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Carbon footprint of drinking water over treatment plant life span (2025–2075) is probably dominated by construction phase

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ABSTRACT

Drinking water companies must limit their effects on climate change. Therefore, in this study, we conducted a hybrid life cycle assessment (LCA) for a new drinking water treatment plant (DWTP) to be built in 2025 and expected to be operational until 2075. We focused on obtaining a nearly complete carbon footprint (CF), including both construction (activities and materials) and operation phases. We compared three DWTP concepts: (i) conventional treatment followed by granular activated carbon (GAC) and ultrafiltration; (ii) conventional treatment followed by reverse osmosis; and (iii) capillary nanofiltration followed by GAC. As the DWTP is to be built in The Netherlands, we considered the current plans of the European Union for reducing CFs using two future scenarios (reductions of 80% and 100% in 2050). We found that the CF of the construction over the lifetime of the DWTP accounts for 20–70% of the total (excluding beneficial effects), depending mainly on the electricity used (Dutch mix, solar, or wind) and the future scenario. This means that the construction phase should be investigated in detail to obtain a complete and accurate estimate of the total CF of drinking water production for new DWTPs.

1. Introduction

With the near-global ratification of the Paris Agreement and the Glasgow Climate Pact agreed upon at the 26th UN Climate Change Conference of the Parties, the world is aiming to reduce greenhouse gas (GHG) emissions to keep the global average rise in temperature to within 1.5 °C. The European Union (EU) is currently on a path to become climate-neutral by 2050. The GHG emissions of the EU are regularly reported, and the four main activities contributing to the largest amounts of emissions in 2018 were (EEA 2020) (i) combustion of fuels (1081 Mton CO_2 eq.), (ii) refining mineral oil (122 Mton CO_2 eq.); (iii) production of pig iron or steel (122 Mton CO_2 eq.), and (iv) production of cement clinker (120 Mton CO_2 eq.). According to the International Energy Agency (IEA), the materials used in construction (i.e. steel and cement clinker) and the buildings built from them account for approximately 40% of direct and indirect GHG emissions globally (IEA 2020a). Furthermore, buildings constructed nowadays in the EU will produce emissions for many years, as they continue to use electricity, gas, etc. Buildings will most likely last beyond 2050, when the net carbon footprint (CF) of the EU should be zero. This means that as the GHG emissions during the use phase decrease with time, the impact of the construction phase becomes relatively more important.

One method of determining the CF of products and buildings is through life cycle assessment (LCA). In the LCA of buildings, the pre-use, use, and after-use phases are separately described, and energy has traditionally been emphasised (Hauschild et al., 2018). In LCAs, buildings are often described in terms of embodied energy and operational energy. The average contribution of embodied energy to total energy use in buildings is approximately 39%. However, this value has a broad inclusion depending on the materials used, location and type of building, and methodology, which are not uniform in the different studies, complicating the drawing of definitive conclusions (Bahramian and Yetilmezsoy 2020).

Many LCAs have been conducted on (drinking) water treatment plants (DWTPs). Although direct comparison of the findings is somewhat complicated due to different system boundaries, water sources, treatment steps, functional units, and methods (Fantin et al., 2014), some conclusions can be drawn. Generally, the use of electricity and chemicals is the main contributor to the CF in the production of drinking water (Vince et al., 2008; Bonton et al., 2012). For some groundwater treatment plants, the direct emission of methane from the extracted

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List of abbreviations

CF –	Carbon footprint
Conv –	Conventional
DWTP –	Drinking water treatment plant
EU –	European Union
GAC –	Granular activated carbon
GHG –	Greenhouse gas
LCA –	Life cycle assessment
CapNF –	Capillary nanofiltration
rGAC –	Reactivated GAC
UF –	Ultrafiltration

groundwater can be the single largest contributor to the CF (Evides 2019). However, the researchers in this field have often excluded the construction of the DWTP (Sombekke et al., 1997; Mohapatra et al., 2002; Barrios et al., 2008; Tapia et al., 2008; Mery et al., 2014; Garfi et al., 2016; Saad et al., 2019). Some researchers have considered buildings and found that they accounted for a small part of the total CF, in general approximately 1–20% (Raluy et al., 2005; Muñoz and Fernández-Alba 2008; Vince et al., 2008; Bonton et al., 2012; Godskesen et al., 2013; Lemos et al., 2013; Igos et al., 2014; Bârjoveanu et al., 2019; Goga et al., 2019; Thomassen et al., 2021). However, we do not know how much of the impact of the pre-use phase was considered in these studies. Loubet et al. (2014) noted that building materials were considered in the reviewed studies of urban water systems, but the impact of the necessary construction work was not. This is also the case for the additional studies on DWTPs that we mention here (Raluy et al., 2005; Bonton et al., 2012; Godskesen et al., 2013; Bârjoveanu et al., 2019; Goga et al., 2019; Thomassen et al., 2021), except for one (Muñoz and Fernández-Alba, 2008), where excavation and transport to the treatment plant were considered. Muñoz and Fernández-Alba (2008) found that the pre-use phase accounted for approximately 2% of the global warming impact of a reverse osmosis brackish water desalination plant. In a review on desalination, Zhou et al. (2014) discussed the issue of the pre-use phase and noted that in a few situations, it can be a substantial (one-third to one-half) contributor to the total CF, mainly in cases in which extended system boundaries and renewable energy are used (Tangsubkul et al., 2005; Frutos et al., 2009; Jijakli et al., 2012).

Evides Waterbedrijf, a Dutch water utility, is currently preparing to construct a new DWTP. The water quality and cost are important criteria. However, as Evides wants to become climate neutral (Scope 1 and 2) and energy neutral (generating as much renewable energy on company-owned land and water (Mathijssen et al., 2020) to be used by the company), the CF of the new DWTP is of special interest. As such, in this study, we investigated the CF of a hypothetical new DWTP for different treatment concepts and scenarios, considering both the construction and use phases.

