

## Low-pressure membrane technology for potable water filtration: true costs

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S.J. Judd\* and I. Carra, Cranfield Water Science Institute, Cranfield University MK43 0AL

\*corresponding author, s.j.judd@cranfield.ac.uk

### Abstract

The overall cost, expressed as the present value (PV), of the construction and operation of low-pressure membrane filtration of inland water for potable water supply has been determined for membrane installations across the UK. The analysis was based on 15 full-scale installations installed with hollow fibre and capillary tube polymeric membranes, for which cost and related data were available. The analysis encompassed labour, in addition to energy, chemicals and critical component replacement. PV data were presented as functions of flow capacity (i.e. as cost curves), delineated as capital (CAPEX), operating (OPEX) and total PV normalised against flow rate (PV') the CAPEX excluding the site-specific civil engineering costs.

Captured CAPEX data revealed these to be lower than those previously reported, and with a reduced economy of scale. The OPEX PV exceeded the CAPEX by a factor of 3-6 based on a 20-year life cycle, the difference increasing with decreasing flow capacities. Costs associated with unplanned (or "reactive") maintenance, partly associated with the repair of breached membranes and/or permeability recovery following membrane clogging, were found to make up around half the labour costs. Labour costs as a proportion of the flow increased with decreasing flow, exceeding the CAPEX at flows below 30,000 m<sup>3</sup>/d.

Outcomes indicate labour costs associated with process upsets to contribute significantly to the overall cost of the installation over its life cycle, particularly at flows below ~30,000 m<sup>3</sup>/d A clear

trade-off exists between supplementary capital investment to allay process upsets and the operational costs associated with such events.

*Keywords: Low-pressure membranes; cost; present value; labour; process upset*

## **1 Introduction**

Whilst there are many elements to process selection in water and wastewater treatment, cost remains the most important governing factor. A number of cost analyses have been conducted within the subject area of low-pressure membrane filtration (i.e. ultrafiltration, UF or microfiltration, MF) technology for water treatment over the past 10 years-or-so. These have tended to concentrate on particular physical or chemical facets of the treatment technology, employing cost analysis for optimisation purposes. Recent examples of such topics (Table 1) include pre-treatment using powdered activated carbon (PAC) (Campinas et al, 2021) or coagulant (Arhin et al, 2019), maintenance optimisation with reference backwashing (Bai et al, 2020) or chemical cleaning (Yoo et al, 2018), module design (Lee et al, 2020), and membrane material – and in particular the cost comparison of ceramic and polymeric membranes (Hurvitz et al, 2018; Park et al, 2015; Guerra and Pellegrino, 2012, 2013).

Whilst these papers have all offered insight into relative costs, analyses have to an extent necessarily been constrained in their scope. Many studies (Hurvitz et al, 2018; Yoo et al, 2018; Zheng et al, 2011) have been limited to operating expenditure (OPEX), based largely on a consideration of energy and consumables. Some of the studies which have encompassed capital costs have been based on a single flow capacity (Bai et al, 2020; Park et al, 2014; Guerra and Pellegrino, 2012, 2013). Correlations reported in these studies have been generated from either outputs from trials conducted at bench or pilot scale (Guerra and Pellegrino, 2012) or a single full-scale reference installation (Bai et al, 2020). The few recent studies that have provided correlations of total cost with flow (Campinas et al, 2021;

Arhin et al, 2019) have been aimed specifically at optimising flux and upstream dosing with coagulant of PAC. As with most other studies, these have been focused primarily on fouling suppression to optimise membrane permeability.

Table 1. Reported cost studies, low-pressure membranes

Authors	Year	Scale or $A_m$	Feed	Membrane state	Key variable(s)	Flow 000s $m^3/d$	Correlations produced
Guerra & Pellegrino	2013	0.15-0.2 $m^2$	Bentonite	Virgin	Pe	18.9	Impact of Pe on cost for different membrane materials
Park et al	2014	1,000-30,000 $m^3/d$	Raw water	Aged	Material	30	LCC vs membrane cost, polymeric vs ceramic based on full-scale plant
Hurwitz et al	2018	2.5-3 $m^2$	Raw water	Aged	None	-	OPEX only (from specific energy consumption)
Yoo et al	2018	72 $m^2$	Raw water	Virgin	Flux	-	OPEX only
Arhin et al	2019	4.5 $m^2$	Raw Water	Virgin	PACI dose, flux	5-100	Cost constituent values vs flow
Bai et al	2020	Full	2ndary Ww	Aged	-	30	Cost per year for different service life values
Lee et al	2020	Single-house	Kaolin, Ww	Virgin	Technology	<0.5	Cost comparison for different household water systems
Campinas et al	2021	0.75 $m^2$	Raw water	Virgin	PAC dose, flux	0-150	CAPEX & OPEX vs flow at various membrane permeabilities

$A_m$  membrane area; Pe Peclet number (flux/mass transfer coefficient); Ww wastewater  
 “Scale” refers to scale of experimental study; “Flow” refers to the flow or flow range modelled.

In practice, it is doubtful that fouling represents the most significant factor in terms of overall cost of low-pressure membrane technology (Judd, 2017). Whilst it is immutably the case that a higher sustainable flux reduces CAPEX due to the decreased membrane area requirement and OPEX from the corresponding membrane replacement, fouling represents only one of three factors impacting of cost, the other two being (a) integrity monitoring and repair, and (b) clogging. Integrity refers to the condition of the membrane with respect to damage and possible breaching by pathogens (Lee et al, 2019; Ferrer et al, 2015); clogging is the agglomeration of solids within membrane channels, and is most often associated with membrane bioreactors (Buzatu et al, 2018; Zsirai et al, 2012). Both phenomena incur additional labour effort which ultimately adds to the OPEX.

It is also the case that estimation of CAPEX is challenged by the paucity of available data, coupled with considerable discrepancies between the few data sets available. The recent analysis of [Arhin et al \(2019\)](#) made use of the correlation of [Guo et al \(2014\)](#) for UF installations:

$$\text{Log (CAPEX, \$)} = 1.003 (\log (Q, \text{m}^3/\text{d}))^{0.830} + 3.832 \quad (1)$$

Whilst this correlation was generated from data pertaining to actual installations, it is based on only six data points - only four of which refer to flows above 100 m<sup>3</sup>/d. According to Equation 1, a 10,000 m<sup>3</sup>/d plant would have cost around \$10 m in 2013, equating to ~£7m at that time and ~£8m today.

The recently reported work of [Campinas et al \(2021\)](#), based on a ceramic membrane, is more exhaustive in determining CAPEX. The authors account for the cost of each component through employing a power law function in terms of the installed membrane area  $A$ :

$$\text{CAPEX} = m A_m^n \quad (2)$$

where  $m$  and  $n$  are empirical constants dependent on the CAPEX component.  $A_m$  can then be correlated with  $Q$  based on the assumption of a constant net flux.

The authors' CAPEX equation exponent values for ancillary equipment (itemised as “membranes”, “pipes and valves”, “instruments and controls”, “tanks and frames”, and “miscellaneous”) were taken from the report of [Guerra and Pellegrino \(2013\)](#), which was also specific to ceramic membranes. Guerra and Pellegrino in turn cited [Sethi \(1997\)](#) as the source of their exponent values, where Sethi's correlations for the “pipes and valves” and “instruments and controls” components were based on those reported by [Gumerman et al \(1979\)](#), whereas the source of the “tanks and frames” cost

components was [Peters and Kimmerhaus \(1991\)](#). These cost function coefficient  $m$  and exponent  $n$  values (Table 2) from Equation 2 therefore date back 30-40 years.

