Economic and environmental assessment of water reuse in industrial parks: case study based on a Model Industrial Park

Birte Boysen, Jorge Cristóbal, Jens Hilbig, Almut Güldemund, Liselotte Schebek and Karl-Ulrich Rudolph

ABSTRACT

Industrial wastewater reuse is a major measure to mitigate the depletion of available freshwater resources in the catchments around industrial areas and to prevent possible future water shortages and the resulting problems for industry, economy and society. Combining a set of environmental aspects and economic aspects of different wastewater treatment technologies, the authors developed a model-based approach for planning and evaluating water reuse concepts in industrial parks. This paper is based on an exemplary Model Industrial Park. The results based on data primarily calculated for Germany show that, for the majority of the indicators, the installation of the Water Reuse Plant seems to be beneficial for all examined reuse options. Considering the economic dimension, due to economies of scale, reuse options with larger volumes of treated water are preferable since the costs per m^3 of reuse water are reduced by up to 33%. On the other hand, the environmentally preferable option depends on the respective indicator, e.g. for freshwater eutrophication, the higher the reuse factor, the lower the impact, leading to reductions between 8 and 12%. For climate change, the best option is dependent on the reuse purpose leading to reductions between 8 and 52%.

Key words | cost function, economic evaluation, environmental assessment, industrial park, LCA, water reuse

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HIGHLIGHTS

- Industrial water reuse can reduce future water shortages.
- Development of a model-based approach for planning and evaluating reuse concepts in industrial parks (IPs).
- Economic and environmental evaluation of a Model IP located in Germany.
- Economic profitability of reuse depends on wastewater effluent discharge and possible alternatives.
- In the evaluated case, reuse was shown to be environmentally beneficial.

doi: 10.2166/wrd.2020.034

INTRODUCTION

Freshwater supply is one of the most urgent challenges in many regions worldwide, presumably posing significant risks to societies in the 21st century if left unaddressed. On average worldwide, the majority of freshwater is consumed in agriculture; however, industrial processes also require large amounts of water. In 2015, the industrial share corresponded to 19% of total global water withdrawal (FAO 2016). In industrialised nations, this share can be considerably higher, accounting for between 50% and more than 90% of the national water withdrawal (FAO 2016). Thus, industrial wastewater reuse is a major measure to mitigate the depletion of available freshwater resources in the catchments around industrial areas and to prevent possible future water shortages and the resulting problems for the industry.

Industrial parks (IPs) are equipped with a wastewater treatment plant (WWTP) whose objective is to remove contaminants from the wastewater (mainly suspended solids, organic matter and, in certain areas, nutrients), so that it complies with legislation and can be discharged back into the environment. When treated wastewater is to be reused, additional treatment is needed in order to ensure its quality for the intended purpose and to minimise health and environmental risks. The additional treatment is called reclamation water treatment (as well as reuse or recycling) and is carried out in a Water Reuse Plant (WRP) (Alcalde Sanz & Gawlik 2014).

It is clear that the need for more treatment beyond the WWTP is associated with environmental and economic impacts that might outweigh the benefits from avoided water production and wastewater discharge. For that reason, water reuse in IPs must be evaluated from a life cycle perspective. Yet very few research papers concerning this topic appear in the literature, and they draw different conclusions. For the environmental dimension, Pasqualino *et al.* (2011) assessed the stages of a Spanish municipal WWTP and compared four urban wastewater reuse alternatives with a no-reuse scenario. While the WWTP of the no-reuse scenario is characterised by a primary and secondary treatment and the subsequent disposal of wastewater to the sea, the reuse scenario incorporates an additional tertiary treatment that includes coagulation, flocculation, sand filtration, chlorination and UV disinfection with subsequent replacement of potable water for non-potable uses. The authors concluded that the addition of a tertiary treatment to the traditional two-stage WWTP and the subsequent utilisation of the treated water for potable water replacement increases the environmental impact of the plant. Tong *et al.* (2013) also compared different reuse scenarios in an IP: no reuse, reuse as industrial process water and reuse for horticulture, and concluded that water reuse in IPs is beneficial from the environmental perspective.

Considering the economic dimension, Giurco *et al.* (2011) evaluated the cost effectiveness of water treatment and industrial reuse concluding that the studied options are not self-sufficient from a cost perspective and, therefore, would not be implemented by companies in the absence of financial assistance or other incentives. On the other hand, in Eco-Industrial Parks such as Kalundborg (Denmark), water reuse has been successfully applied for decades not only due to economically driven actions but also because of water scarcity (Ehrenfeld & Gertler 1997). The economic benefit of water reuse in IPs depends on the costs of the wastewater reuse system compared with the existing water supply. Besides economic and ecological benefits, the implementation of water reuse schemes depends on the regulatory framework, the general availability of water and additional factors like company strategies or demand-related behaviour.

Urkiaga *et al.* (2008) developed a methodology for assessing the performance of water reuse projects including both the environmental and the economic perspective (as well as social factors). That methodology is not particularly focused on industrial reuse but also provides possible industrial reuse purposes. Results have shown possible environmental water quality benefits, whereas an economic analysis of water reuse indicated a potential increase in costs when the WRP is not located near the industrial user.

Based on this literature review, it can be concluded that the implementation of water reuse schemes is dependent on several site-specific framework conditions which determine the economic and environmental impacts. In this context, the joint research project Water Reuse in Industrial Parks (WaReIp) deals with the systematic investigation of wastewater generated within IPs, its treatment and its reuse for various purposes. This paper is written within the framework of WaReIp and its main objective is to assess water management concepts in IPs focusing on water reuse and resource depletion. The main novelty being the updated cost functions used for industrial wastewater in combination with a modular calculation model complemented by an environmental assessment and applied to a theoretical Model Industrial Park (MIP).

This paper is organised as follows: at first, the developed MIP is introduced along with the reuse framework, as well as the reuse options with the specific design of the WRP. Thereupon, the methods for both the economic and environmental assessment are introduced. Results are shown and discussed, and finally, the conclusions of the study are drawn.

MODEL INDUSTRIAL PARK AND REUSE FRAMEWORK

In the context of the WaReIp project, surveys and interviews are conducted in existing IPs in Germany, China and Vietnam. The experiences and results are used for the development of both the composition of a general MIP and the reuse framework shown in Figure 1 in which the wastewater is treated in a central WWTP to an effluent standard adhering to legal requirements. Subsequently, a defined quantity of wastewater is treated further in a WRP in order to be utilised for different infrastructural water use purposes (e.g. street cleaning and toilet flushing) (for detailed information on the developed MIP, see Bauer et al. 2019).