2. Methods

2.1. Goal and scope definition

2.1.1. Goal

Our aim with this analysis was to determine the CF of drinking water produced by a new DWTP. The plant is to be built in 2025 and has an expected lifespan of 50 years based on experience. We compare three different concepts in this section:

(i) Conventional treatment (coagulation, flotation, and rapid sand filtration) followed by filtration through granular activated carbon (GAC) and ultrafiltration (UF) (Conv-UF);
(ii) Conventional treatment followed by reverse osmosis (RO);
(iii) Capillary nanofiltration (CapNF) and subsequent filtration through GAC (CapNF).

Our primary focus in this study was the CF, so we could not draw a final conclusion regarding which option has the lowest overall environmental footprint.

2.1.2. Functional unit

The function of a DWTP is to produce (and temporarily store) drinking water. In this study, the functional unit was 1 m^3 of drinking water (Dutch standards) at the DWTP. We calculated all required inputs based on the expected life span of the DWTP (50-year lifetime, peak factor 1.5, and design capacity 11.5 Mm^3/year) and divided them by the total amount of drinking water that will be produced. We also included the abstraction of raw water and its transport to the DWTP.

2.1.3. Geographical and temporal scope

As a case study, we used the situation in The Netherlands, but the results may also be applicable to plants with a similar lifespan in other countries with similar levels of economy, technical development, and future plans for reductions in carbon emissions. The current EU policy aims to reduce the CF of the EU to zero within the life span of the proposed DWTP, which we considered in two scenarios.

2.1.4. System definitions and boundaries

In this analysis, we considered the following effects and processes in the hybrid LCA (Fig. 1). Unless noted otherwise, we considered them as EcoInvent processes:

- The building materials, work (via input/output database), and transport necessary for construction of the DWTP (the pre-use phase) and the abstraction and transport of raw water to the DWTP (including depreciation of the infrastructure necessary for bringing the raw water to the DWTP obtained from an input/output database).
- Energy, chemicals (reactivation of GAC based on supplier information and others based on EcoInvent), raw materials (e.g. membrane modules and reverse osmosis membranes based on supplier information), and maintenance required for drinking water production (obtained from an input/output database).
- We separately report the local and societal effects due to softening (if any) of raw water (Beeftink et al., 2020) as beneficial effects.
- We separately report the treatment and use of byproducts (iron sludge) resulting from the production processes as beneficial effects (AquaMinerals, 2020).

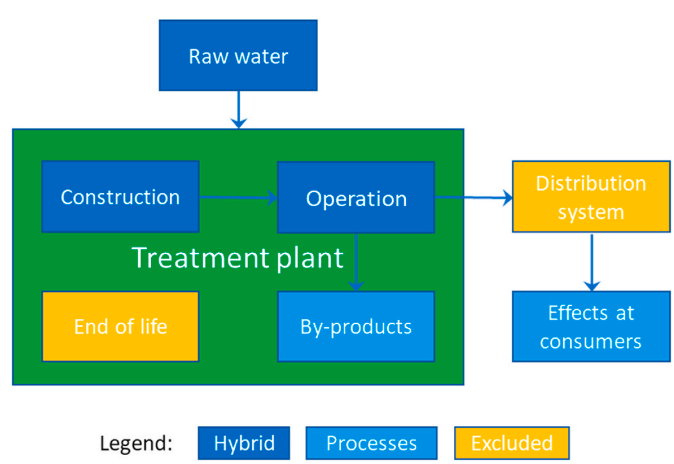

Fig. 1. System boundaries and type of LCA data used (hybrid or processes only).

Our analysis was mostly cradle-to-gate, with the exception of considering the beneficial effects of softening (mostly for consumers) and the use of byproducts. We did not consider the following inputs: demolition and/or recycling of the DWTP, as the environmental costs and benefits of demolition and recycling in 50 years are uncertain. The distribution system was outside the scope of this study, and we did not consider water losses in the distribution system as they are typically low in The Netherlands (approximately 5%, VEWIN 2019) but can be substantial in other countries. We also neglected the potential impact of treating the concentrate stream from reverse osmosis because it is strongly dependent on local circumstances, and information on this topic is scarce. The most likely scenario is disposal into sewers, which has no effect on the CF within the system boundaries.

2.2. Allocation

We applied allocation in this study for abstraction and pretreatment. Raw Meuse River water is transported through three water storage reservoirs of the Water winning Brabantse Biesbosch (WBB) in Biesbosch, where central softening is performed. The obtained raw water is distributed from this location to four DWTPs, and the allocation is performed per cubic meter of water at the point of storage at the WBB, proportional to the total quantity of water produced. For this purpose, electricity is needed to transport the water from the WBB to the DWTP (Table 1).

2.3. Data collection and quality

We conducted the LCA and ran the scenarios using Simapro 9.1.0.11 (PRé Sustainability, Amersfoort, The Netherlands). We calculated the total impact at the endpoint level and the CF at the midpoint level using the ReCiPe 2016 H method for both. We used underlying data in the following order of preference: from suppliers (for reactivation of GAC, production of reverse osmosis membranes, and partly for construction), EcoInvent 3.6 (unless otherwise stated), and the EU and DK input/output database (for maintenance, services, and buildings). For the impact of construction we considered various sources and ultimately decided upon using the most specific data available, a hybrid LCA of an existing water treatment plant (Pré Sustainability and Evides, 2021), as a proxy.