Table 2. Values of empirical constants in Equation 2 ([Campinas et al, 2021](#))

CAPEX component	$m$	$n$	Source
Membranes cost	756	0.97	Guerra and Pellegrino, 2012
Pipes & valves cost	5313	0.42	Gumerman et al, 1979
Instruments & controls	1296	0.66	Gumerman et al, 1979
Tanks & frames	2732	0.53	Peters and Kimmerhaus, 1991
Miscellaneous	7052	0.57	Guerra and Pellegrino, 2012

The use of a ceramic membrane means that the membrane contribution to the CAPEX is substantially higher than that from polymeric membranes, notwithstanding the higher operational flux provide by ceramic materials. The OPEX is conversely lower due to a combination of the increased membrane net permeability and the obviation of membrane repair associated with integrity failure. Combining cost functions from processes with substantially different functional attributes thus becomes problematic.

Although only approximate representations of CAPEX with flow capacity are needed for the purposes of calculating relative cost benefits from altered operational practices, as in the analyses of [Arhin et al \(2019\)](#) and [Campinas et al \(2021\)](#), it remains the case that there are few accurate, up-to-date cost curves for low-pressure potable water membrane technologies. The approach adopted by [Campinas et al \(2021\)](#) is rigorous in including all contributions to the CAPEX as separate functions, but the validity of cost curve exponent values across different applications, dates and geographical regions is questionable. It is clearly preferable to obtain data directly relevant to the region of interest, and pertaining to as narrow time-frame as practically possible. Moreover, the impact of labour costs needs to be taken into account, since this aspect is often either overlooked or else based on simple approximations (such as those presented by [Mulder et al \(2015\)](#) and subsequently used by [Campinas et al \(2021\)](#)). This becomes particularly germane when a significant risk of non-routine maintenance exists.

This paper aims to provide new, up-to-date cost functions (i.e. cost vs. flow) for low-pressure membrane technologies, and to use these to assess potential cost benefit. The functions relate to total cost expressed as the present value (PV), i.e. the cost projected to the present day, and encompass all key cost contributors (Table 3) along with the impact of process upsets and subsequent non-scheduled maintenance on OPEX. Such interventions inevitably incur a higher cost than routine maintenance, since they often arise outside normal working hours, may be conducted by external contractors, and can involve extended time periods. All key data, both CAPEX and OPEX, is taken largely from the plant owner-operators, i.e. the water utilities, from across the UK.

## 2 Methodology

The calculation of PV proceeded through capturing the baseline data (Table 3) and then:

1. determining OPEX, or  $L_O$ , in units of £/m<sup>3</sup> permeate from standard expressions (Appendix B-D), the principal contributors being energy and chemical reagent consumption ( $L_E$  and  $L_R$  respectively), membrane replacement ( $L_M$ ), and waste disposal ( $L_W$ ) which do not change with flow capacity ( $Q$ );
2. determining labour effort (FTE, or full-time equivalent) and thus cost ( $L_L$ ) as a function of  $Q$ ;
3. determining CAPEX,  $L_C$ , as a function of  $Q$ ;
4. normalising all parameters against  $Q$  to generate specific cost ( $L'$ ) in units of £k per 1000 m<sup>3</sup>/d (or £ per m<sup>3</sup>/d) flow capacity;
5. determining the total OPEX contribution to PV through discounting, assuming an annual discount factor value and a 20-year life cycle time; and

summing the normalised OPEX and CAPEX cost contributors ( $L'_O$  and  $L'_C$  respectively) to produce PV', the total cost per unit flow capacity over the plant life cycle

Table 3. Data sources and ranges of values for routine operation

Cost component	Source	Value/range	Comment and/or number of data
<b>CAPEX-related</b>			
Total CAPEX	Owners	£0.6-9 million	15 installations
Membrane module cost	Owners, web	£19-60 m <sup>-2</sup> membrane area; £0.0024-0.011 m <sup>-3</sup>	Dependent on supplier, model and contract. Average price taken for specific product, zero price inflation assumed; 9 products
Membrane module surface area	Owners, web	21-50 m <sup>2</sup>	Product/technology dependent; 9 products
Normalised membrane technology component cost, $L'_c$	Owners	£0.035-0.081 per m <sup>3</sup> /d flow	Calculated from CAPEX data either provided directly or estimated as a proportion of the total CAPEX; 15 data.
<b>OPEX-related</b>			
Flux	Owners	41-109 LMH	Dependent primarily on membrane configuration
Conversion	Literature	95%	Nominal value
Electrical energy cost	Owners	£0.125 kWh <sup>-1</sup> , 2020 price	Mean, cross-sector value assumed
Energy cost index (future energy cost projections)	UK Govt.	0% net	Based on a predicted change of between -0.7% and +0.8% in energy costs per annum between 2020 and 2040 (DBEIS, 2019)
Energy consumption, liquid pumping	Calculated	0.12-0.18 kWh/m <sup>3</sup>	Determined from feedwater pressure recorded from site, assuming a pumping efficiency of 70%
Energy consumption, membrane air scouring	Calculated	0.141 kWh/Nm <sup>3</sup>	Determined from blower rating recorded from site, assuming a blower efficiency of 70% (Appendix B)
Chemicals cost	Web	£0.0004-0.0009 m <sup>-3</sup>	Dependent on chemical (sulphuric acid, sodium hypochlorite, caustic soda, citric acid)
Membrane life	Owners	2-7 y	Dependent on operational facets, and specifically incidence of clogging and integrity failure
Valve & actuator replacement	Owners	£1200	Blanket value assumed
Labour cost	Owners	£35 h <sup>-1</sup> normal; £65 h <sup>-1</sup> overtime	Mean, cross-sector values assumed throughout for normal and overtime rates, inclusive of overhead.
Labour effort	Calculated	1700 h/y	i.e. 1 FTE-y = £59,500
Waste disposal cost	Web	£0.003 m <sup>-3</sup>	Sewer discharge disposal assumed at mean, cross-sector value
CIP volume	Suppliers	0.0007-0.013 m <sup>3</sup> reagent/1000 m <sup>3</sup>	Dependent on CIP frequency
CIP frequency	Owners	per 3.5-30 d	Determined by clogging events

The influence of process upset events on the PV can then be appraised, along with the magnitude of the process upset cost relative to the CAPEX.

## **2.1 CAPEX, $L_C$**

A plant life of 20 years was assumed. The CAPEX  $L_C$  was determined for the membrane technology component of the installation, including the mechanical and electrical (M&E) costs pertaining to the membrane technology but excluding all civil engineering costs. In cases where only the CAPEX of the complete installation was provided, the membrane technology component cost was estimated based on knowledge of the construction provided by the owner-operators.

