University college of London
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Produced water management - A mathematical model to trade-off economic cost and environmental impact for infrastructure utilisation.

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degree of Doctor of Philosophy in Civil and Environmental
Engineering of University College London, 2023

Declaration

I, Afrah AlEdan, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

April 2023

Afrah AlEdan

Acknowledgements

To begin with, I would like to thank God for guiding me through all the challenges that have arisen during this journey.

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Abstract

A substantial amount of wastewater, known as produced water (PW), is generated during oil and gas extraction. Given that PW can have a detrimental effect on the environment, it must be appropriately managed and treated before reuse. Globally, PW management is one of the greatest challenges in the oil and gas industry due to the costly treatment methods and large amounts involved, and there is a lack of expertise in the knowledge of PW management. Kuwait is a leading oil producer, and PW management poses a severe threat to the sustainability of Kuwait's oil fields in terms of cost control and environmental safety.

Here, life cycle and economic assessments are used to develop a mathematical framework for analysing trade-offs between the financial costs and environmental impacts of PW management operations. Specifically, a multi-objective mixed-integer linear programming framework is formulated for Kuwait Oil Company's (KOC) PW supply chain management with different operational and regulatory constraints. A model solution for sustainable operations over the short, mid and long term that aligns with KOC's strategic policy on PW management is presented. A global sensitivity analysis (GSA) also performed to further assess the economic and operational factors that influence KOC's PW management. Finally, risk assessment is conducted to identify and evaluate risks associated with PW utilisation.

Results indicate that treatment operations account for half of total system costs, and electricity consumption accounts for most of environmental impact, affecting the sustainability of the PW supply chain system most significantly. Moreover, KOC's PW supply chain system is impacted by a number of factors, including discount rates, electricity costs, and water treatment costs. In the case of PW utilisation, several types of risks may be posed that may negatively affect health, technology, the environment, and the economy. The findings of this study can be used to assess and guide PW supply chain management at KOC.

KEYWORDS: Produced Water, Oil, Environmental Impact, Fresh Water, Supply Chain, Global Sensitivity Analysis, Kuwait Oil Company.

Impact statement

This research endeavour was motivated by the vision to integrate environmental impact and economic performance within produced water supply chains in the oil and gas industry. The idea emerged from my work experience in produced water management at Kuwait Oil Company.

This research aims to explore the trade-off between economic cost and environmental impact within Kuwait Oil Company. By doing so, it seeks to strike a balance that ensures sustainable practices in the organisation. Moreover, this research endeavours to optimise and develop a sustainable management system for wastewater in oil and gas fields, specifically Kuwait, enhancing their control and reducing adverse effects on the environment. Lastly, it identifies feasible recycling options and recommends their effective implementation, thereby promoting a circular approach to the management of produced water.

The significance of addressing produced water arises from its growing prominence as a critical issue concerning cost control and environmental apprehensions. By identifying essential determinants in controlling Kuwait Oil Company's produced water handling system, it provides valuable insights for policy makers to make informed decisions.

Looking ahead, the mathematical model presented in this study can be extended to incorporate additional major facilities, diverse environments, and various treatment constraints, thus broadening the scope and applicability of produced water management. Moreover, the inclusion of other relevant variables in the mathematical model has the potential to further enhance produced water management practices. This study is committed to ensuring that the produced water supply chains in oil and gas fields demonstrate both positive environmental impacts and commendable economic performance.

The management of produced water supply chains has received limited attention despite its importance, and the results have been inconclusive. The novel information generated by this research serves as a valuable resource for improving produced water management, guiding planning and prioritisation within Kuwait Oil Company and contributing to sustainable practices in the oil and gas industry as a whole.

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Supervisor/ Senior Author (where appropriate)

Tohid Erfani

Date 13th April - 2023

Contents

List of Figures

List of Tables

Nomenclature

Sets

$g \in G$	Sets of gathering centres indexed by g (g_1 and g_2 for gathering centre 1 and 2).
$j \in J$	Sets of reuses locations indexed by j(j=1 for disposal, j=2 for reinjection, and j=3 for reuse).
$t \in T$	Sets of Time periods indexed by t (t=1 for year 1, t=2 for year 2, and t=n for time n).