Water reuse in production processes itself is not considered under the WaReIp project (Bauer et al. 2019) since this is part of internal process optimisation of the independent companies located in the IP. In addition, feedback from both IP operators and production companies shows that the production plant operators have no experience with the use and possible effects of reduced water qualities in their production processes and are reluctant to modify their processes without intensive preparations.

In the development of the MIP, wastewater from 19 different production plants across various industries with different polluting loads are considered, as well as wastewater of a canteen and sanitary wastewater. The calculated overall wastewater flow of the MIP is 94,658 m^3/d (Bauer et al. 2019). For the economic and environmental assessment, the MIP is assumed to be located in Germany.

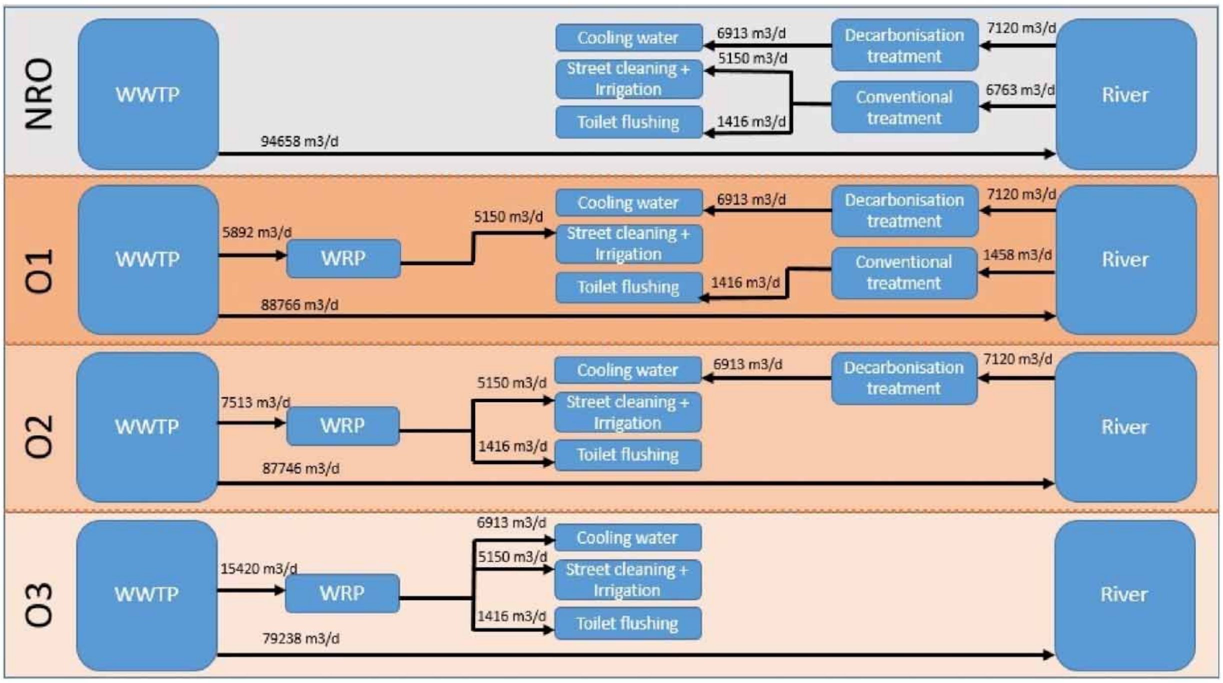

Figure 1 | Model Industrial Park water reuse options.

REUSE OPTIONS

In this paper, three different reuse options within the MIP are evaluated and compared with a non-reuse option (NRO). The reuse options are characterised by the reuse factor (i.e. the percentage of wastewater from the WWTP that is reused) and by the considered reuse purposes, specifically street cleaning and irrigation, toilet flushing as well as cooling water. Whenever the mentioned reuse purposes cannot be supplied by reuse water from the WRP, this demand is assumed to be supplied by groundwater, surface water or external sources treated in a central water treatment plant. Wastewater from the WWTP that is not treated in the WRP for the specific reuse purposes, is considered to be discharged directly into a river. Figure 1 shows the wastewater and reuse water flows of the different reuse options.

The NRO refers to the situation in which the total wastewater flow from the WWTP is discharged into a river. In Option 1 (O1), the WRP is installed to treat approximately 5% of the wastewater from the MIP to cover the demand of street cleaning and irrigation water (i.e. 5,150 m^3/d). In Option 2 (O2), the reuse factor is increased to 7% in order to cover the demand of street cleaning and irrigation water, as well as toilet flushing water (i.e. 6,566 m^3/d). Finally, in Option 3 (O3), the reuse factor is increased to 14% in order to cover all the water demands for infrastructural purposes including cooling water (i.e. 13,479 m^3/d).

WATER REUSE PLANT

The WRP includes the same process steps for all three reuse purposes: sandfiltration, UV disinfection and chlorination. These steps are selected, among other possible technologies for WRP such as ozonation or peroxide addition, based on the project WaReIp experience and the most commonly used technologies for tertiary treatment. Figure 2 depicts the technical process modules dimensioned for O1.

These data are based on the MIP and literature research for the process modules. The sandfiltration is dimensioned for a filtration velocity of 8 $m^3/(m^2\ h)$ (Mann *et al.* 2012; Tchobanoglous *et al.* 2014) and a solids loading of 3 kg $TSS/(m^3\ d)$, according to DWA-A 203 (2019). The energy demand for sandfiltration is assumed as 0.05 kWh/m^3 (Kraus *et al.* 2016). UV dimensioning is based on a hydraulic loading rate of 100 l/(min lamp) with a redundancy factor of 2 (Tchobanoglous *et al.* 2014). Based on Bischoff & Wagner (2012) and Müller *et al.* (2009), an energy demand of 0.035 kWh/m^3 is used. For the last reuse treatment step, chlorination, a contact time of 90 min and a chlorine dosage of 15 mg/l are chosen (Tchobanoglous *et al.* 2014). As it is assumed that the chlorine gas is not produced on-site, the energy demand for chlorination was assumed to be negligible.