We collected the inventory data from the five most recent years (2015–2019) for raw water, pretreatment, and transport to the new DWTP; these are very high quality data as the monitoring has been extensive. For the new DWTP concepts, the inventory data were based on realistic estimates from the RHDHV cost calculator for DWTPs (https://kostenstandaard.nl/de-calculator/, in Dutch), which was the best available data for an initial comparison and were of medium-to-high quality (±30% for investment costs and ±20% for exploitation costs).

Table 1
Inputs and outputs for obtaining 1 m^3 of raw water at the DWTP.

Input	Amount	Unit	Database
Maintenance, depreciation, and other services	0.0376	EUR/m^3	EU and DK input/output
River water	1.2	m^3	EcoInvent 3.6
Wood pellets	2.24	g/m^3	EcoInvent 3.6
$Ca(OH)_2$	24	g/m^3	EcoInvent 3.6
H_2SO_4 (96%)	1.4	g/m^3	EcoInvent 3.6
NaClO	0.43	g/m^3	EcoInvent 3.6
Electricity	0.081	kWh/m^3	EcoInvent 3.6
Heat production from LPG	2.52	kJ/m^3	EcoInvent 3.6
Electricity from diesel (for emergency power)	0.0005	kWh/m^3	EcoInvent 3.6
Output			
$CHCl_3$	0.96	mg/m^3	EcoInvent 3.6
$CHBrCl_2$	0.56	mg/m^3	EcoInvent 3.6
$CaCO_3$ (stored in reservoir)	55	g/m^3	EcoInvent 3.6
Transport to new treatment plant Baanhoek	0.033	kWh/m^3	EcoInvent 3.6

Amounts are the average from Annual reports WBB 2015–2019.

3. Life cycle inventory

3.1. Raw water abstraction, pretreatment, and transport to treatment plant

We used the same raw water from the WBB for all proposed DWTP concepts. Raw Meuse River water is abstracted at the WBB, passed through three water storage reservoirs, and softened by the addition of $Ca(OH)_2$ in the third. The softening had a CF of approximately −0.014 kg CO_2 eq./m^3 and is reported separately, as it is a beneficial effect that mostly occurs in the homes of consumers (Beeftink et al., 2020). In cold winters, pH is corrected by the addition of H_2SO_4. For transport to DWTPs, NaClO is dosed to prevent mussel attachment to the transport pipes. The current location of Baanhoek is the proposed location of the new DWTP, so we measured and considered the electricity usage for transport to Baanhoek.

3.2. Proposed new DWTP concepts

The DWTP is projected to produce 11.5 Mm^3 of drinking water per year according to Dutch standards. In this study, we proposed and discussed three main concepts: (i) Conv-UF, (ii) RO, and (iii) CapNF. The different concepts have different advantages and disadvantages, which are only briefly discussed here, as we focused on comparing the CF of these concepts.

The Conv-UF DWTP option comprises coagulation with $FeCl_3$, flotation, rapid sand filtration, medium-pressure UV, filtration through GAC, and UF. This treatment concept will result in excellent drinking water that adheres to strict Dutch drinking water standards and is expected to positively affect the biological stability of the resulting drinking water (Schurer et al., 2019).

The RO DWTP option comprises coagulation with $FeCl_3$, flotation, rapid sand filtration, cation exchange (to prevent scaling), reverse osmosis, medium-pressure UV, and remineralisation. This last step is required to conform to the minimum water hardness of 1 mM according to the Dutch law for drinking water quality. This concept will produce the highest quality drinking water, but more raw water is needed, and the costs are also high (Table 2).

The CapNF DWTP option comprises CapNF, medium-pressure UV, filtration through GAC, and rapid sand filtration. CapNF is a relatively new technique, and its main advantage is that it can replace the entire pretreatment train ($FeCl_3$, flotation, and rapid sand filtration). It is expected to perform better in terms of environmental friendliness (Futselaar et al., 2002; Van Der Bruggen et al., 2004).

3.2.1. Operational phase

The maintenance costs, expected water recovery, and required electricity of the concepts are listed in Table 2; the investment costs per category in Table 3; and the exploitation costs in Table 4. From these, together with the data for raw water, we calculated the CF. We corrected the raw water amount to account for the water recovered by the DWTP.

Table 2
Projected investment costs, maintenance costs, recovery, and electricity usage for the three DWTP concepts (Evides, 2020).

Option	Investment (M EUR)	Maintenance (M EUR/year)	Recovery (%)	Electricity (kWh/m^3)
Conv-UF	58	0.87	87	0.55
RO	69	0.93	78	0.78
CapNF	57	0.75	85	0.56

Table 3
Investment cost per category for the three DWTP concepts (Evides, 2020) and used CF emission factor (Pré Sustainability and Evides, 2021).

	Civil engineering	Mechanical engineering	Electrical engineering	Design, administration, and supervision	First filling	Other costs	Unit
Conv-UF	17.9	13.9	8.7	8.5	2.8	6.1	M EUR
RO	20.6	18.7	10.1	10.2	1.8	7.6	M EUR
CapNF	15.4	10.0	9.4	8.7	9.4	4.0	M EUR
CF	0.986	1.02	0.206	0.146	0.734	0.146	kg CO_2 eq./EUR

Table 4
Projected consumables for the three DWTP concepts (Evides, 2020).

Consumables (100%)	Unit	Conv-UF	RO	CapNF
NaOH	ton/year	6.9	1.4	10
$FeCl_3$	ton/year	183	195	0
$NaHSO_3$	ton/year	12	5.5	0
HCl	ton/year	3.8	1.4	11
NaOCl	ton/year	3.6	0	4.4
$CaCO_3$	ton/year	0	70	0
CO_2	ton/year	0	78	0
CIEX resin	ton/year	0	17	0
NaCl	ton/year	0	3,759	0
GAC[a]	ton/year	131	0	131
Membranes[b]	m^2/year	2,750	13,714	21,926

The amount of consumables used is given considering their concentration was 100%.

