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Decentralized drinking water treatment using Point-of-Use systems

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Bridging Science to Practice

Report

Decentralized drinking water treatment using Point-of-Use systems

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Managementsamenvatting

Aanpak voor vergelijking verbeterde gecentraliseerde waterzuivering en aanvulling met Point of Use (POU)

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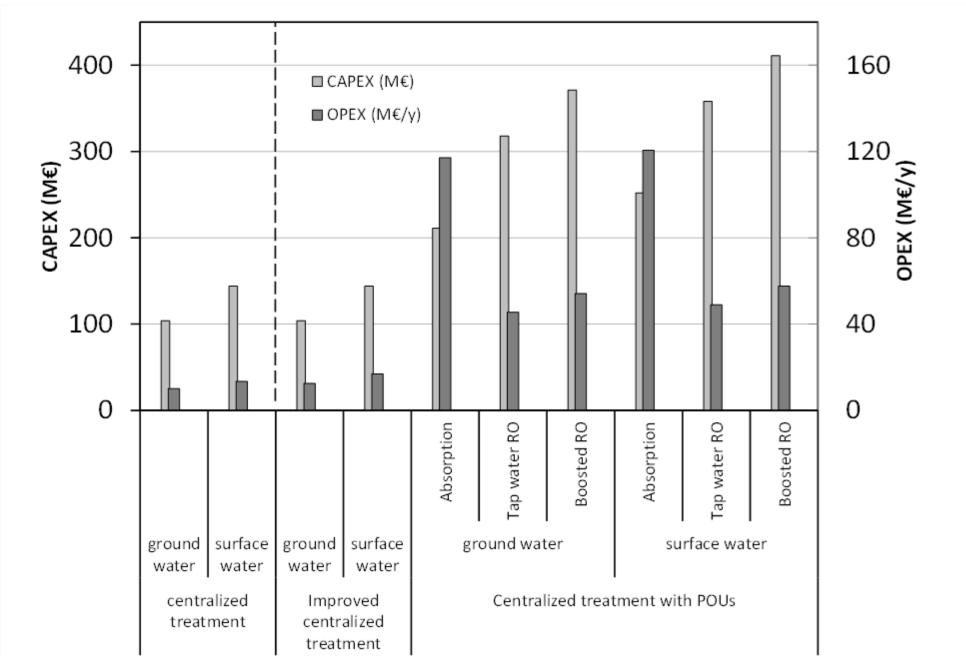
Om te voldoen aan de steeds strengere regelgeving voor waterkwaliteit, kunnen waterbedrijven overwegen “Point-of-Use” systemen te installeren bij de drinkwaterkraan van huishoudens. In dit rapport zijn twee scenario's vergeleken op het gebied van kosten, duurzaamheidsindicatoren zoals waterterugwinning en de risico's en uitdagingen: 1) verbeterde gecentraliseerde zuivering door uitbreiding met verhoogde regeneratiecycli van actieve kool en 2) de bestaande gecentraliseerde waterzuivering aangevuld met POU's aan de drinkwaterkraan van de eindgebruikers. Het verhogen van de regeneratiecycli van actieve kool blijkt kosteneffectiever. Voor door leidingwaterdruk aangedreven RO POU's leidt een lage waterterugwinning tot 22% extra waterverbruik. De conclusies van deze studie kunnen veranderen als gecentraliseerde waterzuivering gebruik maakt van andere technologieën dan bezinking en adsorptie. Daarom moet de toepassing van POUs aan de drinkwaterkraan ook worden onderzocht in andere scenario's. De huidige vragen, zoals gecertificeerd onderhoud, zuiveringsefficiëntie en certificering, blijven open kwesties in POU-systemen in Nederland.



Overzicht van de kosten voor alle scenario's die in dit rapport zijn onderzocht.

Belang: moeten POU's worden overwogen voor toekomstige watervoorziening?

In de toekomst zal de bestaande infrastructuur voor drinkwaterbehandeling mogelijk niet voldoende zijn om te voldoen aan de steeds strengere regelgeving voor waterkwaliteit of om nieuwe verontreinigende stoffen te verwijderen.

Daarom rijst de vraag of het gecentraliseerde systeem in de toekomst moet worden uitgebreid, of dat de bestaande gecentraliseerde behandeling moet worden aangevuld met Point-of-Use (POU) systemen bij de drinkwatertappunten van huishoudens, die alleen een extra behandeling geven aan het water dat wordt gebruikt voor directe consumptie en voor koken.

Aanpak: twee scenario's vergeleken op basis van literatuuronderzoek en deskundigenraadpleging
Er zijn twee scenario's vergeleken qua kosten, waterterugwinning en risico's en uitdagingen:

- gecentraliseerde waterzuivering aangevuld met POU's aan de drinkwaterkraan bij eindgebruikers en
- een verbeterde gecentraliseerde zuivering.

Deze scenario's werden opgesteld voor grondwater en oppervlaktewater, binnen vooraf gedefinieerde aannames rond waterzuiveringstechnologie (op basis van bezinkings- en adsorptietechnologieën) doelverontreinigingen en in beschouwing genomen POU-systemen. Hiervoor werd onder meer ingezet: literatuuronderzoek, raadpleging van deskundigen, raadpleging van commerciële partijen en programmakostensoftware om onder andere CAPEX (kapitaaluitgaven) en OPEX (operationele kosten) te berekenen.

Resultaten: binnen de onderzochte scenario's verhoogt gebruik van POUs de CAPEX en OPEX
De CAPEX- en OPEX-kosten van beide scenario's worden getoond in de figuur. Het eerste scenario is gebaseerd op een uitgebreide gecentraliseerde zuivering, met verhoogde regeneratiecycli van actieve kool. Het tweede scenario is gebaseerd op een bestaande gecentraliseerde zuivering, aangevuld met POU's aan de drinkwaterkraan van de eindgebruikers. Alle scenario's zijn uitgewerkt voor zowel grondwater als oppervlaktewater.

Binnen de onderzochte scenario's is het verhogen van de regeneratiecycli van actieve kool het meest kosteneffectief. Het toepassen van POU's op leidingwater bij de eindgebruikers verhoogt de CAPEX en OPEX. Voor door leidingwaterdruk aangedreven RO POU's leidt een lage waterterugwinning tot 22% extra waterverbruik. De certificering, het onderhoud en de biologische veiligheid van POU's blijven onopgeloste problemen.

Toepassing: POU's mogelijk relevant voor andere scenario's, open vragen nog beantwoorden
Met andere scenario's kan de hier uitgevoerde vergelijking natuurlijk anders uitpakken. Een gecentraliseerde behandeling op basis van RO heeft immers andere kenmerken, zoals hogere kosten, lagere waterterugwinning, maar ook een betere waterkwaliteit. Bovendien zou uitgebreid onderzoek naar duurzaamheidskwesties, gebaseerd op LCA (inclusief materiaalvoetafdruk voor actieve kool en andere materialen van POU-systemen) meer inzicht verschaffen. POU's blijven een mogelijk relevante alternatieve waterbehandelingsstrategie, vooral als ze worden gekoppeld aan andere scenario's dan in dit rapport worden besproken. Open vragen blijven er nog over gecertificeerd onderhoud, zuiveringsefficiëntie en certificering van POU-systemen in Nederland.

Rapport
Dit onderzoek is beschreven in het rapport *BTO 2023.040 Decentralized drinking water treatment using Point-of-Use systems*.

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Contents

1 Introduction

In the Netherlands we have a central system to supply drinking water with strict quality guidelines. However, due to stricter guidelines and emerging contaminants, the current centralized drinking water systems might not be sufficient in the future. Conventional control strategies, particularly relying on sedimentation and adsorption technology, have limited ability to mitigate exposure to emerging contaminants such as per- and polyfluoroalkyl substances (PFAS) or other organic micropollutants (OMPs). Furthermore, contaminants providing from the distribution system, such as lead, are also not being removed by centralized treatment.

The most straightforward option is to upgrade the centralized drinking water treatment plants to filter out these emerging contaminants. An alternative approach would be to keep the current centralized drinking water treatment plants as they are, and treat the water used for cooking and drinking by applying a Point-of-Use (POU) system at the drinking water tap of the household. With such an approach, only the water that is actually consumed is treated to a higher quality, while the water used for non-consumption purposes (e.g. flushing toilets, showering) is not further treated at household level. The purpose of this report is to compare both scenario's in terms of costs, sustainability and risks, namely an upgrade of the current centralized system versus the current centralized system complemented, at household level, with POUs placed at the drinking water tap.

Presently, there are POU systems available to remove all sorts of water contaminants. Therefore, in order to define workable and applicable case-studies to the Netherlands, a selection of POUs to be addressed in this report needed to be made. The selected POUs should allow removal of target contaminants relevant to the drinking water quality of the Netherlands. A group of water treatment experts of KWR was gathered to select, based on their experience and knowledge, which emerging contaminants would be relevant to address in this report. The microbiologically safety of the drinking water is not an issue in the Netherlands. In Chapter 2, the target emerging contaminants to be addressed in this research are described.