Further assumptions of the MIP include an 8% loss of reuse water in the supply network; in O1, this leads to the treatment of 5,598 m^3/d wastewater from WWTP to satisfy the demand of 5,150 m^3/d. The WRP was oversized in such a way that the treatment of the wastewater is carried out at a mean plant utilisation rate of 75% as shown in Supplementary Material, Table A1. Energy and chemical demand were calculated for the mean flow rate. Furthermore, the sewage sludge was not considered in the calculations of the MIP.

METHODS

Economic evaluation

Economic and financial aspects play a major role in the planning of integrated wastewater concepts for industrial zones (Kreuter & Rudolph 2016). An economic evaluation is necessary to determine whether water reuse within IPs

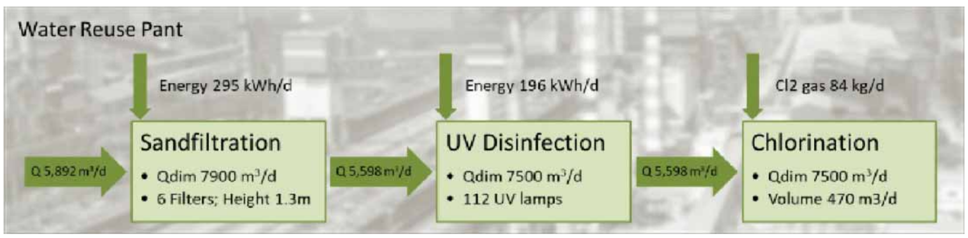

Figure 2 | WaReIp Reuse Plant dimensioned for Option 1.

is viable or not. The economic evaluation here is based on cost functions and a calculation model which can be extended to a financial model. The cost functions are based on literature research of mostly German municipal WWTP including studies like Günthert & Reicherter (2001), Türk *et al.* (2013), and Horstmeyer *et al.* (2014) (For more details, see Hilbig *et al.* (2020), 'Economic Evaluation of Water Reuse in Industrial Parks' in this same special issue). By calculating the arithmetic function of the individual cost functions and introducing a trend line, an average cost function of the municipal WWTP can be derived for individual process steps as shown in Figure 4. This also covers treatment sizes that are not considered in all publications. In order to be able to compare the cost functions of different references, the functions must be converted to one price level and one unit. Cost data from other countries are raised (via price index of the respective country) to a 2017 level and then converted into Euros. The data are mostly based on German WWTPs with exceptions such as data from Hunziker-Betatech (2008) which are from Switzerland and the data for chlorination which are not available for German WWTPs. In order to be comparable, the results are converted to €/m^3/d and €/m^3. For the sake of simplicity, the cost functions of the municipal WWTPs are used for the industrial WRP. As mentioned before, the industrial wastewater is treated in a central WWTP to a legally required effluent standard before it reaches the WRP and, therefore, no longer has higher industry-specific pollution.

The cost functions are split into functions for operational expenses and for investment. As far as possible and useful, investment functions are broken down to civil works, mechanical equipment and, if available electronic instrumentation and control (E/I&C) to later calculate depreciation and to adapt the sections separately to country-specific conditions. If a specific breakdown is not available, a percentage allocation is made.

The investment cost functions of the sandfiltration, UV disinfection and chlorination are shown in Table 1. In order to adapt them to the conditions of the German MIP, they will be validated in expert interviews. The operational expenditures are generally based on the described process modules including energy and consumables; furthermore, they include labour and maintenance costs.

Table 1 | WaReIp WRP relevant investment cost functions

Process	x	y	Cost function investment
Sandfiltration	m^3/d	€/m^3/d	$y = 651.24X^{-0.15}$
UV disinfection	m^3/d	€/m^3/d	$y = 1{,}048.3X^{-0.321}$
Chlorination	m^3/d	€/m^3/d	$y = 1{,}004.4X^{-0.29}$

Examples are the cost functions for UV disinfection, which consists of cost functions provided by Horstmeyer *et al.* (2014), Müller *et al.* (2009) and further data from an internal project database, leading to the average cost function shown in Figure 3. The investment breakdown for sandfiltration is based on Hunziker-Betatech (2008), whereas the breakdown of the UV investment is divided with the help of percentages. The chlorination cost function is based on Das (2002) and U.S. EPA (1999). The potencies in the cost functions (Table 1) show economies of scale for investments. The determined investment cost functions are transferred into the calculation model.

Calculation model

The WaReIp economic calculation model is an assessment tool to model the economic effects of water reuse concepts. The model is built in a modular way to allow for a comparison of different technologies and process chains. The modules integrated in the WaReIp calculation model for example include sandfiltration, UV disinfection, chlorination and a pipeline network. Each of these modules can be modelled independently, so that both the individual effect of a module and its weight in combination with other modules can be evaluated to form a complete water reuse concept. Furthermore, the calculation model is able to calculate three different variants with different technical specifications and volume flows in parallel and compare the results.

Within the model, first of all, global variables which apply to all three scenarios and all modules need to be defined. The time dimension is defined by the number of periods to be considered, the start of the fiscal year and the first period under consideration. For the WaReIp MIP model, a timeframe of 30 periods from 2018 onwards was selected for the German fiscal year structure. This default setting automatically models the reference timeline for all inputs on the following