[a] GAC is largely reused from the old DWTP and by reactivation. For example, in a reactivation cycle, approximately 10–15% of new GAC is needed to compensate for the lost volume.

[b] Membranes are typically purchased at the start and replaced periodically. For simplicity, we used the average expected lifetime and annual use. We do not expect dosage of antiscalant will be needed, either due to pretreatment (in the case of RO) or the specific properties of the membranes (for UF and CapNF).

Mostly, we used data from the EcoInvent and the EU and DK input/output databases, with some exceptions, as outlined below.

To calculate the CF of the DWTP with reverse osmosis, we used the CF provided by the supplier of 3.25 kg CO_2 eq./m^2 surface area (DOW, 2018) for the manufacturing of the membranes, and not the much higher value obtained from the EcoInvent database. The EcoInvent process is outdated, including the emissions of a chemical with a very high CF (CFC-113), resulting in a CF that is 29 times higher for the manufacturing of the membranes than the value provided by the supplier. We discuss this further in the Sensitivity Analysis section.

To calculate the CF of the DWTPs with reactivated GAC (rGAC), we used the value provided by the supplier of 1.53 kg CO_2 eq. mg/kg rGAC as part of the tender, instead of the higher value from EcoInvent.

The production of iron sludge in the coagulation and flotation processes is also considered. According to AquaMinerals (2020), the reuse of iron sludge replaces the otherwise necessary use of $FeCl_3$ in biogas installations and/or wastewater treatment plants. The net CF (including handling and transport) for the reuse of iron sludge is approximately −0.006 kg CO_2 eq./m^3 of produced drinking water for the DWTP concepts Conv-UF and RO (Table 3).

The amount of $CaCO_3$ needed for remineralisation that has to be used for the RO option is relatively low, as the proposed DWTP location also has a groundwater DWTP on site, which normally softens the water with pellet reactors. For the RO option, we assumed that the drinking water from both plants would be mixed. In this case, the groundwater at the DWTP does not need to be softened, and turning it off would reduce the necessary remineralisation for RO by approximately 67% compared with a situation where mixing with hard drinking water is impossible. We subtracted the change in the CF from no longer requiring the softening process, which uses considerable amounts of NaOH (−0.021 kg CO_2 eq./m^3 of produced drinking water in the RO option), from the CF of the RO option. Moreover, the RO option produces drinking water with lower hardness than other concepts. Lowering the hardness from 1.4 to 1.0 mM leads to an estimated additional beneficial effect on the CF of −0.029 kg CO_2 eq./m^3 (Beeftink et al., 2020).

3.2.2. Construction and end-of-life phase

To determine the actual impact of a DWTP over its lifetime, the impacts of the construction phase and, ideally, the end-of-life phase must be considered as well. The impact of the end-of-life phase of a DWTP that is yet to be built and is expected to last 50 years is uncertain but is highly likely to be very small compared with the impact of the construction phase, as the EU currently plans to be carbon neutral by 2050, well before 2075, when the end-of-life phase becomes pertinent. Therefore, we neglected the end-of-life phase.

Several methods can be used to consider the construction phase either via processes and/or input/output databases. The Exiobase input/output database states that the impact of construction in The Netherlands is approximately 0.28 kg CO_2 eq./EUR. The EU and DK input/output database does not have a separate category for construction but has one for nonresidential buildings, which have a CF of approximately 0.72 kg CO_2 eq./EUR. The latter value probably results in an overestimation of the CF of the construction phase, as the average embodied energy in buildings is approximately 39% (Bahramian and Yetilmezsoy 2020). We corrected the figure of 0.72 kg CO_2 eq./EUR for this, which produced a value for the CF of nonresidential buildings of 0.28 kg CO_2 eq./EUR, which is the same as that in Exiobase.

More specific information is available, as CE Delft published a macro-LCA on the CF of the Dutch construction industry (CE Delft 2015). They considered the use of construction materials, transportation, energy used in construction and demolition, and processing of materials released during demolition. The total CF of the Dutch construction industry, estimated by CE Delft, is approximately 9.5 Mton. Together with information from the Economics Institute of the Dutch Construction Industry (Eib, 2011) about the total value of the produced buildings of approximately 51 B€ for the same year as the macro-LCA, the CF is approximately 0.2 kg CO_2 eq./€. This is probably an underestimation of the CF of construction because the CF of demolition is probably lower than that of construction, and only the main contributing activities to the CF are considered in this study.

Here, we have considered the most specific information available, a hybrid LCA (materials taken into account via EcoInvent and work via Exiobase) of an existing water treatment plant (Pré Sustainability and Evides, 2021) as a proxy for the impacts of construction. The impacts of construction on the various DWTP concepts are taken into account via the costs of civil engineering, mechanical engineering, electrical engineering, first filling, other costs (process controls, general facilities, security, installation costs, and construction interest), and estimated costs for design, administration, and supervision (Table 3).

As we use a proxy for the construction and no better information is available, we increased the uncertainty in the CF derived from the construction costs (with an uncertainty of ±20%) to ±40%.

3.3. Future scenarios and sensitivity analysis

3.3.1. Future scenarios

One of the main issues when determining the CF of a new DWTP is that part of the emissions will occur in the future, and expected changes should be taken into account. As the DWTP will likely last 50 years and be built in the Netherlands, the current EU plans to reduce CF should be part of the calculations. As the future is uncertain, any attempt to do so is burdened by significant added uncertainty. Moreover, the magnitude of the uncertainty is unknown. Here, we increased the uncertainty of the resulting CF calculations from ±30% in the exploitation costs from the cost calculator to ±40% and for the construction from 40% to 50%. These uncertainty values are inaccurate at best and should only be considered as a general indication of the real uncertainty.