Parameters

b	Central operational cost coefficient per m^3.
c	Central treatment cost coefficient per m^3.
cp	The capacity of handling produced water at wp facility m^3.
cwd_j	The capacity of treated at j location
d	Central maintenance cost coefficient per m^3.
dg_g	Distance from g to wp location in km.
dp_j	Distance for pipeline from wp to j locations in km.
dr	Discount rate per time period.
dt_j	Distance for trucks from wp to j location in km.
dwd_j	The demand of treated water at j location.
ea	The air emissions coefficients associated with treatment by chemicals.
ee	The air emissions coefficients associated with electricity consumption inside wp.
er	The unit price of electricity produced in wp per Kwh.
$fcpg_g$	The capacity of pipeline from gathering centre gc_1 and gc_2 to treatment plant.
$fcpt_j$	The capacity of truck per unit m^3 from treatment facility wp to j_3 location.
$fcpw_j$	The capacity of pipeline per unit m^3 from treatment facility to j_1 and j_2 locations.
icp_j	The pipe capital cost coefficient per unit km between wp and j locations.
ict_j	The truck capital cost coefficient per unit km between wp and j location.
icy_g	The pipe capital cost coefficient per unit km between g and wp facility.
id_j	Disposal cost coefficient per m^3.
ij_j	Injection cost coefficient per m^3.
k	Central treatment efficiency in wp facility
mn	Minimum capacity of water tank.
mp	Minimum capacity of water pumping.
ms	Maximum capacity of water pumping.
mt	Maximum capacity of water tank.
ocl	The minimum treatment capacity of filters.
ocu	The maximum treatment capacity of filters
q	Max value of TE.
ri	Weight of objective function.
w	Max value of TC.

Variables

ET	Emissions of water treatment.
EU	Emissions during electricity consumption.
$PWG_{g,t}$	Amount of PW transported from g to wp in time t.
PWI_t	Amount of PW inside wp facility.
$PWJ_{j,t}$	Amount of PW treated in wp facility, transported to locations j, in time t.
TCG	Water transportation cost from g location.
TCP	Water transportation (pipeline) cost from j_1 and j_2 location.
TCJ	Water transportation (trucks) cost from j_3 location.
TWC	Water treatment cost.
TWD	Water treatment maintenance cost.
TWN	Water injection cost.
TWS	Water disposal cost.
TOE	Total electricity cost inside wp.
TOE	Total electricity cost inside wp.

Binary variables

YO	0-1 variable. Equal to 1 if onsite treatment technology applied at site wp facility.
YP	0-1 variable. Equal to 1 if wastewater pumping capacity is bounded between mp and ms.
YS_g	0-1 variable. Equals to1 if wastewater is transferred from g to wp facility.
YT	0-1 variable. Equal to 1 if wastewater tank capacity is bounded between mn and mt.

Chapter 1

1. Introduction

Water is a fundamental element on Earth. It is not only essential for life, but also central to society's well-being. While it is estimated that 70% of the Earth's surface is covered by water, only 2.5% of this water is fresh water (USGS, 2019). The problem of water stress is one of the most critical challenges faced by society today (Wang et al., 2021). Figure 1. shows the uneven distribution of water on the Earth's surface and the amount of freshwater.