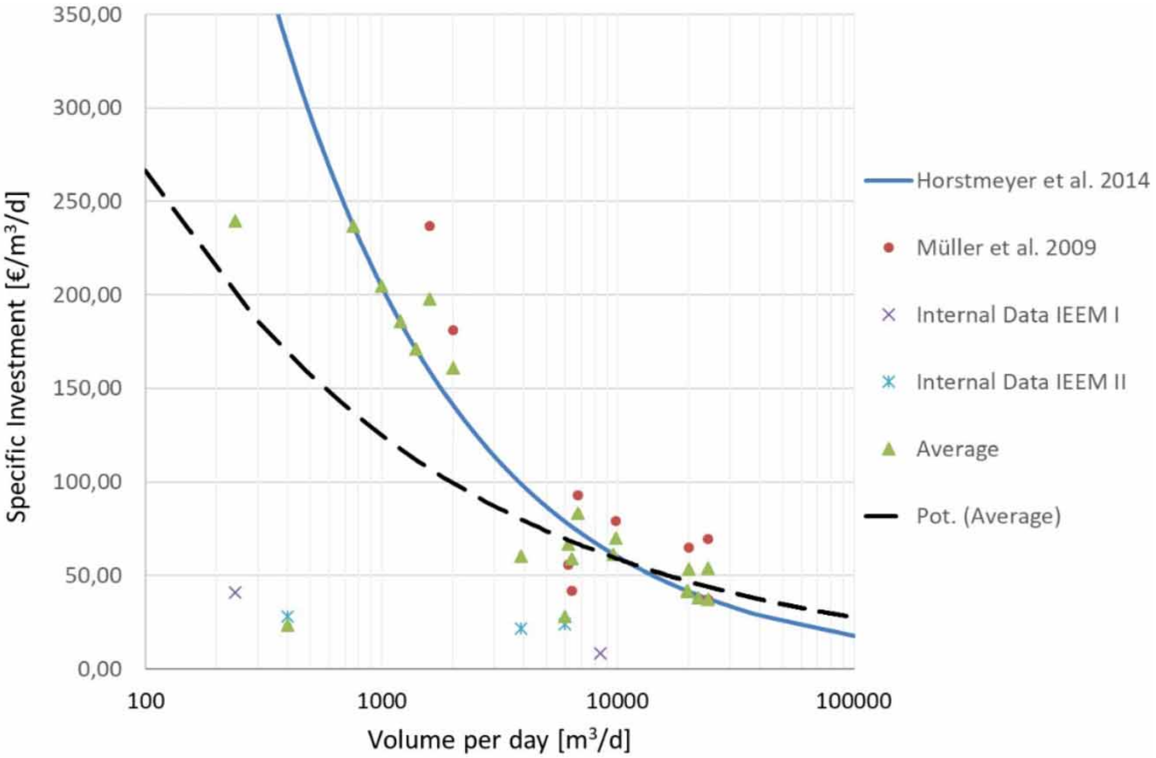

Figure 3 | Specific investment cost function UV disinfection.

calculation worksheets. Furthermore, the underlying inflation rate was set to 1.80% and the applicable value-added tax rate for net inputs to 19%. Monetary inputs are shown in EUR, and the modelled WRP operates 365 days/year.

The next step is to define the parameters of the three reuse options used. These options may differ only in volume sizes or flow rates or may use completely different module combinations at the same time. In the MIP model, the process chains are identical but the volumes change.

The investments are calculated with the previously determined net cost functions, which are (where possible) divided into different subcategories, namely, general costs and fees, groundworks, civil works, mechanical equipment, E/I&C and heating/ventilation/air conditioning. For each subcategory, the depreciation period can be defined individually. General costs and fees, surrounding works and construction are depreciated over 30 years, E/I&C technology over 7 years and heating/ventilation/air conditioning over 10 years. In the case of mechanical equipment, an additional distinction was made between general mechanical equipment (10 years) and UV lamps (5 years). The selected depreciation periods are identical for all three scenarios. The reinvestments depending on the depreciation periods are automatically taken into account in the model over the selected 30-year period.

The operating costs are also divided into subcategories that have been tailored to the underlying calculation formulas: labour costs, maintenance, energy costs and consumables. The inputs needed to calculate the annual operating costs per module and in total are derived on the basis of cost functions and the input of the process modules in combination with results from expert assessments, prices from retail inquiries and hourly wages. For sandfiltration, the labour and maintenance costs are widely based on Hunziker-Betatech (2008). The energy demand of 0.05 kWh/m^3 is defined in the technical process module and multiplied by an assumed company electricity price of 0.12 €/kWh. The UV disinfection energy demand of 0.035 kWh/m^3 is used and automatically multiplied by the defined electricity price. An expert assessment estimated a labour demand of 3 h/day which is multiplied by an hourly wage of 47.40 € (Jekel *et al.* 2016). The price of chlorine gas has been estimated in a retail inquiry to be 2.3 €/kg, and the demand from the process modules is given as 0.015 kg/m^3. For UV disinfection and chlorination, the maintenance costs are calculated via percentages of the investment, for civil works, it is 0.5%, for mechanical equipment 2.5% and for E/I&C 1% of the investment. The extrapolation of the operating costs determined in this way is carried out by simple inflation through the annual inflation rate determined in the global variables of the calculation model.

After entering all necessary information or using the default values, the investment and operational costs are calculated automatically in the model with underlying formulas.

Environmental assessment

As mentioned before, in order to save water resources by reusing water in IPs, a WRP must be installed, which nonetheless entails environmental burdens of its own. A method for the environmental assessment of water reuse concepts must, therefore, be able to highlight the shifting of burdens from one life cycle or process stage to another (e.g. environmental impacts of WRP versus wastewater discharge to river), from one protective good to another (e.g. air, soil and water) as well as from one impact category to another (e.g. climate change, eutrophication and toxicity). With its life cycle approach and the consideration of different impact categories, life cycle assessment (LCA) is an appropriate tool to meet these requirements.

According to the ISO (2006a), the LCA must be performed in the following four well-defined steps: goal and scope definition, inventory analysis, impact assessment and interpretation.

Goal and scope definition

The aim of the environmental assessment is to quantify and compare, for the specific case of the exemplary MIP in Germany, the environmental impacts of the different specified reuse options and the no-reuse reference case in order to identify the environmentally most advantageous alternative.

Through the examination of an exemplary MIP using LCA, generic findings are gained that can be transferred to different water reuse concepts in real IPs. The results of this assessment can, therefore, be used by IPs' operators and planners as well as public institutions to improve the environmental impacts associated with the supply and disposal of water within IPs and to enable scientifically sound decisions between different water reuse concepts.

From the framework of the MIP, the following two functions of the product system can be derived:

- the disposal of the wastewater from the WWTP and
- the supply of water for infrastructural purposes within the MIP.

Therefore, the functional unit selected for this LCA is the disposal of the total wastewater flow from the WWTP and the provision of the required water flows for the different reuse purposes with the required quality.

System expansion is used where one of the above-mentioned functions is not included in the system boundaries. This is the case for those reuse scenarios that do not supply enough reuse water to satisfy all reuse purposes and for the no-reuse reference case. Here, the water for the reuse purposes has to be provided by other means to make a fair comparison. In the environmental assessment, surface water is assumed to be treated by a standard conventional treatment plant for the purposes of street cleaning, irrigation and toilet flushing or by a decarbonisation treatment for cooling water.

The decision, that shall be supported by this assessment, concerns the installation of a WRP. Processes upstream to the WRP are considered not to be modified and are, therefore, outside the system boundaries. Therefore, the operation of the WWTP and the sludge line are not considered. This means that the wastewater from the WWTP enters the system 'burden free'. The provision of energy and chemicals for the WRP are included in the system boundaries as well as the infrastructure of the WRP technologies as shown in Figure 4.

