avoided CO_2e [tCO_2e/y]	18,306	14,862	144,762	3,600,656	4,834,395	6,068,134	3,625,796	103,628,935	114,421,981	125,215,026	95,986,985
	Saved electricity [kWh/y]	28,293,695	75,063,368	530,264,766	15,587,253,790	20,928,116,290	26,268,978,790	15,696,087,218	218,166,180,623	240,888,380,623	263,610,580,623	202,077,862,967
	Saved costs [EUR/y]	3,386,755	10,201,112	60,548,621	2,292,885,033	3,078,525,906	3,864,166,780	2,308,894,430	26,179,941,675	28,906,605,675	31,633,269,675	24,249,343,556
Heat recovery	Avoided CO_2e [tCO_2e/y]	385,134	533,498	5,274,752	106,823,096	106,823,096	106,823,096	80,117,322	1,489,499,897	1,489,499,897	1,489,499,897	1,117,124,923
	Saved costs [EUR/y]	30,746,164	223,638,168	416,500,037	29,591,407,400	29,591,407,400	29,591,407,400	22,193,555,550	188,147,355,464	188,147,355,464	188,147,355,464	141,110,516,598
	Saved heat [MWh/y]	653,172	2,694,436	14,198,300	422,734,391	422,734,391	422,734,391	317,050,794	3,135,789,258	3,135,789,258	3,135,789,258	2,351,841,943
	Fraction of residential heat demand [%]	26%			15%	15%	15%	11%	12%	12%	12%	9%
Direct GHG reduction	Avoided CO_2e [tCO_2e/y]	22,150	51,874	90,842	14,452,308	11,437,787	8,423,265	9,265,121	99,121,660	86,296,659	73,471,658	66,918,901
Total	Avoided CO_2e [tCO_2e/y]	425,590	600,234	5,510,357	124,876,060	123,095,277	121,314,495	93,008,239	1,692,250,493	1,690,218,537	1,688,186,581	1,280,030,809
	Saved costs [EUR/y]	34,132,920	233,839,280	477,048,658	31,884,292,432	32,669,933,306	33,455,574,180	24,502,449,979	214,327,297,139	217,053,961,139	219,780,625,139	165,359,860,154
Savings per PE	*Saved electricity [kWh/PE/y]*	*22*	*25*	*118*	*27*	*36*	*45*	*27*	*50*	*55*	*61*	*47*
	Saved heat [kWh/PE/y]	*502*	*881*	*3,155*	*722*	*722*	*722*	*542*	*722*	*722*	*722*	*542*
	Avoided CO_2e [kg CO_2e/PE/y]	*327*	*196*	*1,225*	*213*	*210*	*207*	*159*	*390*	*389*	*389*	*295*
	Saved costs [EUR/PE/y]	*26*	*76*	*106*	*54*	*56*	*57*	*42*	*49*	*50*	*51*	*38*

Table 3.2 Comparison of 2030 status estimates for wastewater treatment upon implementation of SDG6.3, whereby additional treatment is provided by conventional practices or according to Danish benchmark.

		Scenario 1 2030		Scenario 2 2030		Scenario 3 2030	
		Conventional	**Best practice**	**Conventional**	**Best practice**	**Conventional**	**Best practice**
Electricity	Consumption [kWh/y]	316,487,785,714	261,162,236,188	316,487,785,714	261,162,236,188	316,487,785,714	261,162,236,188
	Production [kWh/y]	63,297,557,143	93,680,150,004	31,648,778,571	93,680,150,004	0	93,680,150,004
	Savings [kWh/y]		*85,708,142,387*		*117,356,920,959*		*149,005,699,530*
	Avoided CO2e emissions [tCO_2e/y]		*40,711,368*		*55,744,537*		*70,777,707*
Heat	Consumption [MWh/y]	0	0	0	0	0	0
	Production [MWh/y]	0	1,209,142,064	0	1,209,142,064	0	1,209,142,064
	Savings [MWh/y]		*1,209,142,064*		*1,209,142,064*		*1,209,142,064*
	Avoided CO2e emissions [tCO_2e/y]		*574,342,480*		*574,342,480*		*574,342,480*
GHG reduction	Direct CO_2 emissions [tCO_2e/y]	272,471,291	233,041,458	252,886,762	220,216,457	233,302,233	207,391,456
	Avoided CO_2e [tCO_2e/y]		*39,429,833*		*32,670,305*		*25,910,777*
Total	Direct and indirect CO_2 emissions [tCO_2e/y]	392,736,649	312,595,449	388,185,290	299,770,448	383,633,931	286,945,447
	Avoided CO2e emissions without heat recovery [%]		*-20%*		*-23%*		*-25%*
	Avoided CO2e emissions with heat recovery [%]		*-167%*		*-171%*		*-175%*