At the time of this study (mid 2021), the EU was, according to its plans to reduce carbon emissions, at 20% lower emissions than that in 1990. In the coming years, this reduction will further increase to (at least) 40% in 2030 and 80–95% in 2050. New plans have recently been accepted for rapid reductions of 55% in 2030 and 100% in 2050. These plans are reasonably likely to be implemented; therefore, we calculated the average CF of the DWTP concepts for two future scenarios: reduction in the CF of maintenance, consumables, and electricity (1) linearly from 20% in 2020 to 100% in 2060 (passing 80% in 2050), and (2) linearly from 20% in 2020 to 55% in 2030 and from there to 100% in 2050. It is possible that past the point of net zero carbon emissions, emissions will become negative. However, this is not considered in future scenarios. If we assume that the new DWTP will be constructed in 2025, the future scenarios 1 and 2 will reduce the emissions of maintenance, consumables, and electricity over the lifetime of the DWTP by approximately 70% and 80%, respectively, compared to those in 2020 (which should already be reduced by approximately 20% from the emissions in 1990).

3.3.2. *Sensitivity analysis*

A sensitivity analysis was performed for the CF of the UF, reverse osmosis, and CapNF membranes, and the CF of the construction phase. The effect of the source of electricity (Dutch mix, solar, or wind) is

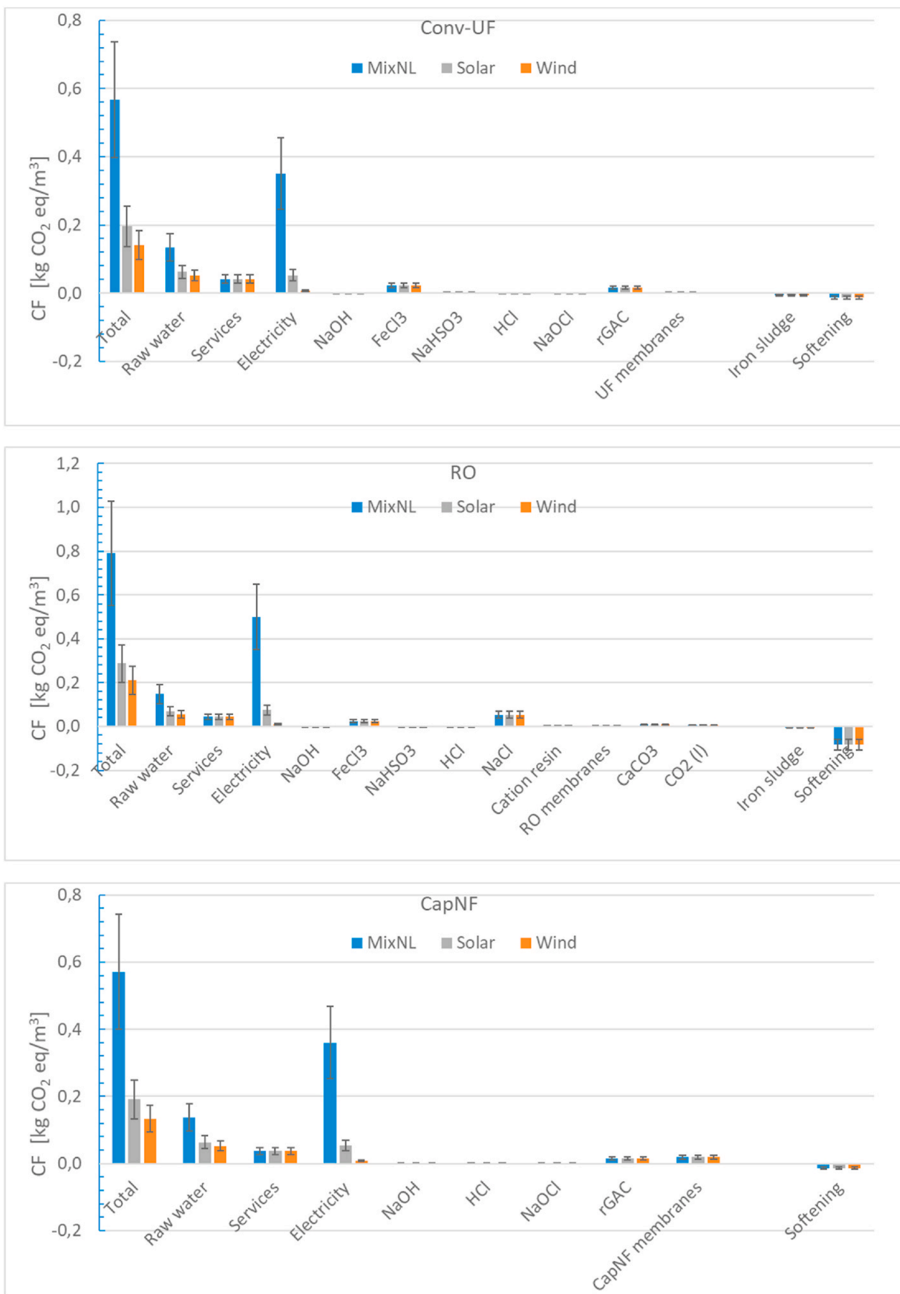

Fig. 2. CF of the operational phase of the three DWTP concepts (Conv-UF, RO and CapNF) in 2020, for three different electricity compositions; mix NL (blue bars), solar (grey bars) and wind (orange bars). The beneficial effects (not included in the total) are also shown, at the end of each graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

discussed in the Results section, as it is central to understanding the CF of the proposed DWTP concepts. The Dutch electricity mix is heavily dependent on fossil fuels, being primarily generated by use of natural gas and coal. Renewables contribute below 20% of Mix NL (IEA, 2020b).