As aforementioned this report aims to compare: the centralized treatment completed with POUs at the drinking water tap of the end-users; and an upgraded centralized treatment to remove the target contaminants. Therefore, a typical centralized treatment, to be subjected to an upgrade needed to be selected. The drinking water treatment in the Netherlands relies on various treatment processes and operations, which vary among other factors per water company and water source. A single typical water treatment train, applicable to the whole of the Netherlands, is therefore not possible to define. On the other hand, some water companies in the Netherlands are aiming to remove target contaminants, addressed in the report, by intensifying the regeneration cycles of activated carbon. Consequently, together with the water experts, also previously supporting the selection of the target components, a choice of water treatment trains based on sedimentation and adsorption was made. Two different water sources would be considered, namely groundwater and surface water. Chapter 2 identifies the water treatment trains addressed in this report, as well as the definitions and assumptions applied in this research.

The selection of targeted contaminants provided the basis for an initial POU choice. Furthermore, the selected POUs should be commercially available. In Chapter 3, a technical overview of common commercial POUs is given aiming at the removal of the target contaminants defined in Chapter 2. The chapter describes the current status of POU systems, technologies applied, efficiency, household location, maintenance and criteria used by previous authors to select POU systems. In Chapter 4, a technical and overall POU selection is proposed, based on criteria such as capacity, efficiency, location and availability. To address these criteria, POU systems providers in the Netherlands were consulted.

In Chapter 5, a comparison between an extended centralized drinking water treatment system, relying on intensified carbon cycle regenerations; and the existing centralized drinking water treatment system, complemented with POUs at the drinking water tap of the end-user, is presented. The comparison addresses costs, sustainability, risks and challenges of both options. Chapter 6 presents the conclusions and recommendations for further research and applications.

The overall goal of this report is to support strategic decisions about future drinking water treatment approaches (centralized or decentralized). The scope of this report is limited to the conventional water treatment plants, namely selected water treatment plants considered representative for surface and groundwater treatment and relying on sedimentation and adsorption technology. Furthermore, the report focuses on POU systems currently available on the market. The report does not take into account future developments in POUs nor in drinking water treatment plants.

2 Scope and assumptions

2.1 Definition of Point-of-Use

In this report we will use the following definition of Point-of-Use (POU) systems:

- A POU system only treats the water being used for drinking and cooking inside one single household.

The remaining definitions associated to decentralized systems, which are useful to understand the context and capacity of POU systems, are given in chapter 3.

2.2 Target pollutants

2.2.1 Organic micropollutants(OMPs)

There is a broad class of Organic Micropollutants (OPMs) which come from industrial and pharmaceutical use, as well as fluorinated ones (further discussed in section 2.2.2). The size, type and properties are dependent on the type and source of water used for drinking water. In general, this class of pollutants is relatively small (80 – 500 Da) and varies greatly in charge and hydrophilicity (Hofman-Caris et al. 2018). Typically their acceptable maximum concentrations are in the order of µg/L but they depend highly on the toxicity of the specific compound.

Hofman-Caris et al. (2018) selected a group of 18 OMPs. The selection was based on compounds which could not be sufficiently removed at current conventional ground or surface water treatment relying based on sedimentation and adsorption techniques. The selection proposed by (Hofman-Caris et al. 2018) includes the following OMPs: dimethylsulfamide; diphenyl clodazon; amidotrizoic acid; acesulfame; diglyme; gabapentine; triglyme; 2,6-dichlorobenzamide; phenazone; metazachlor; salicylic acid; metolachlor; bromoacyl; bentazon; 2-methyl-4-chlorphenoxyacetic acid; meta-chlorophenylpiperazine; dimethenamid.

The Ministerie van Infrastructuur en Waterstaat (I&W), also proposed a list of OMPs as indicators which included the following compounds: 4-5 methylbenzotriazole, benzotriazole, carbamazepine, clarithromycin, diclofenac, hydrochlorothiazide, metoprolol, propranolol, sotalol, sulfamethoxazole and trimethoprim. The selection provided from the *Rijksinstituut voor Volksgezondheid en Milieu* (RIVM), executing the task at the request of the Ministry I&W (RIVM 2019). The compounds in the I&V list were selected because they could hardly be removed in the existing wastewater treatment plants, but there is technology able to remove them. Therefore, it is expected that by implementing the latter technologies, removal of other OMPs not currently mentioned in the I&V list, can also be achieved (RIVM 2019). Stowa extended the list, proposed by I&V, with the following OPMs: amisulpride, azithromycin, candesartan, citalopram, furosemide, gabapentine, irbesartan and venlafaxine (Nieuwenhuis et al. 2021).

The available information regarding the removal of specific OMPs by POUs is very limited. We will report all the information found regarding the removal of OMPs by mentioning the specific OMPs targeted in each research study.

2.2.2 Fluorinated organic micropollutants (PFAS)

Specifically for the fluorinated organic micropollutants, PFAS, there have been a few studies applying POUs, investigating these in more detail. In general, these compounds are chemically very inert (hence the name forever chemicals), have a carbon backbone from C4 up to C10 and typically are negatively charged with either a sulfonic or carboxylic acid group.

In the Netherlands and EU, strict limits on PFAS in drinking water are being implemented. In the EU, the drinking water quality should fulfil the European Drinking Water Directive in 2026. The RIVM conducted a several studies on the state of the Dutch drinking water companies with respect to this limit (Aa et al. 2022). The World Health Organisation (WHO) strives for maximum of this limit by only 20% for drinking water, as food is known to lead to higher PFAS intake. The EFSA limit might be expanded not only to concentrations, but also 'relative potency factors' (RPFs) which take the relative toxicity of the individual PFAS in to account. In this way, one gets the relative 'impact' of each individual PFAS and this makes it possible to see which PFAS should be targeted first. This is then called PFOA-equivalent (PEQ) and expressed in ng/L.

From the RIVM report, the top 5 of PFAS in PFOA-equivalents (PEQ) in drinking water were PFOA, PFHpA, HFPO-DA /GenX, PFOS & PFBA, where it depends if the drinking water is made from surface or ground water.

Table 1- Most abundant PFAS in Dutch drinking water based on source water

PFAS	Type PFAS	RPF	Relative PEQ from surface water(%)	Relative PEQ (%) DW from ground water
PFOA	C8 - COO	1	59	89
PFHpA	C7 – COO	1	22	9
HFPO-DA (GenX)	~C6 – SO3	0,06	18	0
PFOS	C8 – SO3	2	14	5
PFBA	C4 - COO	0,05	12	2

2.2.3 Heavy metals

Heavy metals of concern in the Netherlands are lead, arsenic and chromium. Old piping systems with lead might lead to locally elevated levels of lead in (typically older) houses. The current limit for drinking water is 10 µg/L. In 2020, KWR did a short research on lead removal from tap water (Slaats et al. 2022). Arsenic has a limit of 10 µg/L as well, however, there are some reports that indicate that a limit of 1 µg/L might have improvements for public health. Chromium has a limit of 50 µg/L currently, however, from a toxicological perspective a limit of 0.2 µg/L Cr(VI) might be introduced.

2.3 Centralized water treatment and dual water systems (Type II)

Currently, the drinking water supply in the Netherlands relies on centralized treatment systems. The technology applied for centralized treatment is very varied in the Netherlands. In the scope of this report, we selected as centralized treatment, the conventional ground and surface water treatments relying on sedimentation and adsorption techniques. The selection was required to enable an comparison in terms of costs. Other technologies, for instance applying tight membranes, do allow removal of selected PFAS and OMPs. Water treatment systems relying on tight membrane technologies are therefore less likely to consider a complementary decentralized treatment based on POUs.

The selected centralized treatments addressed in this report, comprise the following technologies:

- Groundwater treatment

    - abstraction/infiltration wells; activated carbon filtration; clean water reservoirs; clean water pumping station;

- Surface water treatment

    - flocculation; sedimentation; transport; ozonation; softening; activated carbon filtration; slow sand filtration; clean water reservoirs; clean water pumping station.

Within these scenarios, the centralized treatment will need to be extended/modified to comply with more demanding water quality supply standards, resulting from the increased contamination of the water sources and knowledge of water contaminants. To comply with new standards two options are considered, namely:

- An extension of the existing centralized water treatment, by increased regeneration cycles of activated carbon;

- Complementing the existing water treatment with POU systems at the tap water of the end-users.

A water supply system relying on centralized treatment, which is complemented by a decentralized treatment, in this case a POU system, to supply drinking water quality is designated as a dual water system-type II (Peter-Verbanets et al. 2009). A dual water system- type I, refers to a dual centralized treatment, supported by a dual distribution system; i.e., where water of two different qualities is being produced, one for drinking water and the other for general use (Peter-Verbanets et al. 2009). In this report, we are referring exclusively to dual water systems-type II, where the existing centralized system is hypothetically complemented by a POU at the tap water of the end-user, aiming to remove OMPs, PFAS and heavy metals, as defined in section 2.2.

2.4 Assumptions

To allow a suitable comparison between extended centralized systems and dual water systems type II (centralized systems + POUs at the tap water), several assumptions were made. A list of assumptions follows, to clarify the scope of this report:

- The current centralized water treatment systems of the Netherlands supply microbiologically safe water; the centralized water treatment technologies/process steps considered in this report are specified in section 2.3.

- The water treatment systems used for comparison in this report produce 27 Mm^3 of water per year, which is considered an medium size drinking water system.

- The present report only addresses extra removal of target contaminants specified in section 2.2;

- The POUs mentioned in this report are meant to be applied at the drinking water tap of the households.

- One household in the Netherlands has an average of 2,13 persons (CBS 2022).