LIFE CYCLE INVENTORY

Detailed data on the Inventory are shown in the Supplementary Material. Inventory of foreground processes is usually obtained by data collection at the plant. In this case, since the study intends to see the suitability of a prospective

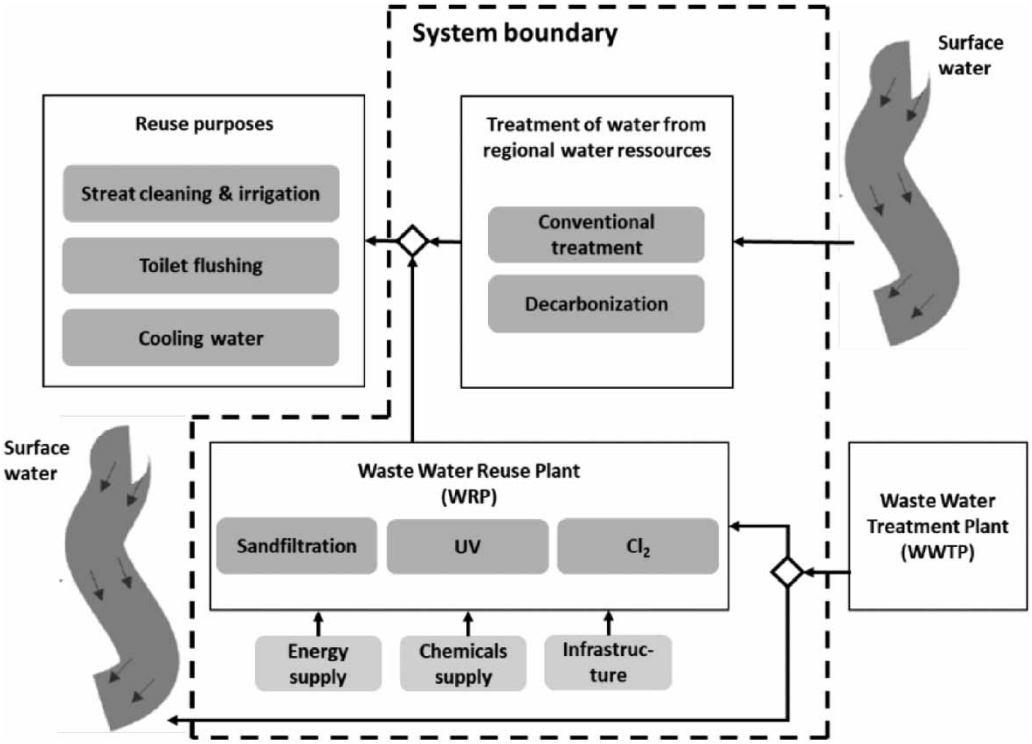

Figure 4 | System boundaries.

WRP (i.e. in the planning stage), data will be obtained through modelling and simulation as proposed by Bisinella *et al.* (2015). Foreground data were mainly provided by the technical process modules and the calculation based on literature and expert estimates from the interviewed stakeholders within the project.

For background data, ecoinvent v3.4 was used. The system model APOS (Allocation at the point of Substitution) was chosen. APOS follows the attributional approach in which burdens are attributed proportionally to specific processes. Further information on this topic can be found in the documentation of the ecoinvent v3 database (Wernet *et al.* 2016). When possible, the data of the background system were chosen to be representative of Europe. Products traded on the global market were modelled with globally representative data sets. The technical infrastructure (e.g. buildings and facilities) is also considered in the system boundaries, but the uncertainty associated with those processes is very high.

Due to the high data uncertainty, several assumptions had to be made, some of which can influence the results considerably. The following assumptions were made within the framework of this LCA:

- It is assumed that the wastewater from the WWTP complies with a minimum quality for emission. Different standards have been used to impose those limits depending on the parameter (MEP 1996; WQA 2013). The values used in this LCA are as follows:
  - COD – 100 mg/l
  - NH_4-N – 15 mg/l
  - P – 0.5 mg/l
  - TSS – 70 mg/l
  - Sulfid – 1 mg/l
  - Nitrite – 1 mg/l
  - Nitrate – 10 mg/l
  - Chloride – 750 mg/l
- In the same line, it is also assumed that the wastewater from the WRP complies with the minimum quality required for the infrastructural purposes (except hygiene parameters).
- The water from the backwash of the sandfilter is sent to the WWTP. Since the WWTP is neither considered

within the system boundaries nor modelled for this case study, an average wastewater treatment process is selected from the ecoinvent database.

- The water losses in the piping system have been included (i.e. 8%) after the WRP. However, since no information is given neither on the fate of those waters nor on the quality, the impact has not been taken into account.
- For the provision of electricity, an electricity mix from Germany was assumed. It can vary from country to country being a determinant for the final results.
- The disposal of sand from the sandfilter is not considered.
- The sewer system is not included in the system boundaries, and the dismantling of the WRP is out of the scope.
- The system expansion accounts for the water provision from conventional processes when reuse is not in place. Those conventional treatments may be more detailed than the modelled technologies in the WRP influencing the results.

LIFE CYCLE IMPACT ASSESSMENT

Due to the lack of primary data on the wastewater quality and the wastewater treatment technologies, only the most important impact categories influenced by the available data have been included within the framework of this LCA. Those impact categories are Climate change, Freshwater eutrophication, Marine eutrophication, Resource depletion – mineral, fossils and renewables, and Resource depletion – water. Other impact categories were neither calculated nor evaluated. The midpoint characterisation methods used are the ones recommended by the ILCD Handbook (Hauschild *et al.* 2011) for life cycle assessments (Table 2).

In particular, the distribution of toxic compounds could not be investigated, as this would require extensive modelling. However, this factor should not be ignored in the decision-making process.

The optional components of the impact assessment according to ISO 2006b, normalisation and weighting were omitted.

RESULTS AND DISCUSSION

Economic assessment

The focus of the calculation model is to determine both the total costs and the costs per m^3 of reuse water per process step and per scenario over the determined period. The modular structure also allows each individual module to be compared with the others and examined for its influence on the overall result.