All CAPEX was converted to 2020 GBP (Great British Pounds) using year-on-year UK consumer price index (CPI) values, for which historical information (App A) indicates a roughly linear trend with year ( $y$ ) since the turn of the millennium:

$$\text{CPI} = 2.002y - 3933 \quad (3)$$

Applying this to 75% of the investment cost, i.e. excluding the membrane component, the present-day (year 2020) CAPEX becomes:

$$L_C = 83 L_{C,y} / (111 - 2(2020-y)) + 0.25 L_{C,y} \quad (4)$$

Equation 4 assumes the membrane module component costs to (a) make up 25% of the investment cost, and (b) be subject to zero inflation: a review of the membrane prices, as

provided by the owner-operators, from 2005 onwards suggested the price to be very erratic with no defined increasing or decreasing trend.

## **2.2 OPEX, $L_o$**

### **2.2.1 Electrical energy**

The cost incurred by the total electricity consumption on site represents the most significant OPEX contribution. However, to maintain consistency, the electrical cost associated only with the operation of the membrane plant itself needs to be determined in isolation.

Contributions to the specific electrical energy consumption  $L_E$  in kWh/m<sup>3</sup> permeate for membrane operation relate to:

- a) liquid pumping during filtration and backflushing,
- b) compressed air used for operation of the pneumatic valves, for conducting the pressure decay test (PDT), and for the backwash cycle, and
- c) heating of chemical reagents used for the clean in place (CIP).

The liquid pumping energy consumption during backflushing can be assumed to be comparable to that during filtration, such that the overall  $L_E$  relates to the inverse conversion (i.e. the ratio of permeate to feed flow). Accordingly, the liquid pumping energy is in the region of **0.146 kWh/m<sup>3</sup>** (App B). In comparison, the energy associated with delivering compressed air for the backflush is negligible, according to a similar first-principles calculation (App B).

Calculation of the energy associated with heating of the chemical cleaning reagents (App C) suggest that this component contributes **0.0010 kWh/m<sup>3</sup>** for a typical 30d CIP interval. This contribution increases with decreasing CIP interval.

### 2.2.2 Chemicals consumption

The chemical reagents used for the CIP comprise sodium hypochlorite (NaOCl) or caustic soda (NaOH), used for control of organic foulants, combined with sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) and/or citric acid (CA) for metal oxides removal. Based on prices for bulk reagent supply and typical doses used for cleaning, the cost incurred is **£0.00022 per m<sup>3</sup>** for routine operation (i.e. a 30d CIP interval) (App C).

### 2.2.3 Critical component replacement

The component incurring the highest cost on replacement is the membrane module itself. According to the available data (App D) the membranes costed between £19 and £60 per m<sup>2</sup> depending on the make and model. The membranes incurring the highest cost were the capillary tube (CT) membranes which operate with in-to-out flow during the filtration cycle. This flow regime provides higher fluxes than the out-to-in hollow fibre (HF) configuration, such that the range of costs per m<sup>3</sup> permeate are broadly comparable.

Replacement costs are sensitive to both the membrane cost per unit permeate flow, given by the membrane price:flux ratio in £/m<sup>2</sup> per L/(m<sup>2</sup>.h) or LMH, and the membrane life. Whilst a design membrane life value of 7 years has been used as the baseline in the costings, practical experience suggests that values are generally lower than this – and dramatically so when severe process upsets have taken place.

The analysis focused on two different HF modules (*HF1* and *HF2*) and a CT module (*CT*), all from established global suppliers.

### 2.3 Present value, PV

The PV is a function of the CAPEX ( $L_C$ ) and OPEX ( $L_O$ ) cost contributions (Jalab et al, 2019):

$$PV = \sum_{t=0}^{t=n} \frac{L_{Ct=0} + L_{Ot}}{(1+D)^t} \quad (5)$$

$D$  being the discount factor and  $n$  the total plant life (or amortisation period), taken as 20 years in the current analysis. A  $D$  value of 3.5% was used throughout, as currently used by the UK Department of Transport for civil engineering project cost projections for periods of up to 30 years (UKDfT, 2021). The baseline date of 2021 was used, such that the calculated  $PV$  refers to the total projected cost from 2021 to 2041.

Annualising all scheduled OPEX, including membrane replacement, simplifies this equation:

$$PV = QL_C + 365QL_O \sum_{t=0}^{t=n} \frac{1}{(1+D)^t} = Q(L_C + kL_O) \quad (6)$$

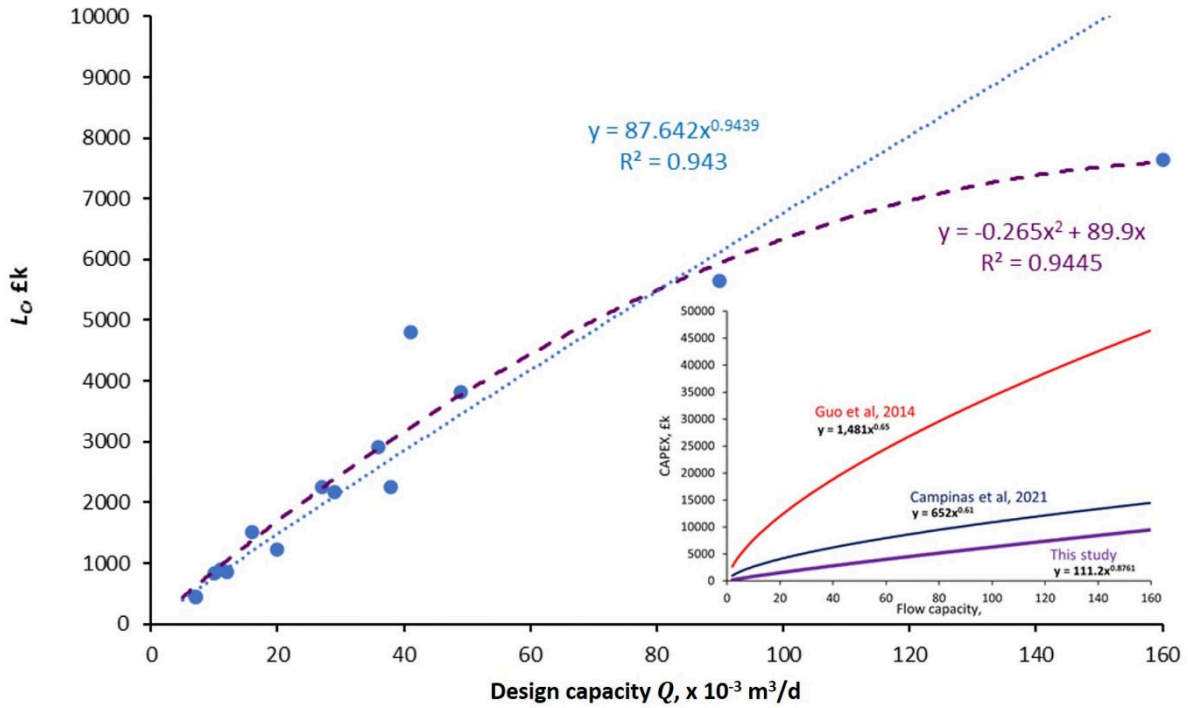
where  $Q$  is the permeate flow ( $Q_{feed}/\theta$ ,  $\theta$  being the conversion) and  $k$  a constant depending on the units employed. All cost parameters can be normalised against the flow (i.e.  $L/Q$ ) to give the *specific cost*  $L'$  or  $PV'$  in £k per  $m^3/d$  flow.