- The drinking water consumed per household in the Netherlands is about 20 L/household/day; the drinking water used for cooking and drinking is between 8 to 10 L/person/day ((Ma et al. 1998, Peter-Verbanets et al. 2009)

- The POUs should be able to produce 3 L/h at peak times; the water consumption can reach this peak about 3 times in one hour (Beal et al. 2014).
- The total consumption of tap water per person per day is : 130 L/person/day (Bakker et al. 2022).

3 Point-of-use (POU) literature review

3.1 Background and current status

Decentralized water treatment is being applied worldwide. Decentralized water treatment approaches include: direct use of alternative water sources (such as groundwater or rainwater); household water treatment systems; dual tap water treatment and distribution; delivery of treated water (Peter-Verbanets et al. 2009). Decentralized water treatment addresses quality and quantity issues and is immensely popular; however, the currently applied decentralized solutions are not always accepted or supported by local government.

There are different definitions regarding decentralized water treatment systems. In this report we will adopt the following definitions as proposed by Peter-Verbanets et al. (2009):

- Point-of-use (POU) systems: treating only the part of water used for drinking in one household; for an average family of 2-4 persons it amounts to 16- 32 L/household/day.

- Point-of-entry (POE) systems: treating all the water supplied to one household; therefore, with a higher treatment capacity than POUs, in the order of 100-150 L/person/day.

- Small-scale systems (SSS): treating all the water supplied to several households or a small village; therefore, with higher capacity than POUs or POEs, with capacities usually varying between 1.000 to 10.000 L/day.

Point of Use (POU) systems, which are the decentralized systems being analysed in this report, are used worldwide. Currently, POUs are mainly applied in developing and transition countries, aiming to provide safe drinking water and control waterborne diseases (K'oreje et al. 2020). Consequently, most available POU studies are focusing on microbiological contaminants removal and describing applications suitable for developing/transition countries or to be applied in emergency situations.

Research on POUs in developed countries has been on-going for more than 30 years (Abbaszadegan et al. 1997). Back then, the attention was also focused on microbiological safety, even if complementary to existing centralized drinking water systems (Abbaszadegan et al. 1997). Currently, POU research and application in developed countries is focused on chemical contamination. For instance, in the United States, despite several standards, regulations and treatments in place, there are reported incidents demonstrating the vulnerability of the tap water to chemical contamination (Brown et al. 2017). In particular, lead and perfluorooctanoic acid (PFOA) have been detected in drinking water systems at levels associated with kidney and testicular cancer in similar exposed populations (Brown et al. 2017). Consequently, in the US there are many types of POU's that were submitted to certification for removal of chemical contaminants in tap water (Brown et al. 2017). Lists of certified devices are provided by the National Sanitation Agency (NSA) International, an independent review organization, affiliated to the American National Standards Institute.

The evaluation of the efficiency of POU devices, while in use, is more limited (Brown et al. 2017). Only a few studies were found where US certified POUs were evaluated on their performance. The most comprehensive research, evaluating POUs in use, describes the case-study of Flint, Michigan, US, where certified POUs, approved for lead removal were distributed to the residents. The POUs were certified by NSF and the US Environmental protection Agency (EPA) monitored and evaluated of the efficiency of the devices. The samples were collected at 238 residences, 1 church and 34 commercial properties. In each location, where possible, 3 samples were collected:

with the POU in use; with the POU removed; and with a new, unused, POU. The samples were analysed for several heavy metals and inorganic elements, including lead and chromium, relevant for this report (Brown et al. 2017, Booscher et al. 2019). Also in the US, two other references testing POUs in use were found: at North Caroline state, 76 POU devices, installed at the water tap of residential homes, were tested for the removal of PFAS (Herkert et al. 2020); at rural central Arizona, 31 homes were tested to evaluate the performance of commercially available POUs. Additionally, a few references were found describing research from South Africa and Egypt addressing pharmaceutical removals by POUs (references provided by K'oreje et al. (2020)). All the aforementioned references are applying POUs systems or target contaminants, within the scope of this report.

3.2 Water treatment technologies

In this section different water treatment technologies are described, which are typically used for POU-systems. In particular, the addressed technologies have the ability, besides other removal capacities, to remove part or all the addressed target contaminants in this report.

3.2.1 Ion-exchange

In POUs ion exchange processes can be used to deionize, disinfect and scavenge macromolecules (Sobsey 2002). Ion exchange uses the principle of a resin with fixed charges, that can exchange with charged contaminants for less harmful ones. An example of less harmful contaminants are sodium and chloride.

Cation exchange resins have a negative fixed charge and can adsorb positively charged pollutants such as some heavy metals (e.g. Pb^{2+}(aq)) and certain positively charged organic micropollutants. Anion exchange resins have a positive fixed charge and can adsorb negatively charged pollutants such as heavy metal oxides (e.g. $H_2AsO_4^-$ (aq)) and negatively charged organics (such as NOM) as well as micropollutants, including shorter PFAS (Dixit et al. 2021). In water treatment, anion exchange is applied for colour removal; while cation exchange is applied for water softening.

Ion exchange processes with adsorbent and scavenging resins are applied in POUs for household use. They are easy to use, however it’s difficult to determine their usable life without the use of additional technology (Sobsey 2002). POUs relying on ion-exchange with adsorbent and scavenging resins, are usually complemented with additional treatment technologies, such as UV or tight membrane filtration, to reduce the microbial loads, because the resins often become colonized with bacteria.

3.2.2 Adsorption

Adsorption processes and adsorbents such as charcoal and clay are being used for water treatment since ancient times (Sobsey 2002). Currently, adsorption processes rely heavily on activated carbon. Usually the adsorption processes are applied as filtration processes. Adsorption mostly uses affinity between the micropollutant and the adsorbent. By offering a high surface area through a porous network structure, a high capacity to adsorb these compound is created. The main interaction is hydrophobic and is therefore suitable to adsorb more hydrophobic compounds such as uncharged micropollutants and larger PFAS (Hofman-Caris et al. 2018).

Most often adsorption is done using a type of activated carbon, but other types are also available such as zeolites or cyclodextrin-based materials (Hofman-Caris et al. 2018). Activated carbon is adaptable to several treatment processes. The main disadvantage of activated carbon is its poor microbe adsorption, which can degrade the microbial quality of the water by facilitating microbial growth (Sobsey 2002). Fresh and virgin activated carbon will adsorb microbes, including pathogens, however dissolved organic matter in the water will rapidly take up the adsorption sites and the carbon will rapidly develop a biofilm (Sobsey 2002). In POUs devices the carbon can be impregnated with silver, which acts as a bacteriostatic agent to reduce microbial colonization. Nevertheless, opportunistic bacteria might still able to colonize the carbon particles. Furthermore, other microorganisms, such as viruses or protozoan cysts, are not inactivated at silver concentrations employed by the POUs (Sobsey 2002). Therefore, additional treatment is required to reduce the microbe levels in carbon-treated water.

Activated carbon filters, where the activated carbon is pressed as a block, combined with UV as pos-treatment, have been tested as POU systems for microbiological removal for several decades (Abbaszadegan et al. 1997). The POU activated carbon filters, combined with UV, have been successful to achieve microbiologically safe drinking water (Abbaszadegan et al. 1997). UV radiation it is very well documented regarding the ability to extensively inactivate microorganisms. However, the use of UV has it's specific requirements namely: electricity source, periodic cleaning of the lamps, finite lifespan and periodically replacement of the lamps (Peter-Verbanets et al. 2009). All of these factors increase the operational costs of the UV system and impact their environmental sustainability.

Regarding the efficiency of activated carbon based POU devices, there are studies documenting its ability to remove OMPs. In the research from Anumol 2015 (as referred by Brown et al. (2017)), 3 pitchers with activated carbon and ion exchange resins, were evaluated up to 150% of the manufacturer expected life-time for reduction of: atrazine, bisphenol A, carbamazepine, diethyl-meta-toluamide (DEET), estrone, fluoxetine, ibuprofen, 4-n-nonyphenol, 4-n-octylphenol, PFOA, PFOS, Primidone, sucralose, sulfamethoxazole, TCEP and trimethoprim. The tap water was spiked to obtain measurable removal. Two of the pitchers achieved an average removal for the 16 OMPs above 90%, while the third one achieved a removal above 80%. Additionally, there were flow rate losses for some of the pitchers at 25% of the manufacturer expected lifetime. The total OMP removal efficiency of the pitchers was calculated as 71, 91 and 95%. As refereed by K'oreje et al. (2020), Anumol et al, 2015, achieved removals of 94% and 99% of atrazine and fluoxetine, respectively, when starting at initial concentrations of 140-1300 ng/l.

Herkert et al. (2020) tested the removal of PFAS in 76 POU systems placed at residential houses in North Caroline and verified that 2-stage filters were effectively removing, i.e. above 90% removal of short- and long-chain-PFAS. The authors did not clarify which filter material was being used in the 2-stage-filters, but it's likely to be a combination of activated carbon with ion exchange resins. Nevertheless, the authors did find that longer chain PFAAs were being removed more efficiently in the activated carbon filters. On average, the perfluoroalkyl sulfonic acids (PFSAs) were being removed better than perfluoroalkyl carboxylic acids (PFCAs), as shown in Figure 1(Herkert et al. 2020).