Reuse O1, with 5,150 m^3/d of reuse water, represents the smallest volume and is only designed for irrigation and street cleaning purposes. The pipeline network has been neglected for this scenario, as a standpipe point at the WRP has been assumed. O2 extends the scope of the water reuse concept by toilet flushing purposes and provides 6,566 m^3/d of reuse water. For O2, investments and operating costs for the pipeline network are added. O3 represents the largest volume size with 13,479 m^3/d of available reuse water. The additional water is intended for cooling purposes in the industrial estate. In Figure 5, a comparison of the undiscounted costs per m^3 of reuse water for the different options is shown.

Table 2 | Impact assessment methods (Hauschild *et al.* 2011)

Impact category	Impact assessment model	Impact category indicators	Source
Climate change	Bern model – global warming potentials (GWP) over a 100 year time horizon	kg CO_2 equivalent	Intergovernmental Panel on Climate Change (2007)
Eutrophication – aquatic	EUTREND model	fresh water: kg P equivalent marine: kg N equivalent	Struijs *et al.* (2009) as implemented in ReCiPe
Resource depletion – water	Swiss Ecoscarcity model	m^3 water use related to local scarcity of water	Frischknecht *et al.* (2008)
Resource depletion – mineral, fossil	CML2002 model	kg antimony (Sb) equivalent	van Oers *et al.* (2002)

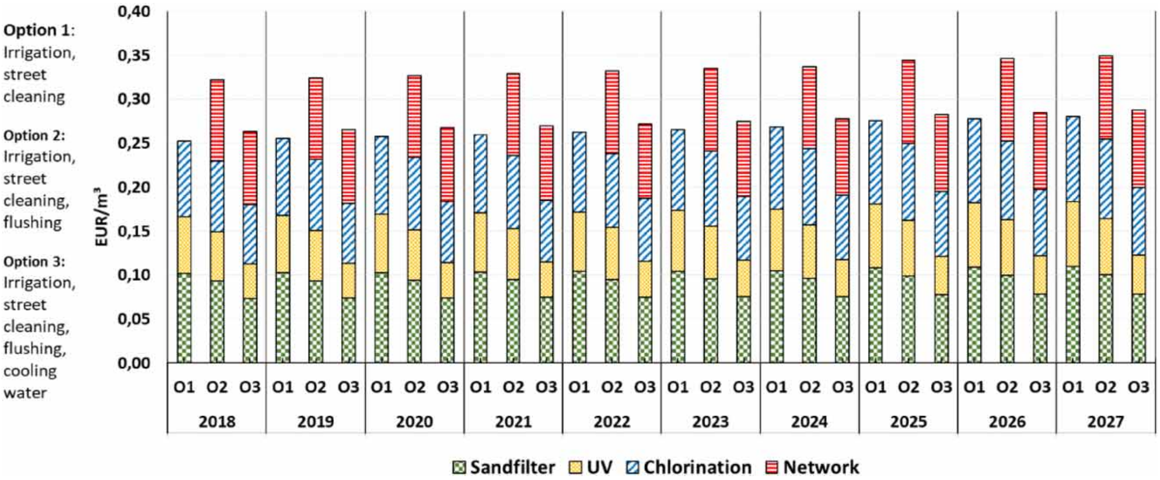

Figure 5 | Cost per m^3 reuse water in each reuse option over 10 years.

Comparing the interim results, O1 has the lowest costs per m^3 of produced reuse water, but mainly because it does not integrate costs for the pipeline network. If the pipeline network costs for O2 and O3 are neglected, there is a trend of slightly decreasing costs per m^3 with increasing size of the water reuse volumes, and a cost degression is identifiable. The economies of scale are an important factor when considering different reuse purposes and options; it might lead to a lower cost per m^3 when an additional application is included as noticeable comparing O1 and O3. UV costs for example amount to 0.06 €/m^3 in O1 and decrease by 33% to 0.04 €/m^3 in O3. The overall costs per m^3 decrease by 28% from 0.25 €/m^3 in O1 to 0.18 €/m^3 in O3. The overall economies of scale almost balance the costs of the pipeline and leave a difference of 0.01 €/m^3 between O1 (0.25 €/m^3) and O3 (0.26 €/m^3). Option 2 with the pipeline network and not profiting as much from economies of scale is the most expensive option.

The second trend is slightly increasing costs per m^3 of reuse water produced over time. This trend has two basic causes. First, the operating costs increase from year to year due to the inflationary projection, and second, renewal investments lead to increased depreciation over time, as the model also inflates the renewal investments, these results need to be included in a potential financial model. In the above time axis over 10 periods, only few renewal investments come into effect, so that it can be expected that this trend will intensify over time as renewal investments increase.

The calculated results are slightly higher than those stated by Bischoff (2013) for example, where UV costs are given with approximately 0.02–0.03 €/m^3. Costs for sandfiltration are given between 0.03 €/m^3 and 0.15 €/m depending on site-specific conditions (Hunziker-Betatech 2008) while chlorination with gas can be as low as 0.03 €/m^3 (Elefritz 2000) and chlorine dioxide as an alternative is given as 0.05–0.13 €/m^3 in Bischoff (2013). In contrast to the cost functions, the results presented here are not inflated and can, therefore, be lower. Furthermore, discounting, a heterogeneous study design and different plant sizes can lead to deviating results.

IPs have to treat their effluent to a specified discharge quality according to legal requirements and their operating licences. For that reason, only the costs of the additional WRP are considered without the costs of the mandatory WWTP. Furthermore, alternatives in the no-reuse option are the usage of tap water or the extraction from the river as cooling water. To extract water from a river in Germany, a permit is required (Wasserhaushaltsgesetz WHG § 8; Federal Water Act article 8). Additionally, a fee is charged for the permit and the water extraction. This fee may vary according to local conditions and state regulations. Given the assumed volumes in the MIP, such a fee would be below 6 cent/m^3 with no further treatment, which is significantly lower than the further treatment at the reuse plant. However, water needs to be available at any time and the extraction has to be permitted. Depending on the duration of the permit, renewals are necessary and planning security may be limited, as the regulating authority may alter the conditions or volumes of abstraction (e.g. due to water stress). Under certain conditions, river water needs to be decarbonised at a cost of 0.46 €/m^3 (ecoinvent v3.4) which is higher than the calculated price for the reuse plant water. Besides the extraction from a river, tap water or lower quality factory water can be used. In an inquiry in Germany, a price of 0.70 €/m^3 was determined for factory water, which in comparison would be more expensive than the cost for the reuse.