A cost of £0.125 per kWh was assigned to a unit of electricity at the baseline year of 2020 (Table 2). The trend in future electrical UK energy costs presented in the most recent UK government report (DBEIS, 2019) stipulates a predicted change of between -0.7% and +0.8% in energy costs per annum between 2020 and 2040. The current cost was therefore assumed to be unchanged over the project life cycle (i.e. zero energy cost inflation).

### 3 Results and discussion

#### 3.1 Capital expenditure (CAPEX), $L_c$

Extracted CAPEX data for 15 reference installations (Fig. 1) suggests that  $L_c:Q$  is best represented by a polynomial trend,  $Q$  being the design flow capacity, within the range 4,000-160,000 m<sup>3</sup>/d:



**Figure 1:** Trend in CAPEX ( $L_c$ ) with design flow capacity  $Q$ , 14 reference installations. Inset: comparison with published CAPEX curves, Equations 1 & 2 (Guo et al, 2014; Campinas et al, 2021). All costs converted to 2020 GBP.

$$L_c, \text{ £k} = 90 Q - 0.265 Q^2 \quad (7)$$

The above equation indicates the specific CAPEX  $L'_c$ , in £k per 1000 m<sup>3</sup>/d flow capacity, to be given by:

$$L'_c, \text{£k} = 90 - 0.265 Q \quad (8)$$

This equation was used in all subsequent PV' calculations.

Expressing the trend as a power function, in keeping with most published trends (Fig. 1, inset), reveals the values to be substantially lower than that presented by Campinas et al (2021) and, in particular, by Guo et al (2014). This may be because the CAPEX determined in the current study (a) relates only to the membrane technology component, and explicitly excludes civil engineering costs, (b) refers to the design capacity of the installation, and (c) refers specifically to the UK region, as distinct from the US or mainland Europe. The other notable difference is in the exponent value, which indicates there to be a much lower economy of scale than that suggested in the two previous reports.

## 3.2 Operating expenditure (OPEX), $L_o$

### 3.2.1 Flow-independent parameters

Values for all flow-independent OPEX-related parameters (Table 4) were taken or estimated from site information, extracted from literature publications and/or calculated from standard expressions (App 2-4). Accordingly, all contributions to  $L_o$ , the cost per unit treated volume (and, by implication,  $L'_o$ , the cost per unit flow rate) other than the labour effort  $L_L$  are considered independent of plant flow capacity. Summing all components:

$$L_{O,Q \text{ independent}} = L_E + L_M + L_R + L_W = \text{£}0.0288/\text{m}^3 \quad (9)$$

The distribution of these costs indicates the expected dominance of energy consumption (Fig. 2). Waste disposal costs are notional, since they are highly site specific.

Table 4. Assumed data values, OPEX contributors

<i>Parameter</i>	<i>Value</i>	<i>Units</i>	<i>Ref</i>
<u>Energy consumption</u>			
Energy consumption	0.147	kWh/m <sup>3</sup>	
Energy cost	0.125	£/kWh	
<b>Energy cost, <math>L_E</math></b>	<b>0.0173</b>	£/m <sup>3</sup>	App B
<u>Membrane replacement</u>			
Membrane element cost	25	£/m <sup>2</sup>	
Life	7	y	
Net flux	45	LMH	
<b>Membrane replacement cost, <math>L_M</math></b>	<b>0.0091</b>	£/m <sup>3</sup>	App D
<u>Chemical reagent consumption</u>			
<b>Chemicals cost, <math>L_R</math></b>	<b>0.0002</b>	£/m <sup>3</sup>	App C
<u>Waste disposal</u>			
Waste generation rate	-	kg/d	
<b>Waste disposal cost, <math>L_W</math></b>	<b>0.0011</b>	£/m <sup>3</sup>	-
<b>TOTAL</b>	<b>0.0288</b>	£/m <sup>3</sup>	

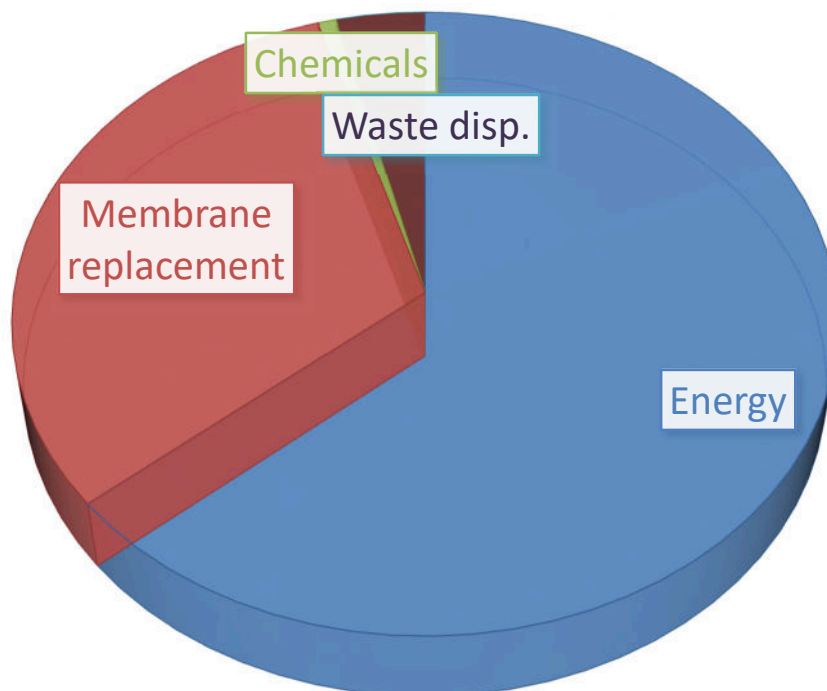


Figure 2: Distribution of non-flow capacity related OPEX contributors (from Table 4).

### 3.2.2 Labour

12 data sets were used to determine the labour cost as a function of design flow capacity (Fig. 3). Data were either extracted directly as costs, or determined from allocated hours or full-time equivalents (FTE) based on the mean hourly gross rate of £35 (Table 3). Labour costs included both sub-contracted and water company staff effort. In most cases these were itemised separately by the owner operators.