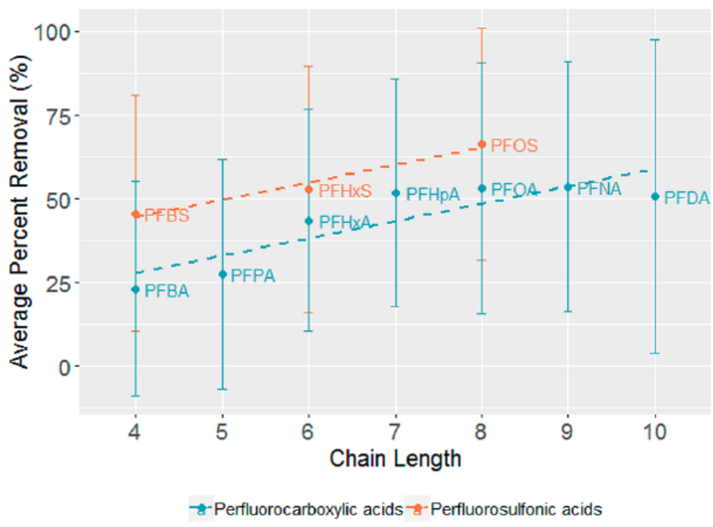


Figure 1- Average percent removal according to chain length of PFAS in POUs with activated carbon filters. (source: Herkert et al. (2020))

3.2.3 Membrane filtration (Reverse Osmosis)

Membrane filtration typically uses a thin film composite membrane to separate on size and/or on charge . For drinking water application, and specifically for removal of small pollutants nanofiltration (NF) and reverse-osmosis (RO) are typically suitable membrane types. NF does not have a high retention for salts (especially monovalent ones) but does have retention for divalent ions and larger as well as charged micropollutants (such as PFAS). RO has high retention for most compounds, even the smaller and neutral micropollutants.

The main limitations of membrane systems is potential membrane fouling. Additionally, water recovery on POUs systems reaches a maximum of about 65%, which is lower than average recovery in full-size water treatment systems. For NF and RO systems, the fouling prevention strategies require some form of pre-treatment and/or automated process control and cleaning, leading to increased investment costs (Peter-Verbanets et al. 2009).

The majority of the commercially available POU in industrialized countries apply RO as the key water treatment technology (Peter-Verbanets et al. 2009). The same industrial-grade membranes applied in large-scale water treatment plants have been also applied to POU or POE systems. The RO-based system needs pre- and post-treatment stages, which varies according to the treatment goal and previous treatment processes. For RO-based systems pre-treatment with sand filters, micro- or ultrafiltration (for particulates) or activated carbon (for chlorine) can be used. Post-treatment filters can also include activated carbon filters. In POU systems, the maintenance of the RO- based systems includes the replacement of pre- and post-treatment every 6 to 18 months, while the membrane life-time is of about 2 to 3 years (Peter-Verbanets et al. 2009). The maintenance needs are currently defined by the suppliers. Regular water quality monitoring being produced by POUs, RO-based or others, is not a common practice.

Lothrop et al. (2015) researched the removal of metals, including lead and arsenic in 31 homes of rural Arizona using POU's. A total of 18 houses did not use home treatment devices (namely POUs), while 13 homes did use POU or POE systems. The installed POU systems were all placed at the tap water entry and were either based on RO, AC or a combination of treatment technologies. In particular, RO was either combined with AC or with a water softener. A total of 9 homes had installed POUs with RO-based technology. The authors verified that RO reduced the arsenic concentrations by as much as 99%, while AC reduced it by as much as 45%. Regarding lead, RO consistently reduced concentration by an average of 61%, while AC did not produce consistent reductions. The arsenic results obtained in RO based POUs are shown in Figure 2.

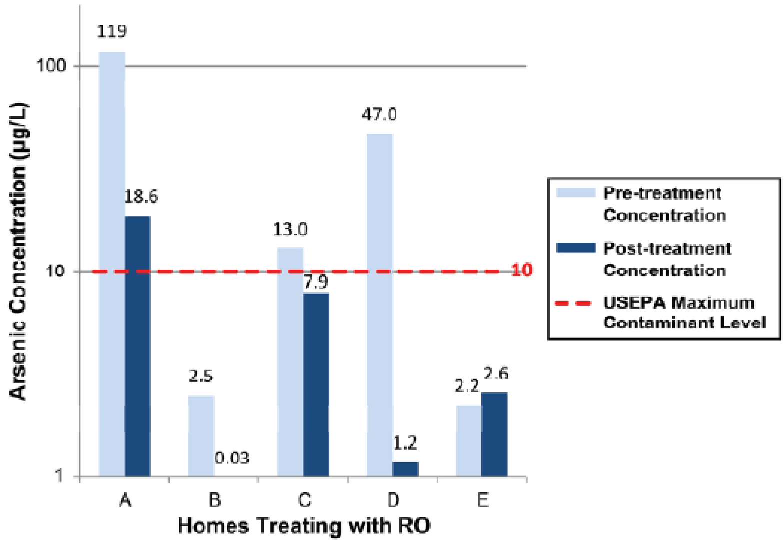


Figure 2- Arsenic concentrations in water samples before (pre-treatment concentration) and after POU-RO treatment (post-treatment concentration) from homes (A to E) with paired samples, according to the research performed Lothrop et al. (2015). (source: Lothrop et al. (2015))

Previous research referred by Brown et al. (2017), Walker (2008) and Slotnick (2006), also reported increased removal of arsenic by RO-based POU systems. Walker (2008) measured an average of 80% removal in 59 RO systems of private houses; Slotnick (2006) reported the highest average arsenic removal for RO systems, namely 86%, while testing POU devices of 196 private houses. Walker (2008) also reports that the RO systems perform better on municipal water and water containing measurable chlorine. In the referred studies, the water source varies from private wells, surface water, groundwater to municipal water.

3.2.4 Combination of technologies for POUs

As mentioned in the previous sections (3.2.1 to 3.2.3), the POU systems are usually applying a combination of technologies, either to achieve removal of additional contaminants; either to prevent biological growth (possibility occurring at ion-exchange or activated carbon filters) or to prevent fouling (potentially occurring in membrane based systems). Examples of POUs applying combinations of technologies and currently applied at households, can be found reported in literature, as follows.

Recently, many US certified POU filters apply an outer fabric or fibre filter surrounding a solid block of primarily activated carbon, augmented in some filter cartridges with ion exchange or sorption media for metals removal (Booscher et al. 2019). The filling materials are compressed to form a block of uniform pore size, of about 0.5-1 µm. These systems are usually designated by Solid Block Activated Carbon (SBAC), even if they might include ion-exchange resins and metals absorbents. To the residents of Flint, only POU filters with a SBAC matrix were approved for distribution, namely PUR® and Brita® filters with certifications NSF/ANSI-53 (total lead) and NSF/ANSI-42 (Class I particulate) (Booscher et al. 2019). The schematic of the SBAC POU systems, in use at Flint, is shown in Figure 3, as well as the flow path of the water. The activated carbon POU filters should be changed after 6 months to 1 year of use.

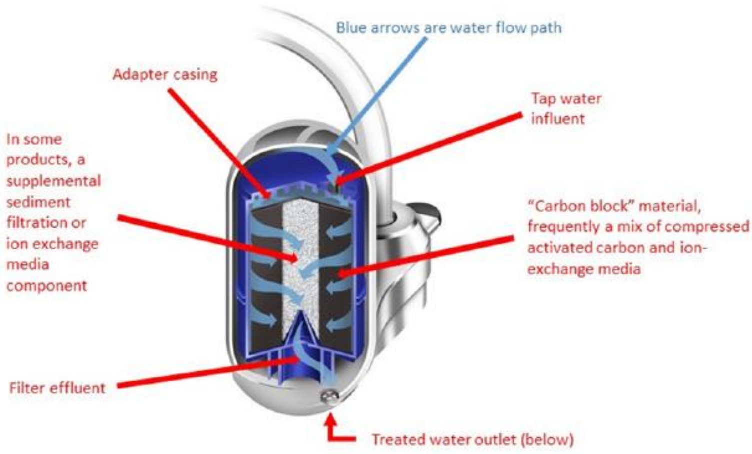


Figure 3- Schematic diagram of tap water mounted POU filters, representative of the models tested at Flint, Michigan, US. (Source: Booscher et al. (2019)).

Typical RO POUs have a combination of activated carbon (either before the RO to remove chlorine that can damage the membrane and/or after the RO to further polish the treated water on taste/odour). The following schema (Figure 4) shows a concept of such an extensive RO-based POU system. Pretreatment consist of a sediment filter that removes particles and an activated carbon filter removes organic components as well as chlorine (which damages the membrane). The RO membrane filters out 98% of all dissolved species, and can filter out even the smaller molecules as well as salts. These RO membranes have a varying recovery from 20% up to 85%, and can achieve such higher recoveries by installing a booster pump to enhance the pressure difference over the membrane. Post-treatment adsorbs any remaining contaminants and/or odours to enhance storage capacity in a tank.