Environmental assessment

This sub-section shows the results of the impact assessment for the impact categories previously mentioned. Figure 6 shows the comparison of the three proposed options reusing water with the NRO. Thus, the vertical axis would be the NRO, and the results of the different impact categories show the decrease or increase in the percentage of each option compared with the NRO.

The results for climate change, freshwater eutrophication and marine eutrophication are analysed in detail below. The other impact categories' results are further commented upon within the Supplementary Material.

As shown in Figure 7, the results for the climate change impact category show a general decrease in the impact when reuse is implemented in comparison to the NRO. Thus, the NRO presents an impact of around 2,002 kg CO_2 eq./day, whereas 97% of this impact is due to the production of water from the conventional treatment for the purpose of irrigation, street cleaning and toilet flushing. The main contributor to this impact is electricity production. When the WRP is installed and reuse water is used to cover the demand of irrigation and street cleaning (O1) and additionally toilet flushing (O2), the impact is reduced to 1,181 and 955 kg CO_2 eq./day, respectively. Thus, avoiding the production of water using conventional treatment, the climate change impact is reduced by 41 and 52%, respectively. Finally, for O3, the results for the climate change impact increase (i.e. 1,838 kg CO_2 eq./day) in comparison to O1 and O2. Nonetheless, the impact on climate change is still lower compared with the NRO (i.e. a reduction of 8%).

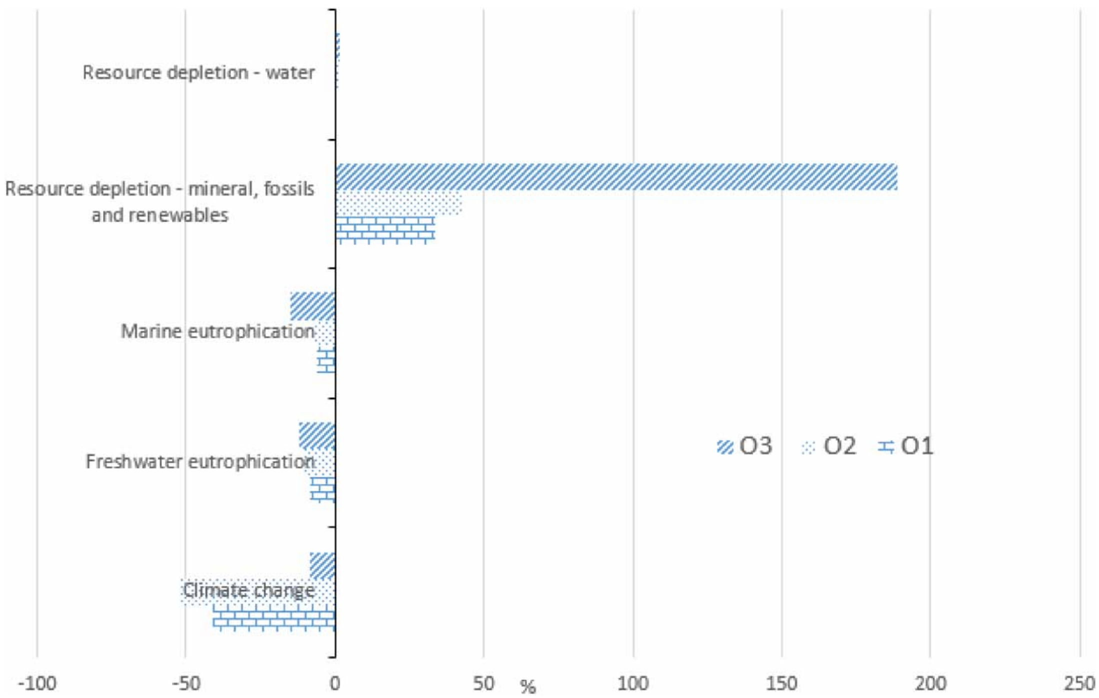

Figure 6 | Impact results for the comparison of the three proposed options reusing water with the NRO.

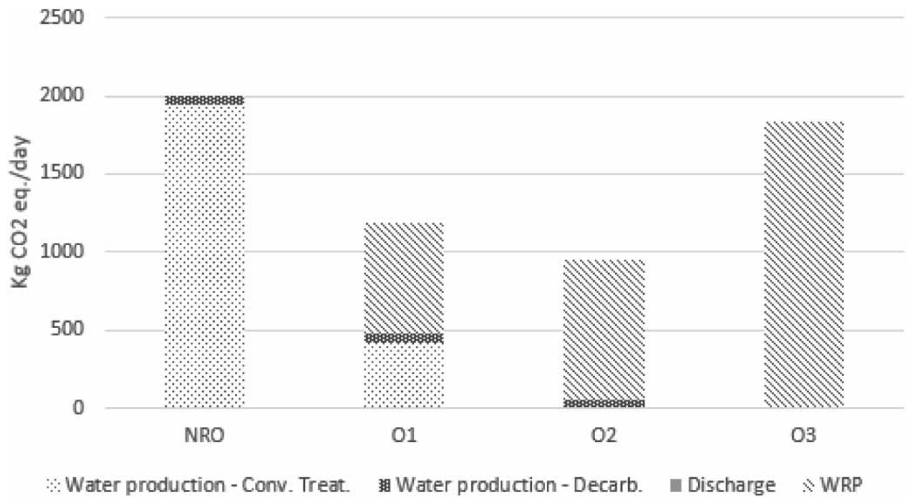

Figure 7 | Results for the impact category climate change.

Replacing the supply of cooling water by the WRP using the decarbonisation technology leads to an increase of GHG emissions mainly due to the electricity production, infrastructure and the treatment of the backwash water in the sandfilter. Those results are in line with Tong *et al.* (2013) who report larger environmental credits for scenarios in which treated water is used for higher value applications.