4. Results and discussion

4.1. LCA results

4.1.1. Operational phase

Here, we show and discuss the CF of the operational phase in 2020 (Fig. 2) as the construction and end-of-life phases are neglected. It can be seen that for the Dutch electricity mix (Mix NL, blue bars), the CF of the operational phase of RO is the highest (0.79 kg CO_2 eq./m^3 in total) and that of Conv-UF and CapNF is nearly the same (0.57 kg CO_2 eq./m^3, total for both). The main share of the total CF is caused by the impacts of used electricity, raw water (whose CF is largely composed of electricity, chemicals, and services), services, and used NaCl. For electricity and chemicals, this is in agreement with previous findings (Vince et al., 2008; Bonton et al., 2012) except for the contribution of services, taken into account here for the DWTP concepts via the expected costs for maintenance and the EU and DK input/output database. This contribution seems to have been overlooked in published studies on LCA of DWTPs.

If solar and wind are used as the electricity source, the CF of the operational phase of the DWTP with RO in 2020 remains the highest at 0.29 and 0.21 kg CO_2 eq./m^3 for solar and wind energy, respectively. For Conv-UF the CF decreases to 0.20 and 0.14 kg CO_2 eq./m^3 for solar and wind energy, respectively. For CapNF, it decreases to 0.19 and 0.13 kg CO_2 eq./m^3, respectively. For solar, electricity, and raw water are two of the largest contributors to the CF. For wind, the contribution of electricity to the CF becomes smaller than that of some of the individual chemicals, such as $FeCl_3$.

4.1.2. Construction phase

The costs of the various categories of the construction phase determine the CF of the construction phase in the calculations. The proxies used, the same categories from a complete LCA of a water treatment plant including materials and work (Pré Sustainability and Evides, 2021), probably provide a reasonable estimate of the CF of the construction of the DWTP concepts. This will allow us to compare, at least indicatively, the CF of the construction phase to that of the operational phase.

The total CF of the construction of the Conv-UF and CapNF DWTP concepts, over a lifetime of 50 years, are approximately the same (Table 5) at 0.066 ± 0.026 kg CO_2 eq./m^3 and 0.063 ± 0.025 kg CO_2 eq./m^3 respectively. The CF of the RO DWTP construction is larger at 0.079 ± 0.032 kg CO_2 eq./m^3, as civil and mechanical engineering is more expensive. The calculation of the relative contribution of the construction phase to the total is very uncertain; because of the propagation of the uncertainty, the total uncertainty in the calculation needs to be added, and thus becomes ±70% in comparison with the operational phase in 2020. Nevertheless, the part of the CF of the construction phase of the total can be calculated, leading to a figure of approximately 10% (5–19%, including the uncertainty) of the total if the Dutch electricity mix is used and for 2020. If solar and wind power are used, this increases to approximately 24% (11–40% including the uncertainty) and 30% (15–48% including the uncertainty), respectively. This is somewhat in agreement with the results presented thus far in the literature regarding the contribution of the construction phase to the CF of DWTPs, which were mostly found to be small (Raluy et al., 2005; Muñoz and Fernández-Alba 2008; Vince et al., 2008; Bonton et al., 2012; Godskesen et al., 2013; Lemos et al., 2013; Igos et al., 2014; Bârjoveanu et al., 2019; Goga et al., 2019; Thomassen et al., 2021; Tangsubkul et al., 2005; Frutos et al., 2009; Jijakli et al., 2012).

4.2. Future scenarios and sensitivity analysis

4.2.1. Future scenarios

To determine the CF of drinking water from a DWTP over its lifetime of 50 years, the future needs to be considered, not just the present. Obviously, making predictions on these long timescales is fraught with uncertainties. Nevertheless, it can lead to useful insights. We propose two future scenarios for the EU, where this decrease has been considered for all the resources used in the operational phase. First, we discuss the conservative scenario where the CF of the EU will decrease by only 80% in 2050, and second, the scenario where the CF of the EU will decrease by 100% by 2050.

In Fig. 3, the CF of the three DWTP concepts are shown for the conservative future scenario, including both construction and operation. The CF of the construction phase is basically the same as that shown in Section 4.1.2.2, as it does not depend much on the future. The CF of the operational phase however, is decreased strongly – from 0.79 to 0.24 kg CO_2 eq./m^3 for RO, and from 0.57 to 0.18 kg CO_2 eq./m^3 for Conv-UF and CapNF, respectively. This effect has already been shown for future electricity mixes (Godskesen et al., 2013), but to the best of our knowledge, it has not been shown before for the entire operational phase.

The decrease in the CF of the operational phase when considering the Dutch electricity mix increased the contribution of the construction phase from approximately 10% (5–19%) to approximately 26% (12–47%). Although these numbers are burdened with considerable uncertainty, this shows that, for a DWTP built in 2025, the CF of the construction phase should not be neglected if one wants to determine the CF of the produced water over the lifetime of the DWTP.

In the case of solar, the CF of the operational phase is also decreased strongly, from 0.29 to 0.09 kg CO_2 eq./m^3 for RO, and from 0.20 to 0.19 to 0.06 kg CO_2 eq./m^3 for Conv-UF and CapNF, respectively. This, together with the added uncertainty for the future scenario, increases the contribution of the construction phase when solar power is used from 24% to 50% (again, with large uncertainties). Wind power increases from 30% to 59% when considering the reduction in the CF of the EU by 80% in 2050. This again shows that the construction phase should be considered when determining the CF of produced drinking water for a DWTP which is to be built in the near future.

In Fig. 4, we show the CF of produced drinking water over the lifetime of the three DWTP concepts for the future scenario, where the CF of the EU is reduced by 100% by 2050. The CF of the construction phase is the same as that shown in section 4.1.2.2. The CF of the operational phase for the Dutch electricity mix is decreased even further compared

Table 5
CF of the construction phase of the three DWTP concepts.