4 Further considerations

The assessment performed in this study focused on process optimization, advanced real-time control and implementation of heat pumps as means to achieve energy positive WWTP operation, produce electricity and heat and reduce the carbon footprint of WWTPs. The reduction of CO_2e emissions targeted the main contributors to the operational carbon footprint of WWTPs, namely energy-related, N_2O and CH_4 emissions (Parravicini et al., 2020).

The present assessment did not cover other factors influencing the carbon footprint of WWTPs, such as the use of chemicals (e.g., P-precipitants, polymers for sludge dewatering) and sludge transport and disposal. The use of chemicals has been estimated to be a minor contributor to the carbon footprint of WWTPs compared to the factors considered in the present study (Parravicini et al., 2020), while emissions associated to sludge disposal (e.g., landfilling, agricultural use) are typically considered outside the scope for WWTPs (Coelho Brotto and Lake, 2022).

Owing to its widespread adoption, anaerobic digestion has been considered as the state-of-the art technology for sludge stabilisation. Other technologies (e.g., pyrolysis, gasification) are emerging as promising, alone or in combination with anaerobic digestion, for sludge management, contributing to avoided CO_2e emissions by increasing the recovery of biogas, reducing the volumes of stabilized sludge and facilitating carbon sequestration in soil. While it is beyond the scope of the present study, future assessments may require considering these technologies and their positive contribution to the carbon footprint reduction in the wastewater sector.

Globally, recovery of electricity and heat are the main destinations of the biogas produced from anaerobic digestion (Nguyen et al., 2021), therefore contributing to increasing the share of renewables in the energy production. With the progressive implementation of other renewable sources for energy production (e.g., wind energy), the contribution of biogas to avoided CO_2 emissions may become less evident, and alternative destinations can become of relevance. Biogas can be upgraded to biomethane, which is used as transportation fuel and/or sent to the natural gas network (IEA, 2020d). This strategy has been recently supported by the Swedish government (Regeringenkansliet, 2022) to increase the country's energy self-sufficiency, providing for avoided CO_2e emissions by replacing non-renewable energy sources for transportation and residential use. Alternative uses of biomethane (e.g., for microbial protein production) are emerging, which can further contribute to CO_2e emission reductions through more efficient feedstock and food production (Matassa et al., 2015). An assessment of the benefits deriving from alternative biogas destinations was beyond the scope of the present study and may deserve attention in the near future due to the rapidly increasing fossil fuel prices and the increasing reliance on biomethane.

5 Conclusions

The current report presents an evaluation of the current status of the wastewater treatment sector with respect to energy and carbon footprint and provides an estimate of the potential benefits to be achieved upon implementation of the Danish benchmark for energy-efficient, -positive and sustainable WWTP operation.

Energy optimization and direct GHG reduction

The estimation of the potential benefits was performed at city-wide, regional, and global scale. Findings from the evaluation highlighted that energy optimization of WWTPs and reduction of direct GHG emissions:

- can contribute to reducing a city's CO_2 footprint by 1% to 2%, corresponding to avoided CO_2e emissions of 40,000 to 235,000 tCO_2e/y for cities like Krakow, Valencia and Chicago
- can reduce operational (non-infrastructure related) CO_2e emissions from the European wastewater treatment sector, under realistic assumptions, by more than 50% while providing for cost savings of up to 2.3 billion EUR per year
- can reduce the total CO_2e emissions from the global wastewater treatment sector by up to 20%, while providing energy savings of more than 200,000,000 MWh/y and cost savings of up to 200 billion EUR per year
- can support the achievement of Sustainable Development Goal 6.3 through the implementation of state-of-the-art technologies and solutions for new WWTPs, helping to avoid up to 100,000,000 tCO_2e/y as compared to implementation of state-of-the-art treatment

Heat recovery

Heat recovery from WWTP effluents through the implementation of heat pumps has showed great potential and can contribute to satisfying 15-25% of residential heat demand at local, regional and global level. Its implementation is dependent on the availability of a district heating system, where the recovered heat can be used. When its implementation is feasible, heat recovery has the potential to support the wastewater treatment sector in becoming climate neutral and even climate positive, while representing a reliable solution to promote energy efficiency, grid stability, and energy independence.

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