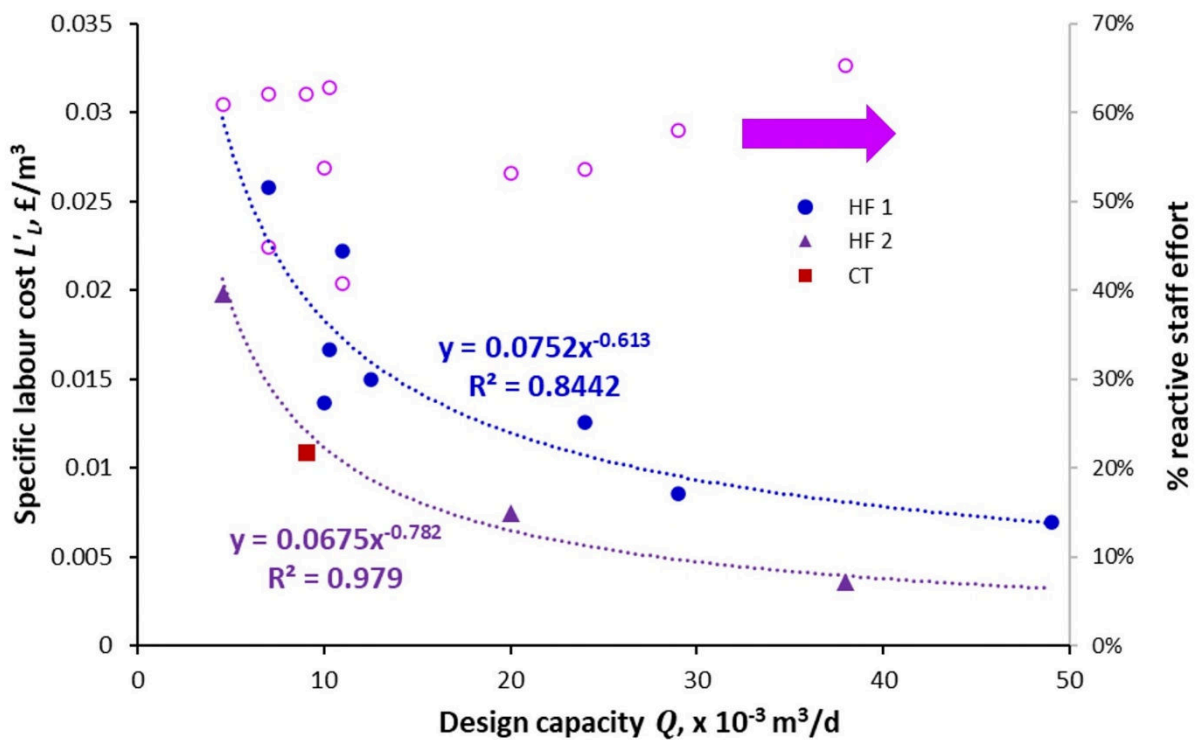


Figure 3: Specific labour cost in £/m<sup>3</sup> permeate vs design flow capacity

A distinction was made between the eight data points relating to the most widely used HF technology (*HF1*), and the other technologies (*HF2* and *CT*, App D). Also, for all but one of the data points, “planned” and “reactive” staff effort were differentiated. No trend with flow capacity was evident for the percentage reactive effort with flow, the average being  $56 \pm 8\%$  (standard deviation) across the entire flow range of 4,000 – 50,000 m<sup>3</sup>/d (Fig. 3).

The specific labour cost (planned + reactive) was found to decrease with flow according to the following power-law expressions for the different membrane technologies:

$$L'_L = 0.0752 Q^{-0.613} \quad HF1 \quad R^2 = 0.8442 \quad (10)$$

$$L'_L = 0.0675 Q^{-0.782} \quad HF2, CT \quad R^2 = 0.979 \quad (11)$$

Equation 10 was used for all subsequent PV correlations, since eight of the 15 sites for which CAPEX data were available were based on the *HF1* technology. The exponent value of -0.613 is in good agreement with the value of -0.59 used by [Campinas et al \(2021\)](#), taken from [Mulder et al \(2015\)](#).

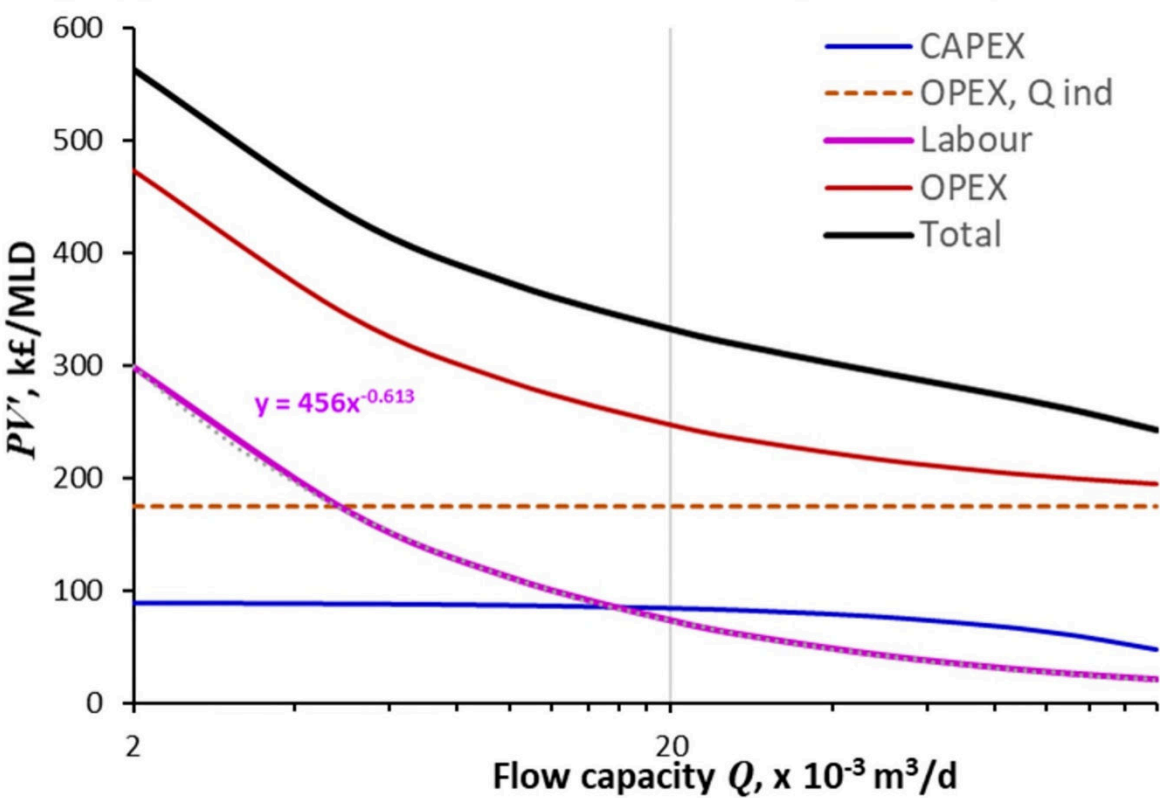
### 3.3 Specific present value, $PV'$

Equation 7 was used to compute specific present values ( $PV'$  in k£ per 1000 m<sup>3</sup>/d flow capacity), along with the capital and operating expenditure contributions, as a function of  $Q$  ([Fig. 4](#)). The trends encompass the expression for the flow-related labour cost (Equation 10), also shown in isolation, and the single mean value for the flow-independent parameters (Equation 9). Trends relate to a discount factor of 3.5% and a life cycle of 20 years.

According to all assumptions made, the overall total  $PV'$  is given by the sum of the three individual components of specific CAPEX ( $L'_C$ ), and the flow-independent and flow-dependent contributions to the specific OPEX  $PV$ :

$$PV' = -0.652Q^2 - 90Q + 456Q^{-0.613} + 174 \quad (12)$$

The constant value of 174 represents the contribution of the flow-independent parameters, depicted as the horizontal dotted line in Figure 4, and is most sensitive to the energy consumption and membrane life (Table 4). All other terms include the flow capacity  $Q$  and are sensitive to all assumptions made in interpreting the data set.



**Figure 4:** Specific present value (PV' in £ per  $\text{m}^3/\text{d}$  flow capacity) vs plant flow capacity for CAPEX, flow-independent OPEX, Labour OPEX, total OPEX and total cost.