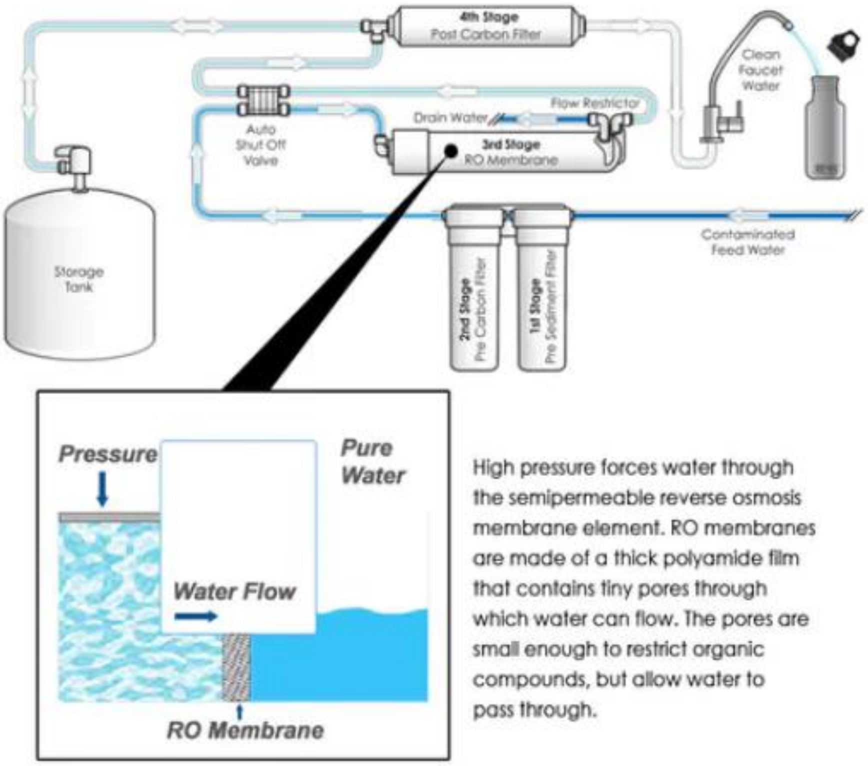


Figure 4- Schematic diagram of RO-based point-of-use system with pre- and postfilters as well as storage tank (source: Woodard (2022))

3.3 Efficiency

There are only a few studies concerning POU removal of heavy metals, PFAS and OMPs. The few existing studies evaluating efficiency of POUs in use, mainly focus on the traditional contaminants related to microbiological safety, without addressing chemicals of emergent concern, such as pharmaceuticals, personal care products or PFAS (Brown et al. 2017). Brown et al. (2017) found a total of 17 papers, with 15 reporting case-studies in the US and Canada, describing POUs efficiency on the removal of inorganic and organic contaminants. Additionally, KWR assessed the removal of this reported target contaminants by researching water treatment technologies, which are also being in use in the POUs addressed in this report. Below, the results related with the targeted contaminants removal are presented, both for aforementioned technologies applied at full-scale plants and on POU systems.

As mentioned in section 3.2.3, Lothrop et al. (2015) investigated commercially available POUs for metal removal in rural central Arizona. The RO-based POUs reduced arsenic levels by as much as 91%, while activated carbon reduced concentrations by as much as 45%. Lead was removed in average 61% by RO, however activated carbon provided inconsistent reductions. Chromium was not analyzed in this study.

In the Flint monitoring program, concentrations of lead were substantially and statistically reduced with the use of the NSF approved faucet-mounted solid block activated carbon filters (Brown et al. 2017), shown in Figure 3. A combination of soluble and particulate lead in the water, with concentrations greater than 150 µg/l, was reduced to below 10 µg/L, which is the applicable certification acceptance criterion in the US. Both faucet-mount or under-sink solid block activated carbon filters removed 80-99% of lead, with effectiveness both on the dissolved and particulate lead (several references by Brown et al. (2017). In the literature review performed by Brown et al. (2017), 7 of the 11 analysed papers reported reduction of arsenic by POUs; RO units were able to reduce 79 to >99% of arsenic in the water; while increasing arsenic influent concentrations and water hardness decreased the effectiveness of arsenic reduction by RO units. Solid block activated carbon (SBAC) filters, seem to be able to remove multiple classes of contaminants , including both inorganic such as lead and organic contaminants (Brown et al. 2017).

Technologies based on affinity-adsorption, are suitable to remove organic micropollutants (OMPs) (Hofman-Caris et al. 2018). Hofman-Caris et al. (2018) verified that 66% of compounds selected, with the exception of N,N-dimethylsulfamide which could only be removed by about 20%. As mentioned in section 3.2.2, pitchers with activated carbon combined with ion-exchange resins, had a total OMP removal efficiency between 71 and 95% (Anumol 2015, referred by Brown et al. (2017)).

According to Herkert et al. (2020), the treatment technologies that can effectively remove PFAS in drinking water treatment plants are activated carbon, anion exchange and high-pressure membrane filtration, such as nanofiltration and RO. Herkert et al. (2020) tested the removal of PFAS in 76 POUs, installed in at the water tap of 76 households at North Caroline, US. Perfluoroalkyl carboxylic acids (PFCAs) with eight or more carbons; and perfluoroalkyl sulfonic acids (PFSAs) with six or more carbons, were removed more than 90% by POUs with RO and POUs with 2-stage filters (Herkert et al. 2020). In the latter context the 2-stage filter is actually composed by two filters, the first acting as a sand trap, rust or dirt, with 5 µm sediments; while the second filter is a activated carbon filter. Both the 2-stage filters and RO-based POUs, were also able to remove more than 97% of per- and polyfluoroalkyl ether acids (PFEAs), while GenX was removed above 74%. However, GenX was present in very low concentrations in the unfiltered samples, and below measurement detection level after the POU. The authors concluded that both RO and 2-stages POU's were effectively removing both long and short-chain PFAS, as well as novel PFEAs. Regarding the 2-stages POUs, the authors were not able to clarify which materials were being used as filter-material, but it likely that the filters material were activated carbon with ion-exchange exchange resins. The remaining POU systems tested, namely other activated carbon filters as well as one-stage filters, provided lower PFAS removals.

Overall, the existing literature on RO-based and activated carbon based POU's does indicate the removal of target contaminants addressed in this report. However, the applied water sources are varied, the literature references are not abundant and not all target contaminants of this report have been addressed.

3.4 Household location and maintenance

In this report we are limited to POU systems which can be installed on tap water of the household (see section 2.4). Therefore, we are excluding POU systems in pitchers.

The POUs to be placed at the tap water of the household can be:

- faucet-mounted, i.e. at the drinking water tap;
- placed under the sink, connecting to the water tap.

Solid block activated carbon filters can be faucet-mounted or placed under the sink (Brown et al. 2017). The activated carbon filters, or combinations of activated carbon with ion exchange resins, do not require electricity, relying on tap water pressure(Peter-Verbanets et al. 2009). The filters do require annual replacement.

The RO-based POU systems are usually placed under the kitchen sink. The RO-based POUs do not require electricity , since the required pressure is provided by the feed tap water in the system (Peter-Verbanets et al. 2009). Although nowadays there are booster RO-based POU on the market which do require electricity to enhance the water recovery by increasing the pressure of the feed water. The maintenance requires the replacement of the pre- and post-filters once in 6 to 18 months, and the RO membrane lifetime is of 2-3 years (Peter-Verbanets et al. 2009). In general, all the RO-based POU systems require service and replacement of parts on a regular basis.

3.5 Selection criteria for POUs

The criteria of POUs selection should include, among other factors, the treatment efficiency, for the different target compounds, and system costs. Peter-Verbanets et al. (2009) presented a POU systems overview, where environmental sustainability, socio-cultural acceptance and potential for dissemination, as availability of skilled personnel and spare parts, were also considered. The POU overview of the authors (Peter-Verbanets et al. 2009) regarding the POU systems being considered in this report as shown in Table 2.

Table 2- Overview of available POUs (source: adapted from Peter-Verbanets et al. (2009).

Technology applied	Type of supply	Costs (1)		Evaluation Criteria					
		Investment	Operation	Performance	Ease of use	Maintenance	Sustainability	Utilities required	Social acceptability
Activated carbon	Faucet mounted	35	35	safe water quality (not performing well with turbid water)	yes	annual replacement	maybe be produced locally	tap pressure	available studies showed good social acceptability
	Under a sink	209	70						
RO	Single tap	418	84	WHO water quality(2)	yes	annual	chemicals and possibility non-renewable energy required for operation	tap pressure or electricity	not clear, available studies are contradictory

(1) Converted from $US; maximum prices from 2009; 1 € Euro= 1.4365 $US; (2) (WHO 2017)

According to Peter-Verbanets et al. (2009) time-consuming and complicated maintenance is one of the main problems limiting the application of POUs. Nevertheless, certified POUs, properly installed and maintained, should be able to perform according to the certification characteristics. For example, certified POUs are expected to reliably reduce lead exposure from drinking water, even when water has concentrations greater than 1000 µg/L(Booscher et al. 2019). The few current studies on POUs effectiveness while in use suggest that certified POUs are effective in reducing levels of chemical contaminants in drinking water (Brown et al. 2017).

Sobsey (2002) compared POU technologies for household water treatment in developing countries. The applied criteria were as follows: microbial reduction; diarrheal disease reductions; disinfectant residual, quality requirements of water to be treated; chemical changes in water; microbial growth potential in treated water; skill level and ease of use; availability of needed materials; limits to water volume treated; performance verification requirements; acceptability; sustainability; length of treatment time. The first three criteria used by the author (Sobsey 2002), do not apply to the context of this research. As mentioned in section 2.4, the water source of the POUs will be pathogen free. Nevertheless, single technology POU filters based on non-iodide IEX resins or activated carbon filters might lead to biological growth. The comparison presented by Sobsey (2002) is shown in Annex I.