Freshwater eutrophication and marine eutrophication impact categories follow the same trend for the different options. Thus, for freshwater eutrophication (see Figure 8), the NRO presents an impact of around 17.2 kg P eq./day, with 92% of this impact due to discharge of water into the river and the other 8% mainly due to the production of water from the conventional treatment for purposes of irrigation, street cleaning and toilet flushing. The main contributor to this impact is the phosphate emitted to the river. When the WRP is installed and reuse water is used to cover the demand of irrigation, street cleaning (O1) and additionally toilet flushing (O2), the impact is reduced to 15 and 15.4 kg P eq./day, respectively. By avoiding the discharge of the wastewater into the river, the impact on freshwater eutrophication is reduced by 8 and 10%, respectively. O3 presents an impact of 15.2 kg P eq./day with a small contribution of the WRP of around 8% mainly due

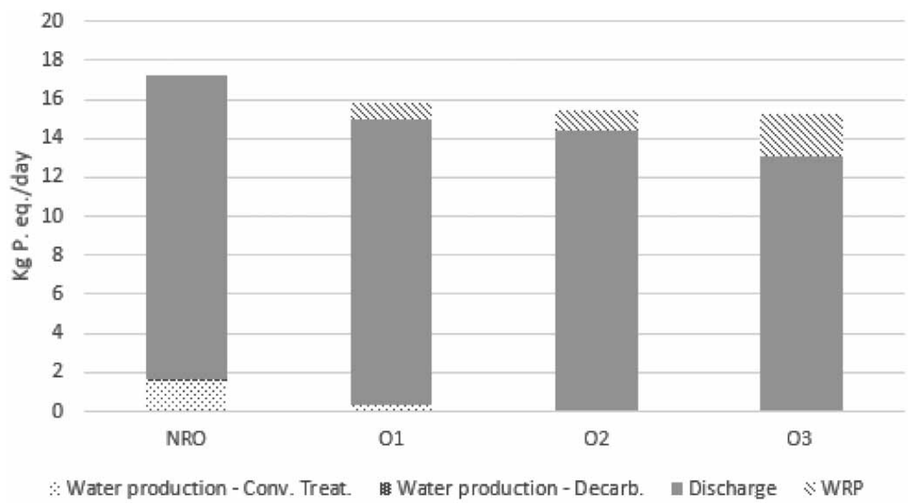

Figure 8 | Results for the impact category freshwater eutrophication.

to the treatment of the backwash water from the sandfilter. The total reduction of O3 for this impact category in comparison to the NRO is around 12%.

Those results are in line with Pasqualino *et al.* (2011), who conclude that the global warming potential and the freshwater eutrophication potential of the reuse scenario are reduced by 14 and 5%, respectively, compared with the no-reuse scenario. Nevertheless, it has to be mentioned that the system boundaries of Pasqualino *et al.* (2011) are slightly different including the sludge treatment and not considering the plant construction.

In the same line, for marine eutrophication (see Supplementary Material, Figure A1), the NRO presents an impact of around 1,349 kg N eq./day, with 100% of this impact due to the discharge of water into the river. The main contributor to this impact is the ammonium emitted to the river. When the WRP is installed and reuse water is used to cover the demand of irrigation and street cleaning (O1) and additionally toilet flushing (O2), the impact is reduced to 1,270 and 1,248 kg N eq./day, respectively. Avoiding the discharge of the wastewater to the river, impact is reduced by 6 and 8% for O1 and O2, respectively. O3 presents an impact of 1,144 kg N eq./day. The total reduction of O3 for this impact category in comparison to the NRO is around 15%.

Finally, LCA results show that impact categories behave in two different ways. On the one hand, for eutrophication impact categories (both marine and freshwater), the higher the reuse factor, the lower the impact in the respective categories. Thus, avoiding wastewater emissions to the river decreases these impacts. On the other hand, climate change experiences a higher decrease for O1 and O2, when the water is used for street cleaning and irrigation, and toilet flushing, compared to O3 in which the water is used additionally for cooling. In that case, results show that using the reclaimed water for low impact value applications is detrimental for the environment.

CONCLUSION

For the WaReIp MIP located in Germany, the economic and environmental assessment leads to promising interim results. The economic evaluation of the reuse options shows higher costs compared with the extraction from a water body with no further treatment but lower costs per m^3 compared with factory water when only the costs of the WRP are calculated. Furthermore, the costs show economies of scale, which is beneficial for O3 and especially relevant when reuse purposes and, therefore, volumes of required reuse water are chosen. Due to the economies of scale, an increase in volumes like in O3 reduces the costs per m^3 of reuse water by 28% from 0.25 €/m^3 in O1 down to 0.18 €/m^3 and would, therefore, be the preferred option. On the other hand, in O1, the pipeline is not needed, while in O3, the pipeline network is included and amounts to 0.08 €/m^3, summing up the cost of O3 to 0.26 €/m^3 in the first year and of O1 to 0.25 €/m^3. Hence, the total costs in O1 are lower even though the actual reuse water costs per m^3 are higher.

Despite the great uncertainty, it can be concluded from the LCA results that the installation of the WRP seems to be environmentally beneficial for all examined reuse options in comparison to the NRO considering all impact categories, except resource depletion. Considering the global warming potential, the reuse options lead to reductions between 8 and 52% for O3 and O2, respectively, compared with the NRO. Freshwater and marine eutrophication are reduced between 8–12% and 6–15%, for the different reuse options, respectively. In contrast to the above-mentioned impact categories, the impact on resource depletion increases for all three reuse options, being for O3 188% higher compared with the NRO.

Depending on the focus of the comparison, different reuse options were identified as favourable. This applies to the economic versus ecological dimension as well as to different environmental impacts. Therefore, decision makers need to weight the results depending on individual situations, circumstances and local requirements of the specific IP. Therefore, the application of further decision-making tools is necessary to evaluate the relative relevance of the two dimensions as well as of each impact category, making it possible to determine a definite preference for decision-making. In addition to the environmental and economic perspective, further factors like legal requirements, planning security and the company's strategy play an important role and must be considered in decision-making concerning water reuse strategies in IPs.

In future research, the data will be further validated and confirmed by industry experts and adapted to China and Vietnam. In water-scarce regions like North-Western China, the economic and environmental assessments of reuse concepts are not the only criteria for decision-making, political decisions to promote economic development and job creation may be an additional driver for water reuse practices.

ACKNOWLEDGEMENTS

The authors express their gratitude to the BMBF for the financial funding of the WaReIp project (Grant No. 02WAV1409), as well as the experts and partners in Germany, Vietnam and China for their cooperation and contribution. J. C. acknowledges financial support from the Spanish Ministry of Science, Innovation and Universities through the 'Beatriz Galindo' grant BEAGAL18/00035. The authors thank Dagmar Pohl and Dr Maike Beier for their contribution and fruitful discussions as well as the reviewers for their valuable comments.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 3 April 2020; accepted in revised form 29 September 2020. Available online 23 October 2020