According to Figure 4:

1. The operating PV' decreases more sharply with flow than the capital PV;
2. The total operating PV' is 3-6 times the capital PV over all flow capacities;
3. The labour cost makes up more than half of the operating cost at flow capacities below  $5,000 \text{ m}^3/\text{d}$ , increasing sharply with decreasing flows;
4. The labour PV' exceeds the capital PV' at flows below  $15,000 \text{ m}^3/\text{d}$ ;

The above outcomes are consistent both with expectations and cost analyses reported elsewhere for low-pressure membrane installations both for potable water (Campinas et al, 2021; Guo et al, 2014) and wastewater (Jalab et al, 2019). Whilst the absolute values of the labour costs are much lower than those determined for wastewater membrane plants (Qiblawey and Judd, 2019; Young et al, 2013), they none-the-less contribute more significantly to the total OPEX due largely to the relatively low energy demand of potable water membrane filtration compared with membrane bioreactors used for wastewater treatment. At flow capacities below 6,000 m<sup>3</sup>/d labour costs exceed the electrical energy cost, becoming the primary contributor to OPEX.

Figure 4 correlates cost with design flow capacity. Very few membrane plants operate at or even near their design capacity for any extended period. A conservative assumption would be that the actual flow is, on average, 75-80% of the full flow. This would then commensurately increase the flow-normalised labour and capital costs, but leave all other normalised OPEX contributions largely unchanged. For such an assumption the labour cost would make up more than half the operating cost at flows below 27,000-32,000 m<sup>3</sup>/d. This implies that, for most of the plants surveyed, the labour cost represents the largest component of the OPEX. Moreover, the CAPEX cost curve becomes more closely aligned with that of Campinas et al, 2021.

### **3.4 Impacts of process upsets**

Causes of process upsets can generally be identified as:

1. hardware replacement;
2. excessive membrane integrity failure; and
3. ineffective chemical cleaning.

Hardware most prone to failure is normally the actuators and valves, to which a nominal replacement cost of £1500 including labour can be assigned. This would imply that valve replacement costs exceed £0.001 per m<sup>3</sup> if more than 1 valve per 1,000 m<sup>3</sup>/d flow is replaced every four years.

Membrane integrity is monitored through the off-line pressure decay test (PDT). A PDT failure necessitates identifying the module responsible for the failure followed by repair. Whilst identification and repair protocols have been improved since the initial implementation of membrane technology in the UK in the early 2000s, it remains a manual and often labour-intensive process.

Ineffective chemical cleaning, i.e. a poor and short-term recovery or permeability following a CIP, is normally indicative of clogging of the HF membrane channels, which is not substantially removed by chemical cleaning. Its impacts can be very onerous with reference to many cost components (Table 5). There was no evidence of similar events for CT configuration.

Table 5. Process upset impact on six OPEX ( $L_O$ ) components

<i>Cost contributor</i>	<i>Clogging issues</i>	<i>Integrity issues</i>	<i>Impacts</i>
Spec. energy cost, $L'_E$	Increases slightly	Unchanged	Increased heating requirement and CIP reagent demand
Spec. membrane replacem. cost, $L'_M$	Increases	Increases	Decreased membrane life
Spec. chemicals cost, $L'_C$	Increases	Unchanged	Increased CIP frequency
Spec. labour cost, $L'_L$	Increases	Increases	Increased effort, removing/replacing modules
Spec. waste disp. cost, $L'_W$	Increases slightly	Unchanged	Increase in waste chemicals

The impact of operating under challenged conditions can be assessed based on the following approaches:

- a) comparison of labour costs associated with planned and reactive staff effort; and
- b) ad hoc site-based information.

The increase in operating costs attributable to the process upset can then be compared to the capital cost, to assess whether it is realistic to increase the level of investment (quantified as the specific CAPEX  $L'_C$ ) to reduce the risk of process upset.

### 3.4.1 Planned vs. reactive staff effort

According to the current analysis, the reactive staff effort makes up  $56 \pm 8\%$  of the total staff effort. If it is assumed that the reactive effort can be obviated by appropriate process design modifications, then this assigns the maximum supplementary CAPEX  $\Delta L'_C$  value.

According to this assumption, and based on the data depicted in [Figure 5](#), eliminating the cost associated with reactive labour ( $\Delta L'_L \sim 50\%$  of  $L'_L$ ) produces a PV cost saving of between 20% (at 160,000 m<sup>3</sup>/d design flow capacity) and 180% (at 2,000 m<sup>3</sup>/d flow capacity) of the CAPEX. In absolute terms this equates to £370k at the lowest flow and £2.0m at the highest.

The  $L'_L:L'_O$  appears to be largely insensitive to the base values assumed for the key parameter of design flux. For example, a 30% change in the design flux (from 45 LMH to either 30 LMH or 60 LMH), producing a corresponding 8% change in the CAPEX, produces no more than a 3% change in the absolute  $L'_L:L'_O$  percentage value.

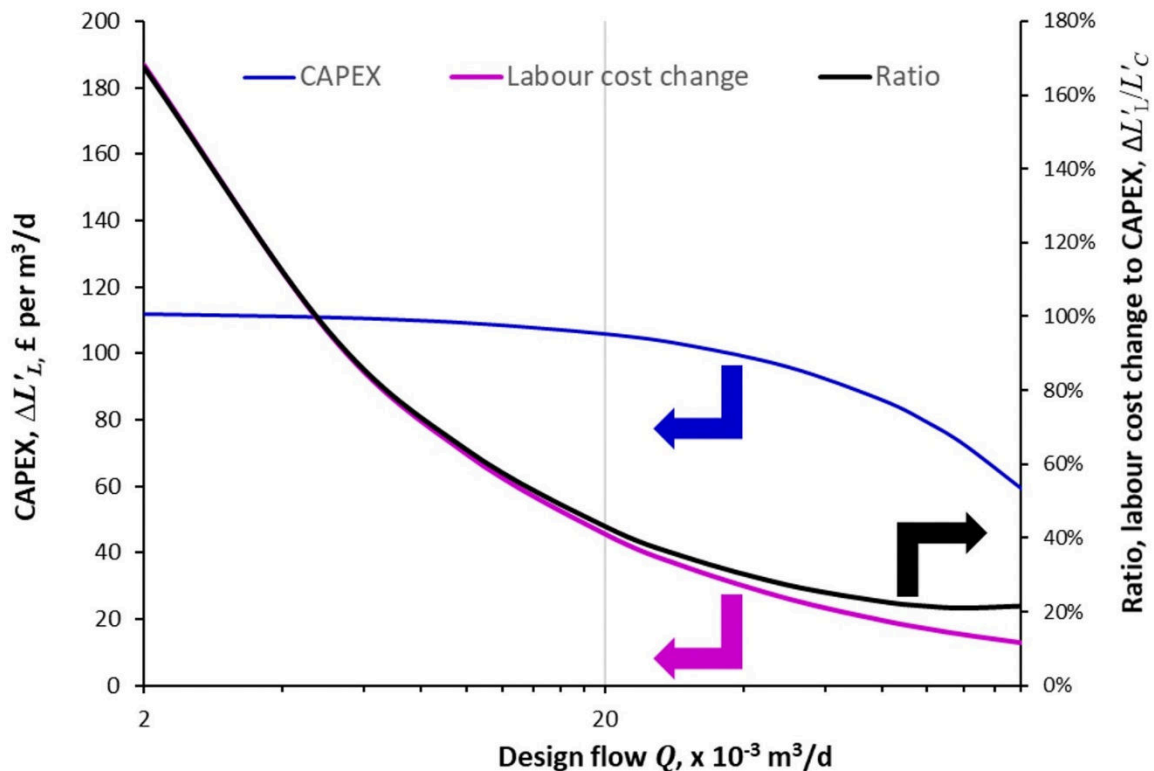
### 3.4.2 Impact of excessive pinning

Anecdotal evidence from the owners, including published commercial data ([Bristol Water, 2018](#)), suggests that supplementary effort of 0.4 FTE associated pinning is perceived as being unacceptably high for a 25,000 – 30,000 m<sup>3</sup>/d flow capacity plant. Using the same approach as previously this flow equates to a labour PV of £680k over a 20-year cycle, compared to a CAPEX PV of ~£2.3m. So, in this instance an investment of up to ~30% of the CAPEX for this

plant capacity would be cost effective if this resulted in a 0.4 FTE reduction in the labour effort from the reduced pinning frequency. It would also significantly reduce the risk of compliance failure, as well increasing the membrane life.