4 POU selection

4.1 Technology based selection

The POU systems that will be considering in this study, should be able to remove the target pollutants as defined in section 2.2. These pollutants are relatively small organic compounds (order of few hundred Dalton) or heavy metal ions (for instance caused by older piping systems). Three main technologies are selected for removing these compounds, these are listed in Table 3 with their respective treatment capacity for the selected substances.

Table 3- Suitable POU technologies and their targeted substances for treatment

	OMPs	PFAS	Heavy metals
Activated Carbon adsorption	Good	Good (longer PFAS)	Average (Pb)
Ion Exchange	Only charged ones	Good (shorter PFAS)	Good (Pb, As)
Membrane filtration (Reverse osmosis)	Good	Excellent	Good (As)

Often POUs combine several treatment technologies to treat multiple contaminants. A combination of two technologies are assumed as suitable for this study. POU's are selected which combine charge interaction (ion exchange) and hydrophobicity (activated carbon) or combine an absolute barrier (reverse osmosis) with pre- or post-adsorption, those are shown in Table 4.

4.2 Overall POU selection

In section 4.1, a technology based POU selection relevant for this study was presented. Now we will look at relevant capacities and efficiencies of these POUs. In the assumptions (section 2.4) it was stated that the POUs should have a production capacity of 20 L / day, however during peak times these POUs should be able to produce up to 3 times the average capacity, hence they should have at least 20/24*3= 2.5 L / h production. Most POUs fulfil this criterium with ease, as most are designed for full household scale and not only drinking water consumption.

In terms of water efficiency, adsorption-based POUs do not reject much water, while membrane-based POUs have a large variation in water recoveries. Typically the water recovery varies between 25% and up to 65%. To cover this wide range of water recoveries in POUs, three classes have been defined, namely adsorption, tap water RO and boosted RO. The recovery rate of the RO has a large implication on the water footprint as well (often at the expensive of larger CAPEX/OPEX).

For each of these classes a POU is selected which was readily available, pricing was known and had proper technical documentation (including water recoveries, used technology and capacities). The result is shown in the Table 4.

Table 4- Point of use (POU) class overview with technical specifications and costs.

POU class	Brand	Name	Type	Capacity (L / h)	Water Recovery (%)	Installation / CAPEX (€)	Cartridge Lifetime (months)	Cartridge Costs (€)	OPEX (€ / year)
Adsorption	Brita	Purity C1100 Xtrasafe	IEX AC	100	100%	400	6	200	400
Tap water RO	Bluewater	Cleone Classic	RO AC	7,92	25%	800	6 (AC) 48 (RO)	50 (AC) 130 (RO)	133
Boosted RO	Aquaporin	ONE	RO AC	105	65%	1000	12 (AC) 24 (RO)	85 (AC) 160 IRO)	165

5 Extended centralized systems versus dual water systems (type II) with POUs

5.1 Costs

A cost comparison is made between:

- the extended centralized system, i.e. the current centralized system with increased activated carbon regeneration cycles, enabling the retention of the target pollutants;
- the dual water systems-type II, i.e. the current centralized system with POUs placed at the drinking water tap water of the households, to allow retention of the target pollutants.

The first step of the cost calculation is to define a centralized system, which afterwards can be subjected to extension or to which POUs can be added, to enable the total costs calculations. However, there are considerable differences in the treatment train of surface and ground water, as referred in section 2.3. Therefore, two different centralized systems will be considered, depending on the water source:

- one water treatment system for surface water;
- one water treatment system for ground water.

Ideally, typical centralized systems for surface water and for groundwater would be defined. However, are considerable differences in treatment strategy between different water companies, resulting in a wide variation of combinations of different treatment processes, particularly from surface water treatment. Furthermore, current water treatment systems relying on sedimentation and adsorption techniques, are less likely to remove the target contaminants of this study, namely OMPs and in particular PFAS. Consequently, water companies applying the former and latter mentioned technologies, are more likely to assess the use of POUs. Therefore, to comply with this context and assure that this exercise remains as close as possible to real practice, two locations were selected, one of surface water and the other of ground water. The selected locations are the following:

- The location WeesperKarspel for surface water treatment;
- The location Groenekan for ground water treatment.

One considerable difference between the two locations, Weesperkarspel and Groenekan, besides the water source, is the scale of the plant. While Weesperkarspel produces 27 Mm^3 per year, Groenekan produces 5 Mm^3 per year. The different water sources, surface water and ground water, are associated with larger and smaller water treatment systems, respectively. For the sake of comparison, the same amount of water being produced by both surface- and ground water treatment systems, will be considered, namely 27 Mm^3 per year.

The following assumptions were made for the calculation of the centralized system:

- A drinking water consumption of 130 L/person/day (Bakker et al. 2022);
- a household in average has 2,13 persons (CBS 2022).

Therefore, a centralized water treatment system with 27 Mm^3 production per year will serve a total of 267.146 households, assuming that all end-users will be domestic users. The same number of households as served by the centralized system, will be equipped with a POU system, so both scenario's cover an equal amount of households.

The extended centralized system costs were obtained assuming the following:

- the removal of target pollutants is be achieved with activated carbon filtration;
- to guarantee the removal of the target pollutants, the regeneration frequency of activated carbon is increased by a factor of four (based on the practice from Waternet);
- the existing activated carbon filter vessels and pumps at the water treatment plant are sufficient to assure the water production capacity of the plant, even with extended downtime due to more frequent carbon regeneration cycles.

All the cost calculations for the centralized and extended centralized system were made using the RH-DHV cost-calculator. The POU costs were obtained by consultation with POU suppliers and resellers. Replacement and lifetimes of filter cartridges has been taken from suppliers. Included are additional electricity consumption values for the RO-type systems as well. However, these are negligible compared to the cost of the replacement cartridges (< 10%).

Centralized system costs

The CAPEX and OPEX of the centralized system are shown in Table 5. The centralized system costs are calculated assuming an average project horizon of 20 years.

Table 5- CAPEX and OPEX costs of the centralized water treatment system for surface water and ground water. The costs in bold will be used for further costs considerations.

costs water source/capacity	CAPEX (M€)	OPEX (M€/ year)
Surface water/ 27 Mm^3	**144,0**	**13,5**
Ground water/ 5 Mm^3	19,3	1,9
Ground water/27 Mm^3	63,0	7,1
Ground water/ 5Mm^3x 5.4= 27 Mm^3	**104,0**	**10,1**

Table 5 shows three different results for the ground water system. The "ground water- 5 Mm^3"scenario corresponds to the actual data at the Groenekan location. The "ground water- 27 Mm^3" scenario does not correspond to reality, because the ground water treatment systems are usually of smaller capacity. Therefore, an extra calculation was made, the "Ground water/ 5Mm^3x 5.4= 27 Mm^3", to achieve similar volume production as the surface water system. The latter calculation assumes that the larger capacity of ground water treatment is achieved by a combination of small ground water treatment plants. The CAPEX and OPEX costs of the five smaller ground water treatment plant ("Ground water/ 5Mm^{3}x 5.4= 27 Mm^3") are larger than a single larger ground water treatment plant ("Ground water/27 Mm^3"), due to economy of scale. However, the "Ground water/ 5Mm^{3}x 5.4= 27 Mm^3" option is closer to reality, therefore it will be the one considered for further costs calculations.

Extended centralized system costs

The costs of the extended centralized system, for surface and ground water sources are shown in Table 6.

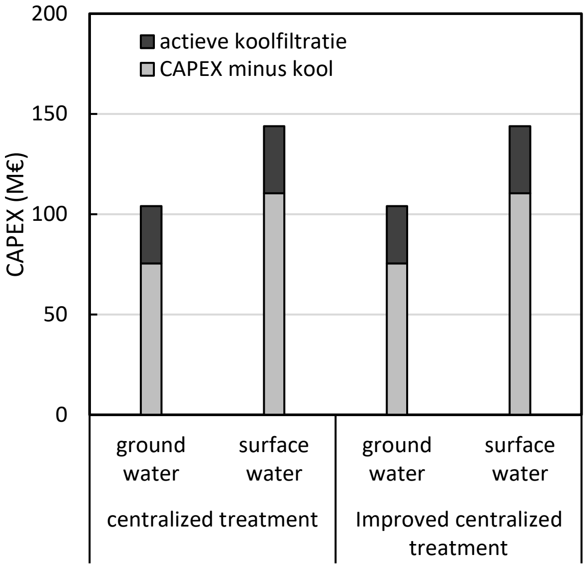
Table 6- CAPEX and OPEX costs of the extended centralized water treatment system for surface water and groundwater.

costs water source/capacity	CAPEX (M€)	Additional OPEX for extension (M€/ year)	Total OPEX (M€/ year)
Surface water/ 27 Mm^3	144	3,5	17,0
Ground water/ 5Mm^{3}x 5.4= 27 Mm^3	104	2,5	12,6

As mentioned, it was assumed that the existing carbon filters at the water treatment plants will be sufficient to guarantee the plant capacity, even with increased carbon regeneration. Therefore, in the extended centralized systems, the CAPEX will remain equal to the centralized systems and the OPEX, associated with the carbon filters, will be increased. In particular, the following costs of the activated carbon filters were increased by a factor of 4:

- costs of new carbon added in each regeneration cycle;
- maintenance costs;
- operation and optimization costs;
- administration costs.