	Civil engineering	Mechanical engineering	Electrical engineering	Design, administration and supervision	First filling	Other costs	Total	
Conv-UF	0.031	0.025	0.003	0.002	0.004	0.002	0.066	kg CO_2 eq./m^3
RO	0.035	0.033	0.004	0.003	0.002	0.002	0.079	kg CO_2 eq./m^3
CapNF	0.026	0.018	0.003	0.002	0.012	0.001	0.063	kg CO_2 eq./m^3

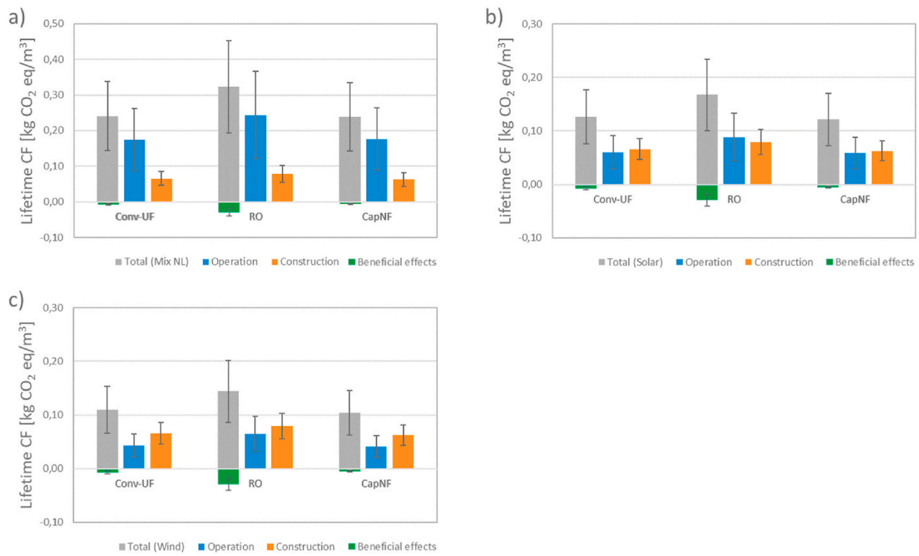

Fig. 3. CF of the three DWTP concepts for conservative future scenario 1: 80% reduction in the CF of the EU by 2050. The CF is calculated over the lifetime of the DWTP concepts for three electricity sources: a) the current Dutch electricity mix, b) solar, and c) wind, including the construction, operation, and beneficial effects (use of iron sludge and softening).

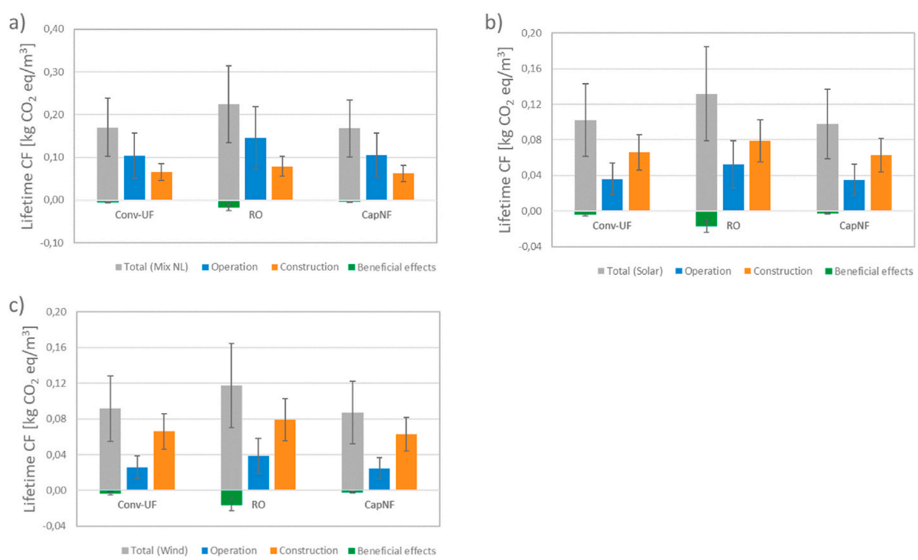

Fig. 4. CF of the three DWTP concepts for future scenario 2: 100% reduction in the CF of the EU by 2050. The CF is calculated over the lifetime of the DWTP concepts for three electricity sources: a) the current Dutch electricity mix, b) solar, and c) wind, including the construction, operation, and beneficial effects (use of iron sludge and softening).

with the conservative future scenario, to 0.15 kg CO_2 eq./m^3 for RO and to 0.10 kg CO_2 eq./m^3 for Conv-UF and CapNF, respectively. This decrease increased the relative contribution of the construction phase to the CF for the Dutch electricity mix to approximately 37% (19–64%, including uncertainty). For solar and wind energy, this increased to approximately 63 and 70%, respectively. Even though the underlying number has a very large uncertainty (±80%), this shows that the contribution of the construction phase probably becomes the largest contributing factor in the CF of the produced drinking water when renewable sources of electricity and the long term of the DWTP are considered.

4.2.2. Sensitivity analysis

For the UF and CapNF membranes, the footprints as provided by the manufacturer and obtained for similar membranes from EcoInvent are similar, so the sensitivity of the CF for these is low. The increase in CF was only 0.002 and 0.0002 kg CO_2 eq./m^3, respectively for UF and CapNF, respectively. For reverse osmosis membranes, however, the CF of the membranes is approximately a factor of 29 higher for the process data in EcoInvent than using data reported by the manufacturer. This has a rather large effect on the CF of the operation of the RO DWTP concept, which increases by 0.11 kg CO_2 eq./m^3, which is 12%, 27%, and 34% for the Dutch mix, solar, and wind, respectively (Fig. 5). The high impact of reverse osmosis membranes is owing to the emissions of CFC-113, a member of the chlorofluorocarbons, in the EcoInvent process. The use of CFC-113 has been increasingly regulated and has been eliminated since 2010 under the universally ratified Montreal protocol (UNEP, 2020). Thus, it is unlikely that this is a realistic scenario.