### 3.4.3 Impact of clogging

As indicated in Table 5, clogging impacts negatively on all key OPEX contributors due to increase incurred in both the labour effort and the CIP frequency. The latter increases both the chemicals and energy consumption, since the CIP requires heating of the reagents (App C).



**Figure 5:** Impact of eliminating reactive staff effort component of labour cost, as a proportion of capital cost

Under extreme conditions the CIP frequency may be reduced from every 30 d to every 3.5 d. In this case, the energy demand would increase by 5% from 0.147 to 0.155 kWh/ $\text{m}^3$ , with a corresponding increase in the specific energy cost,  $L_E$ , to £0.0194 per  $\text{m}^3$ .

The chemicals cost increases proportionately: a decrease from 30 to 3.5 days increases the chemical usage by a factor of  $30/3.5$ , i.e 8.6. This cost therefore increases to £0.002 per  $m^3$ . The waste generation would also increase, although the primary waste stream is the backwash water rather than the spent CIP reagents.

The membrane life is also affected by clogging. A conservative estimate would be a reduction to 3 years from the baseline life 7 years. The specific membrane replacement cost  $L_M$  increases commensurately, from £0.0091 to £0.0211 per  $m^3$ .

However, the most significant OPEX impact is on the labour cost. According to experience, an increase in labour effort by between 26 and 40% can arise during the clogging event for a 10-50,000  $m^3/d$  plant according to information provided from two of the sites studied. Taking an average of these two ranges, a 33% increase in labour effort for a 30,000  $m^3/d$  plant increases the specific labour cost from £0.0094 to £0.0125 per  $m^3$ .

The overall impact of clogging is thus to increase the OPEX  $L_O$  from £0.0382 to £0.0568 per  $m^3$ , a change of 0.0186 per  $m^3$  or £560 a day for a 30,000  $m^3/d$  capacity installation. Thus, a 3-month clogging event incurs a cost of ~£50k in addition to the routine running costs, representing a ~50% increase.

## 4 Conclusions

A cost analysis of low-pressure membrane filtration for potable water production from inland raw waters has been conducted based largely on data provided by the installation

owner/operators and their service providers. Outcomes indicate the capital expenditure (CAPEX) to be significantly lower than that suggested by previously published trends, and for the economy of scale (the exponent value in the power law trend) to be less. The total operational expenditure evaluated as the present value (i.e. the OPEX PV) was found to exceed the CAPEX by a factor of 3-6 over the 20-year life cycle, the difference increasing with decreasing flow capacities.

Labour costs, segregated into routine (or “planned”) and non-routine (“reactive”) trends and normalised against flow rate, were found to increase with decreasing flow capacity, exceeding the contribution of energy to cost at flows below 5,000 m<sup>3</sup>/d and exceeding the CAPEX at flows below 30,000 m<sup>3</sup>/d. “Reactive” labour contributed around 50% of the total labour cost, and was associated with excessive membrane pinning (i.e. repair of breached membranes) and/or permeability recovery following clogging events.

Since the cost incurred by process upsets increases as a proportion of the total cost with decreasing flow capacity, the cost effectiveness of any remedial measures depends on (a) the total period of the process upset in which the additional cost is incurred, and (b) the absolute cost of the remedial measure, as a function of flow capacity. This then provides a benchmark for determining the potential cost benefit from modifying the installation to reduce the risk of process upsets.

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## Appendix A Consumer price index CPI

Historical information (Fig. A1) indicates the UK consumer price index to have followed a roughly linear trend with year (y) since the turn of the millennium:

$$CPI = 2.002y - 3933 \quad (R^2 = 0.98)$$

The CPI thus increased by roughly two units a year from a value of 71 from the year 2000 onwards, reaching 111 in the year 2020.

The CPI was used to correct the CAPEX component excluding the membrane module cost, which was determined from owner data to represent ~25% of the cost of the membrane technology component cost. The 2020 capital cost ( $L_C$ ) thus correlates with the capital cost  $L_{C,y}$  at year y according to:

$$L_C = 111 \times 0.75 L_{C,y} / (111 - 2(2020-y)) + 0.25 L_{C,y}$$

$$= 83.3 L_{C,y} / (111 - 2(2020-y)) + 0.25 L_{C,y}$$

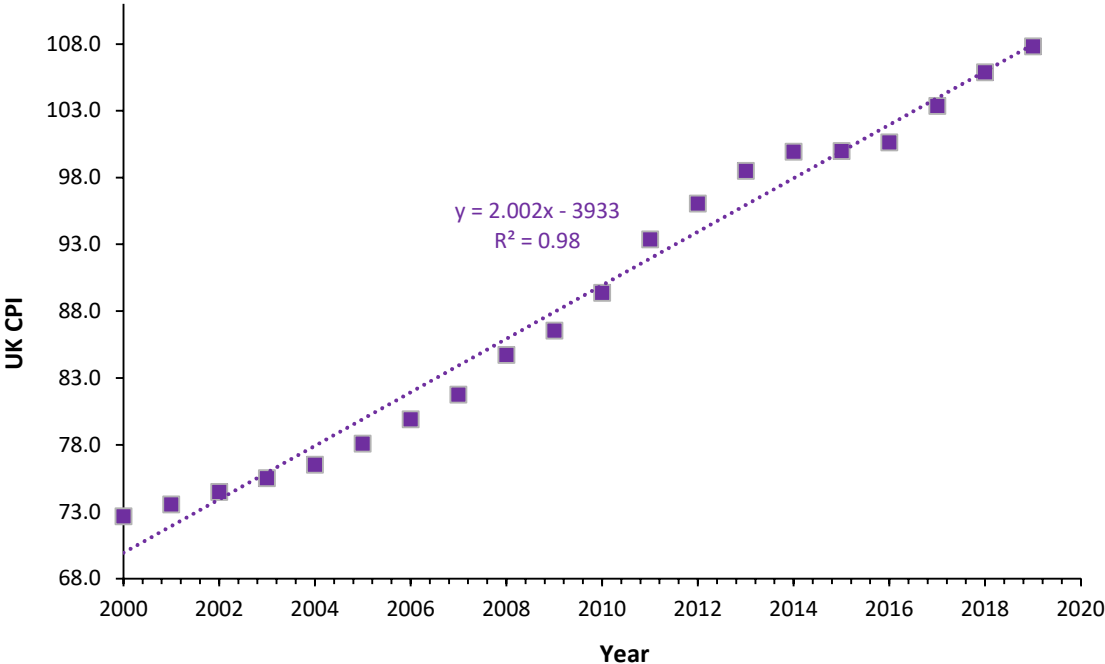


Figure A1: UK Consumer Price Index trend

## Appendix B Liquid and air pumping energy

### Liquid

The energy demand for permeate pumping is approximately given by:

$$E'_L = (P + P_{losses})/(36\varepsilon_p\theta)$$

where  $P$  is the average feed pressure in bar,  $P_{losses}$  represent the system losses,  $\varepsilon_p$  is the pump efficiency and  $\theta$  is the conversion. This assumes that the liquid pumping energy consumed during the backflush cycle is approximately the same as for the filtration cycle. If  $P$  is assumed to be 0.3 bar and the system losses add a further 0.05 bar, the pumping efficiency 70% and the conversion 95%, then the energy consumed by liquid pumping is:

$$E'_L = (0.3 + 0.05)/(3.6 \times 0.7 \times 0.95) = \mathbf{0.146 \text{ kWh/m}^3}$$

### Air

Compressed air is used during the backwash cycle. The total energy consumed for air pumping per  $\text{m}^3$  permeate thus depends on the backwash frequency, the minimum value for this being 30 minutes.

The aeration energy consumption in  $\text{kWh/Nm}^3$  air is given by:

$$E'_{A,air} = k ((0.0987h + 1)^{0.283} - 1)/\varepsilon_b$$

where  $k = 0.102 \text{ kWh/Nm}^3$ ,  $h$  is the head of pressure in m water, and  $\varepsilon_b$  the blower efficiency.

For a maximum pressure of 10 bar (100 m head) and a blower efficiency of 70%:

$$E'_{A,air} = 0.102 \times ((0.0987 \times 100 + 1)^{0.283} - 1) / 0.7 = 0.141 \text{ kWh/Nm}^3$$

The assumed air consumption rate is  $2.5 \text{ Nm}^3$  for a minimum permeate volume of 1 ML, based on a backflush frequency of 30 minutes, equating to an energy consumption of 0.352 kWh. If this energy is expended for a *minimum* permeate volume of 1 ML, or  $1000 \text{ m}^3$ , then the *maximum* specific energy consumption for air pumping per  $\text{m}^3$  permeate is:

$$E'_{A,permeate} = E_A' = 0.352 / 1000 = \mathbf{0.000352 \text{ kWh/m}^3}$$

The energy expended for air pumping is thus negligible.

## Appendix C Chemical cleaning

### **Chemical cleaning reagent consumption**

The chemical reagents used for the cleaning in place (CIP) are sodium hypochlorite (NaOCl), caustic soda (NaOH), sulphuric acid (H<sub>2</sub>SO<sub>4</sub>), and citric acid (CA) (Table C1). Data used to calculate the specific cost for chemicals supply are indicated below for a 30d CIP interval. The chemical consumption cost for either a hypochlorite or caustic soda based clean, in both cases with supplementary mineral/citric acid cleaning, is therefore roughly given by:

$$L'_R, \text{ £/m}^3 = 0.22 \times 10^{-3} \times 30/t_{CIP}$$

where  $t_{CIP}$  is the interval between CIPs used in practice, normally at least 28 d unless there is a clogging event, such that for a 30-day cleaning interval  $E'_R \sim \text{£0.00022}$  per m<sup>3</sup> permeate for a hypochlorite or caustic soda based CIP.

**Table C1:** Costs, based on 30 d CIP interval

<i>Reagent</i>	<i>Concentration</i>	<i>Demand</i> L/ML	<i>Supply cost</i> £/L reag	<i>Specific cost</i> £/ML
NaOCl	10%	0.15	£0.60	£0.1080
NaOH	32%	0.12	£0.63	£0.0905
H <sub>2</sub> SO <sub>4</sub>	50%	0.08	£0.45	£0.0432
Citric A	50%	0.067	£0.90	£0.0720

### **Chemical cleaning liquid heating**

CIPs are usually conducted using cleanants heated to 30-35°C, incurring an additional cost penalty to the reagent consumption. For a temperature change of  $\Delta T$ , a specific heat capacity of  $C_p$ , a total CIP liquid volume of  $V_{CIP}$ , a heating efficiency of  $\epsilon_h$ , and proportional heat losses of  $\epsilon_l$ , the heating energy, then:

$$E'_H = \Delta T C_p V_{CIP} / (t_{CIP} \varepsilon_h (1 - \varepsilon_l))$$

Baseline values used (Table C2) imply a  $E'_H$  value of **0.0010 kWh/m<sup>3</sup>** for a typical 30d CIP interval, increasing to **0.0086 kWh/m<sup>3</sup>** for a 3.5 d interval, as may be expected during a severe clogging event. Severe clogging thus adds ~6% to the energy consumption.

**Table C2:** Baseline values, CIP reagent liquid chemicals heating

<i>Parameter</i>	<i>Value</i>
Maximum temperature change $\Delta T_{\max}$ , °C	25
Specific heat capacity, $C_p$ , kJ/°C/kg	4.2
Volume of cleaning liquid, $V_{CIP}/Q$ , m <sup>3</sup> per 1,000 m <sup>3</sup> /d flow	0.5
Heat efficiency, $\varepsilon_h$	60%
Losses, $\varepsilon_l$	20%
Interval, d	30
<b>E kWh/(CIP·Q)</b>	<b>0.00101</b>

## Appendix D Critical component replacement

The membrane module represents the most significant critical component in terms of OPEX.

The averaged specific cost for membrane replacement  $L'_M$  in  $\text{£}/\text{m}^3$ , ignoring discounting and inflation, is given by the membrane cost per  $\text{m}^2$  ( $L_M$ ), the flux  $J$  in  $\text{L}/(\text{m}^2 \cdot \text{h})$  and the membrane life  $t_M$  in years (Table D1)

$$L'_M, \text{£}/\text{m}^3 = 1000 L_M / (J t_M \times 365 \times 24) = 0.114 L_M / (J t_M)$$

**Table D1:** Example membrane costs

<i>Technology</i>	<i>Area, m<sup>2</sup></i>	<i>L<sub>M</sub>, £/m<sup>2</sup></i>	<i>J, LMH</i>	<i>t<sub>m</sub>, y</i>	<i>L'<sub>M</sub>, £/m<sup>3</sup></i>
<i>HF1a</i>	23.4	£27.78	61-76	7	0.0060-0.0074
<i>HF1b</i>	34.8	£24.43	41	7-8	0.0054-0.0089
<i>HF1c</i>	34.5	£18.84	61-62	5-8	0.0065-0.011
<i>HF2</i>	50	£25.00	69-97	10	0.0024-0.0027
<i>CT</i>	40	£60.00	100-110	10	0.0065

*HF1a-HF1c*: these products refer to different models from the same technology supplier (*HF1*)

Based on a fairly conservative flux of 45 LMH, a cost of  $\text{£}25/\text{m}^2$ , and a life of 7y, an undiscounted cost of **£0.0091 per m<sup>3</sup>** permeate can be assigned to membrane replacement.

# Low-pressure membrane technology for potable water filtration: true costs

Judd, Simon J.

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