The CAPEX and OPEX are shown in Figure 5 a) and b). The CAPEX remains equal, but for comparison it is added to see the proportion of activated carbon on the total CAPEX. For the OPEX, there is a minor increase for the activated carbon step due to the enhanced regeneration. Also here, the activated carbon is shown separately for comparison.



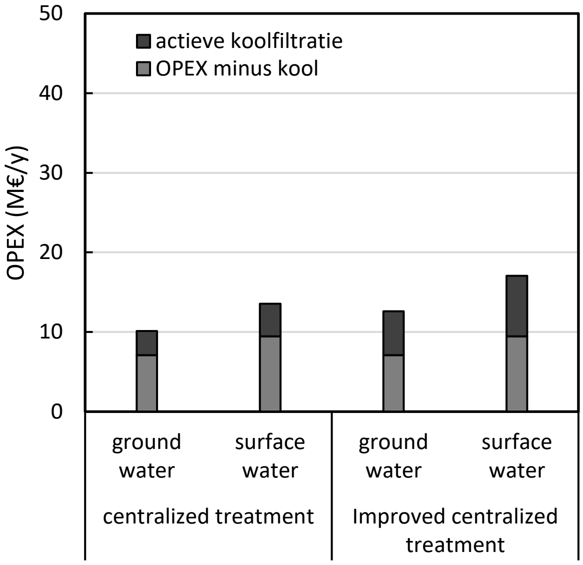


Figure 5- Overview of CAPEX (a) and OPEX (b) for the centralized and improved centralized treatment (as extended centralized system) . The activated carbon filtration is shown separately for highlighting the change.

Dual water system-type II-costs (centralized with POU)

The costs of different POU systems are shown in Table 7, which also shows additional water consumption, since RO-based systems will produce a concentrate stream with higher concentrations of compounds. This stream is not suitable for consumption.

Table 7- CAPEX and OPEX costs of the POU systems; and additional water spent (not consumed).

costs water source/capacity	CAPEX dual system [M€]	OPEX for dual system (M€/ year)	Additional water spent-not for consumption [Mm^3/year]
Adsorption	107	107	0,0
Tap water RO	214	35,4	5,9
Boosted RO	267	44,1	1,1

Table 8 shows the total costs of the dual water system-type II, relying on a centralized water system complemented by POUs at the tap water of the consumers.

Table 8- CAPEX and OPEX costs of the dual water system- type II; and total volume of water.

costs water source/capacity	POU	Total CAPEX [M€]	Total OPEX (M€/ year)	Total volume of water [Mm^3/year]
Surface water 27 Mm^3	Adsorption	251	120	27
	Tap water RO	358	48,9	33
	Boosted RO	411	57,6	28
Ground water $5Mm^3$x 5.4= 27 Mm^3	Adsorption	211	117	27
	Tap water RO	318	45,5	33
	Boosted RO	371	54,2	28

Comparison

Economics

When comparing the dual system with the extended centralized system, the extended centralized system has a considerable lower CAPEX and OPEX (Figure 6). This is due to the large number of POU units needed, while in the extended centralized treatment only single (but very large) unit operations can be used.

For extended centralized treatments, an additional 25% on OPEX is calculated, due to four times shorter activated carbon regeneration cycles. This holds for both surface as well as ground water treatments.

For the dual water system (with POUs), an additional 75 – 357 % of CAPEX is needed to install a large number of POUs. In addition, OPEX is increased by 369 – 1158% due to the large number of replacement cartridges.

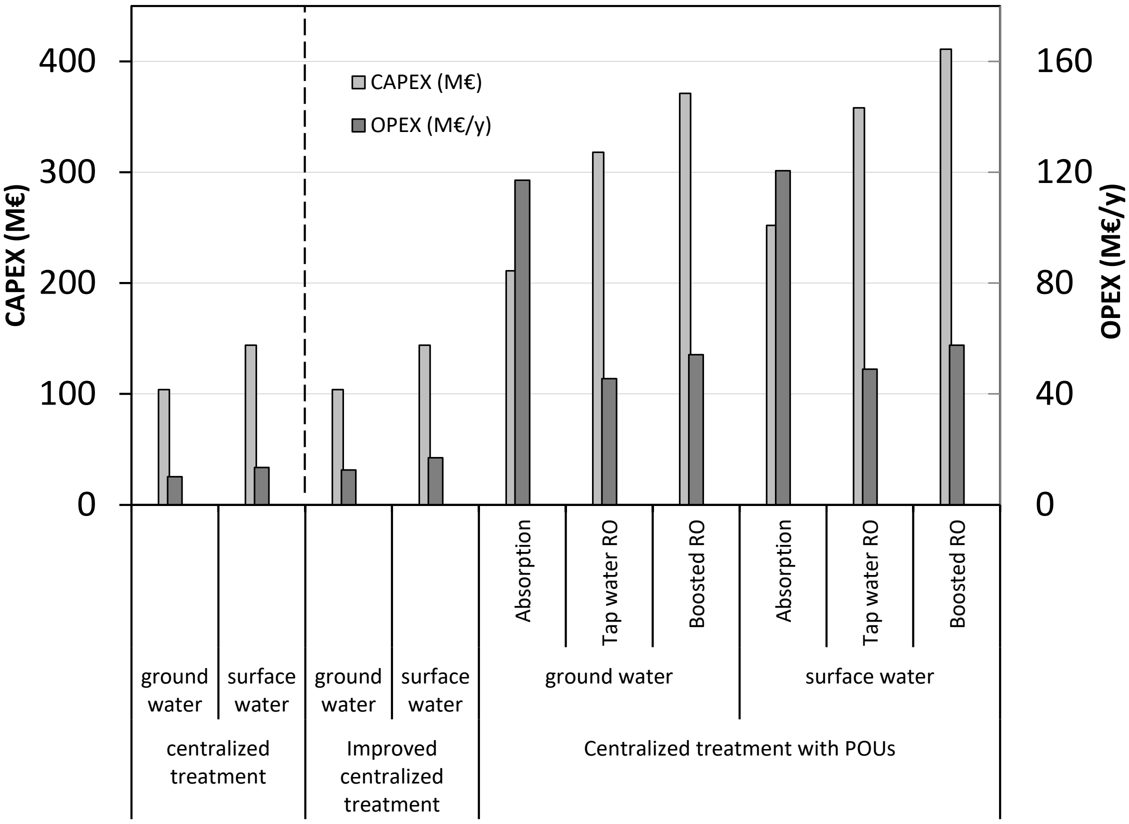


Figure 6- Overview of costs for all scenarios studied in this report.

A potential development can be a reduction of POU cost prices when they are produced on a larger scale. When taking margins on low-volume consumer products into account, there might be room for reducing POU prices such that prices might be reduced by 30-50%. Even in this case, this still means that the extended centralized system will be significantly cheaper by a factor of 2-3 in OPEX.

The lifetime of POU systems is likely to be shorter compared to centralized treatment plants due to less frequent and/or less professional maintenance. All in all, the scenario of a dual water system is not beneficial from an economical perspective.

Water consumption

The additional water consumption, with low water recovery RO POUs, leads to an increased total water consumption of 22% (Figure 7). Next to increased water consumption, POUs also lead to a large number of replacement cartridges that either have to be recycled or discarded.

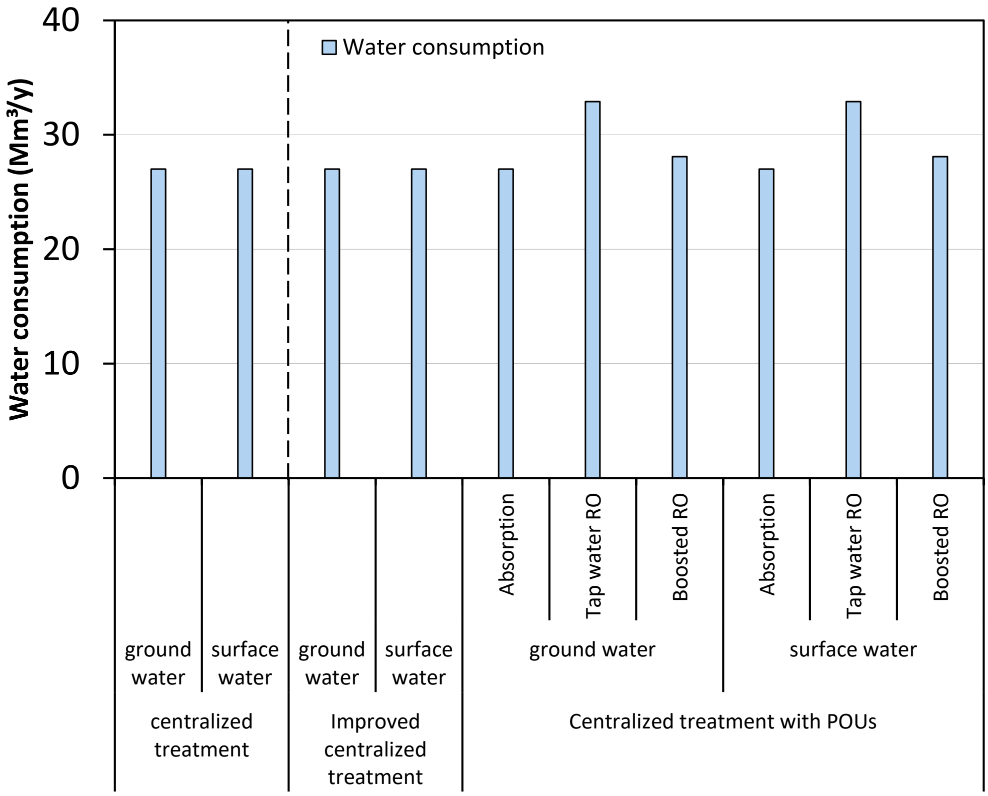


Figure 7- Overview water consumption for the scenarios studied in this report.