For the CF of construction, we used proxies based on the hybrid LCA of a water treatment plant. Other values are available: CE Delft published a macro-LCA for construction and demolition in the Netherlands, leading to a CF of 0.28 kg CO_2 eq./m^3. The CF from Exiobase (an input/

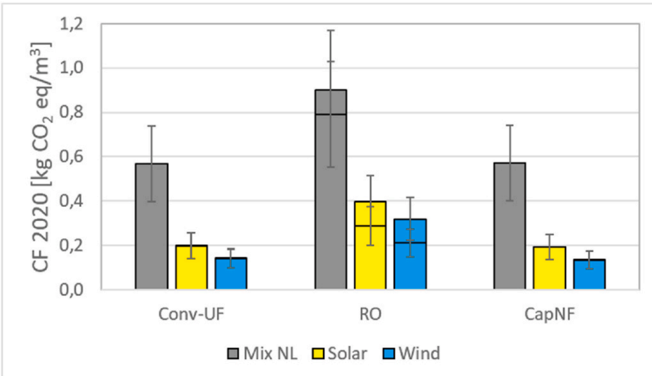

Fig. 5. Sensitivity analysis for the CF of the membranes for baseline year 2020. The increase in the CF is shown as a second bar on top of the baseline case.

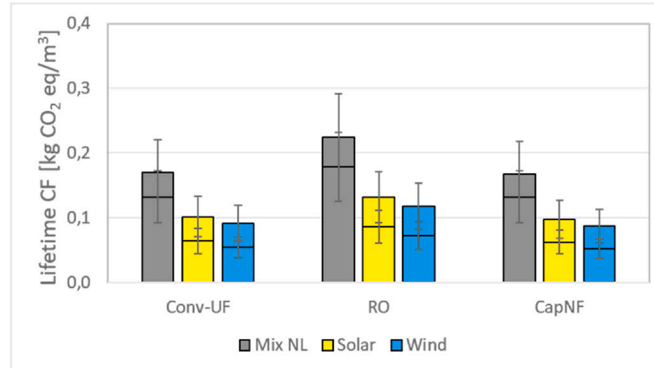

Fig. 6. Sensitivity analysis of the effect of low (Exiobase) and baseline (proxy) CFs for construction on the total lifetime CF of the three DWTPs for the Dutch mix, solar, and wind, and the scenario with 100% reduction by 2050.

output database) for construction was the same at 0.28 kg CO_2 eq./€. The EU and DK input/output database gives a much higher value for nonresidential buildings of 0.72 kg CO_2 eq./€, which is comparable to those derived for the construction of DWTP concepts. As the values from CE Delft and Exiobase were approximately three times lower than the values we derived here, we analysed the sensitivity of the CF of construction from Exiobase.

The sensitivity analysis for the three DWTP concepts; for the scenario with a 100% reduction in the CF of the EU by 2050; and for the Dutch mix, solar, and wind is shown in Fig. 6. The total CF of the DWTP concepts varies from 0.13 to 0.22 kg CO_2 eq./m^3 for the Dutch mix, and from 0.052 to 0.13 kg CO_2 eq./m^3 for solar and wind power. The impact of the construction phase for the low-CF construction is approximately 20%, 42%, and 51% for the Dutch mix, solar power, and wind power, respectively (again, with large uncertainty margins). For the baseline case, it was approximately 37%, 63%, and 70% for the Dutch mix, solar power, and wind power, respectively. This sensitivity analysis showed that the impact of DWTP construction on the CF of the produced drinking water for Conv-UF when using the Dutch mix would be 20%–39% of the total CF (excluding the estimated 40% error in the obtained figures). This finding showed that the construction phase is a crucial factor in LCA. With wind as the electricity source, the contribution ranges from 52% to 72% of the total. This analysis showed that much more attention needs to be paid to the impact of construction in LCAs on this topic, especially when renewable energy is to be used as the main source of electricity.

5. Conclusions and recommendations

In this study, we estimated the CF of drinking water production from three DWTP concepts (Conv-UF, RO, and CapNF) to be built in 2025 and expected to be in operation for 50 years for three electricity mixes (Dutch mix, solar, and wind power), including the construction and operational phases. We proposed two future scenarios: one conservative scenario with a reduction in the CF by 80% by 2050 and one with a reduction of 100% by 2050. We found the RO concept has the highest CF owing to its relatively high electricity demand. Conv-UF and CapNF have similar CFs.

We showed that the contribution of the construction phase to the total CFs of the DWTP concepts is an important factor that is currently uncertain because the underlying data are not specific. Until data specificity is improved, estimates of the CF of drinking water production will remain inaccurate.

The realistic CF for producing drinking water by a DWTP to be built in the EU in 2025 is described by the future scenarios. These results indicated that when renewable energy sources are used, the CF of the construction phase can exceed half of the total CF over the expected lifetime of 50 years. Again, this shows that this contribution should be modelled in much more detail (including needed work and used materials, e.g. concrete and steel). If ensuring that produced drinking water has a low CF is a priority, the construction phase must be included in the calculations.

CRediT authorship contribution statement

Bas Hofs: writing—original draft, writing—review and editing, conceptualisation, project administration, investigation, methodology, data curation, visualisation, and funding acquisition. **Wilbert van den Broek:** writing—review and editing and methodology. **Andries van Eckeveld:** writing—review and editing and data curation. **Albert van der Wal:** writing—review and editing and funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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