5.2 Sustainability

A complete sustainability analysis would have to include the origin of the extra materials, spent on the extended centralized treatment and on the selected POUs. Additionally, particularly on the case of RO-boosted POU, the energy sources would have to be classified as renewable or non-renewable. In both cases, extra assumptions would have to be made to calculate the sustainability of the systems, which are out of the scope of this report. Therefore, a complete sustainability analysis, cannot be made at this moment.

A comment can be made regarding the water wastage in the RO-system (concentrate stream), which is not being consumed as drinking water, and the materials (replacement cartridges) being spent. The concentrate might be reused for less demanding water quality uses (e.g. flushing toilets). Nevertheless, water consumption might increase depending on the selected POU. In particular, for low water recovery RO systems, an increase in the overall water consumption was calculated of about 20%. Even when the rejected water from the RO can be reused, the number of used cartridges each year also creates a substantial waste stream. Consequently, it is likely that from a sustainability perspective, the dual water system does not provide a positive result. In both scenario's (extended centralized or dual water systems) more activated carbon is used. In general, the sustainability of both concepts is worse compared to the currently applied centralized system.

5.3 Risks and challenges

Overall, POU technologies offer interesting opportunities to reduce human exposure to chemicals of emerging concern at household level in developing countries; however, much more data is needed to assess their performance and possible risk implications during POU treatment (K'oreje et al. 2020).

Our review in chapter 3, shows that while there are promising results, there are many knowledge gaps related with the performance of POUs, particularly related with the removal of specific contaminants. The following gaps have been identified, regarding the application of POU's (adapted from Peter-Verbanets et al. (2009)):

- Development of POU systems in urban areas, resulting in POUs with lower costs;
- Long-term tests of POUs with a wide range of feed water qualities, to enable prediction of process performance depending on local conditions;
- The coupling of decentralized systems (POUs) with centralized supervision; and the availability of services to assure continue and certified maintenance.

Moreover, we assessed POU systems in this report assuming that the water was biologically stable. However, water might not be biologically stable, especially while stagnant. Additional small disinfection steps might be needed to guarantee biological safety. In a recent news item by *Keuringdienst van Waarde* and KWR, it was observed that some POU systems already experienced biological growth after a few months of use (NPO3). Therefore, the first step for the implementation of POU's in the Netherlands is setting a system of POU's certification, followed by a centralized supervision system and service centres for performance and operational support. Furthermore, clear definition of responsibilities in case of failure and assurance of customer safety are required.

Additionally, the possible introduction of POU's should be preceded by a Water Safety Plan, which should include at least the following sections (Sobsey 2002):

1- Risk assessment to define potential health outcomes of the water supply;

2- System assessment to determine the ability of the water supply system to remain pathogen free and achieve defined water quality targets;

3- Process control applying “Hazard Analysis at Critical Control Points” (HACCP);

4- Process/system documentation for both steady state and incident-based (such as failure of fault event) management.

Moreover, research and extended practice in developing countries has shown that introducing water treatment technologies without behavioural, motivational, educational and participatory activities, taking into account the socio-cultural aspects of the community, are not likely to succeed or be sustainable (Sobsey 2002). Placing POUs at each household requires an adaptation from the end-user side, which will only work if people are involved at an early stage in the transition process. For a successful introduction of household water treatment strategies including health education, community mobilization, social marketing, motivational interviewing, focus groups should be employed (Sobsey 2002).

Economic analyses shows that the costs of water use and treatment can be shifted to a new system of improved household water treatment, when the communities are made aware of the substitution and accept that is better than the remaining options (Sobsey 2002). Strategies as pricing schemes, short-term subsidies and price support strategies (to obtain an increased demand) can be applied.

6 Conclusions & recommendations

In this report an alternative drinking water treatment strategy, namely decentralized treatment using POUs, is discussed. In this report 2 scenarios were compared: an upgraded centralized treatment for both ground- and surface water, with increased activated carbon regeneration cycles; and the current centralized treatment being complemented with point-of-use (POU) systems, at the drinking water tap of the households. The centralized treatment, for both scenarios, was based on sedimentation and adsorption treatment processes.

In short, for the investigated scenarios, at this point in time, the scenario with current centralized treatment complemented by POUs at the drinking water tap, is not beneficial in terms of costs or water recovery.

The results of this study can change if other scenarios are considered. For example, centralized treatment based on reverse osmosis has different characteristics, compared to the centralized treatment considered in this report, namely higher costs, lower water recoveries but higher water quality levels.

In addition, more extensive investigation of sustainability based on LCA (including material footprint for activated carbon as well as other POU systems materials) would provide more insight regarding the scenarios analyzed in this report.

Therefore, POUs remain a valid alternative water treatment strategy, particularly if associated to different scenarios other than the discussed in this report. Consequently, current gaps such as, certified maintenance, treatment efficiency and certification, remain an open issues that should be dealt with.

I Comparison of POU devices for household water treatment

Table I-1- Comparison of recommended technologies for household water treatment. The focus of the author was microbiological safety (Sobsey 2002)

Criterion	Boiling with Fuel	Solar Disinfection with UV + Heat (SODIS or SOLAIR)	Solar Disinfection with Heat Only (Opaque Vessels and Solar Panels)	UV Disinfection with Lamps	Free Chlorine and Storage in an Improved Vessel ("CDC Safewater")	Chemical Coagulation-Filtration + Chlorine Disinfection
Microbial Reductions	Yes, extensive	Yes, extensive for most pathogens	Yes, extensive for most pathogens	Yes, extensive for most pathogens	Yes, extensive" for most pathogens	Yes, extensive
Diarrheal Disease Reductions	Yes	Yes, 9-26%; two studies	None reported from epid. studies, but expected due to high temperature (55+°C)	None reported from epid. Studies, but expected due to germicidal effects	Yes, 15-48%; many studies	None reported from epid. Studies yet, but expected due to multiple treatments
Disinfectant Residual	No	No	No	No	Yes	Yes
Quality Requirements of Water to be Treated	No	Low turbidity (<30 NTU) for effective use; pre-treat turbid water	None	Low turbidity (<30 NTU) and low in UV-absorbing solutes, such as NOM, iron and sulfites	Low turbidity (<30 NTU) and low chlorine demand for effective use; pre-treat turbid water	None; applicable to poor quality source water
Chemical changes in water	No, usually except deoxygenating and chemical precipitation	None or not significant	None or not significant	None or very little	Yes; may cause taste and odor and disinfection by-products	Yes, may cause taste and odor and disinfection by-products
Microbial regrowth potential in treated water	Yes, with storage beyond 1-2 days	Yes, with storage beyond 1-2 days	Yes, with storage beyond 1-2 days	Yes, with storage beyond 1-2 days	None to low if chlorine residual maintained	None to low if chlorine residual maintained
Skill level and ease of Use	Low skill, easy use	Low skill; very easy use	Low skill; easy use with training	Moderate skill, training needed for maintenance cleaning and lamp replacement	Low skill; easy use with training	Moderate, training needed in adding chemicals, mixing, decanting and filtering
Availability of Needed Materials	Requires a source of fuel	Requires plastic (PET) bottles and dark surface (on one side of vessel or on surface where vessel is placed	Requires black bottles of cook vessels and a solar reflector or solar cooker	Requires UV units and replacement lamps and a reliable source of electricity (power)	Requires source of free chlorine or chlorine generator and source of safe storage vessels	Requires a source of the chemical mixture (coagulants and chlorine disinfectant); may limit availability
Limits to Water Volume Treated	Yes, difficult to scale up above usual	Yes, treats 1-1.5 liters per bottle; can simultaneously treat multiple	Yes, treats 1-4 liters per container; can simultaneously treat multiple	No, units can treat several liters per minute and much.	No, easily scaled up	Yes, chemical mixture treats fixed volumes of 10-20 liters; repeated

	cooking volumes	bottles	vessels with multiple solar panels or solar cookers	depending on lamp size and number and reactor volume		treatment of additional volumes
Performance verification requirements	Observe water for a rolling boil	Measure that target temperature is reached (thermometer or wax indicator	Measure that target temperature is reached (thermometer or wax indicator)	Must verify lamp output; may be a limitation if unit lacks a UV sensor	Measure chlorine residual or microbial quality (indicators) or both	Observe (measure) turbidity reduction and measure chlorine residual
Accept-ability*	High	High to Moderate	High to Moderate	High	High to Moderate	High to moderate
Sustain-ability	High, unless fuel is scarce	High, probably	High, probably	High, probably	High	High, probably; limited data
Length of Treatment Time	Minutes to tens of minutes	Hours (full sun), days (clouds), not effective if no sun	Hours (full sun), days (part sun), not effective if no sun	Seconds to minutes, depending on water volume treated and reactor design	Tens of minutes	Tens of minutes

*High is >75%; moderate is 50-75%

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