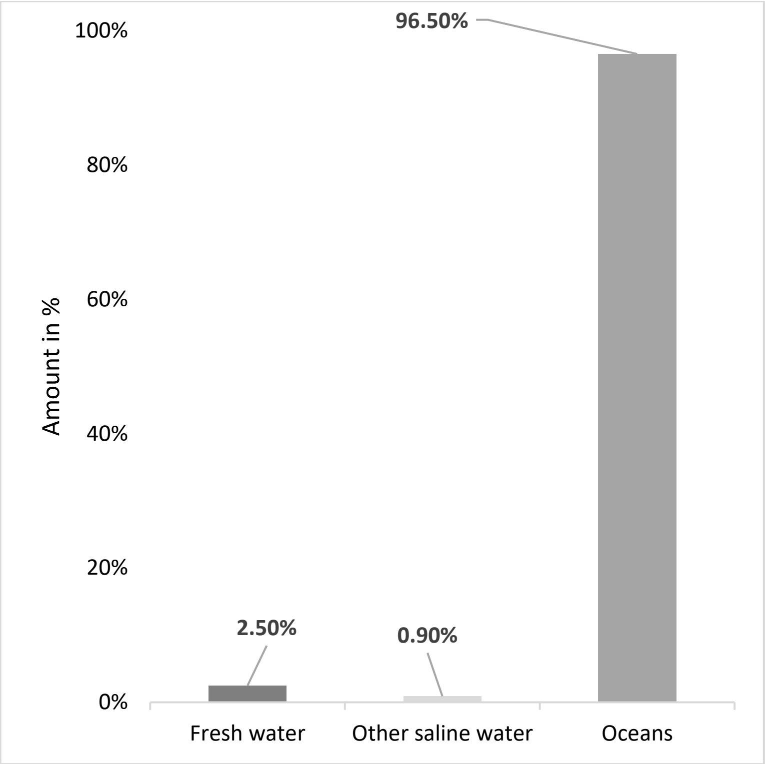


Figure 1. Distribution of water on Earth
Source: (USGS, 2019).

A global population of 8.6 billion is expected by 2030 (United Nations, 2017). Moreover, by 2030, half of the world's population will experience considerable water shortages due to climate change and increasing water scarcity (Echchelh, Hess and Sakrabani, 2018). As the population of many water-stressed regions increases, the associated industrialisation and limited freshwater resources increase the need to reuse other water resources (Sudharsan, Agarwal and Kudapa, 2020). In Kuwait, the amount of total renewable water resources is very low and, according to widely accepted definitions, Kuwait is qualify as ‘water scarce’ country (Siderius et al., 2019).

Due to the high demand for fresh water worldwide and the vital need for alternative water sources, wastewater from industrial sources is becoming increasingly important (Scanlon et al., 2020). The term ‘wastewater’ refers to used water that may contain substances such as human waste, food scraps, oils and chemicals (USGS, 2018). A reduction in water stress can be achieved by treating wastewater in dedicated treatment facilities and using the resultant water for various beneficial purposes (Wang et al., 2021).

During oil and gas extraction, large amounts of wastewater are generated, with an estimated global production surpassing oil production at a volumetric ratio of 2:4. This includes the water originally present in the reservoirs, as well as the water injected into the wells (Salem and Thiemann, 2022). This wastewater is known as produced water (PW) and contains a high level of total dissolved solids (TDS) that can reach concentrations of up to 400,000 mg/L, as well as a number of toxic organic and inorganic compounds (Jiménez et al., 2018). In terms of volume, PW is by far the largest by-product or waste stream associated with petroleum production; therefore, managing PW in the oil and gas sector is challenging due to the high costs associated with the control methods, the treatment requirements and the environmental impacts (Veil et al., 2004). The treatment and management of PW demand urgent attention, due to its direct impact on oil production costs (Karapataki, 2012). A greater focus on PW management requires a greater understanding of the complications that it may create during oil production operations and of the issues associated with PW contamination, quantity and transportation (Goodwin, 2014).

1.1. Problem statement

Due to the world’s growing energy needs and consumption, demand for crude oil is rapidly increasing and the oil and gas industry is continuously increasing production to supply hydrocarbon fluids and gas to the market (Nashawi, Malallah and Al-Bisharah, 2010). A large amount of PW is often generated during the production of oil and gas from wells (Salem and Thiemann, 2022), and with considerable amounts of PW being generated in most countries, it has become imperative to manage this type of wastewater. Globally, there are approximately 300 million barrels of PW, and 83 million barrels of oil produced each day with nearly 55% of it coming from Saudi Arabia, UAE, Kuwait and Qatar (Liang *et al.*, 2018; Jones *et al.*, 2019). A number of factors affect the management and reuse of PW, including not only its volume, but also the quality of its content (Al-Ghouti et al., 2019).

As outlined in Kuwait Oil Company's (KOC) strategic plan, it is expected that more than four million barrels of PW will be produced daily by 2040 (Kuwait Oil Company, 2021). As Kuwait's oil fields generate a greater amount of PW, it is important to pay further attention to this issue (Nabzar and Jean-Luc, 2011). The increased production of PW will have a variety of impacts on the field, and specific concerns have been raised regarding the treatment capabilities, the transportation methods, the limited capacity of water-handling facilities and the high costs associated with building more water-handling facilities (Al-Ballam et al., 2018; Al-Fadhli et al., 2020). Furthermore, due to the high salinity of the PW in KOC fields, it is difficult to treat PW in the area given the limited options available (Salem and Thiemann, 2022). Thus, KOC will be required to take significant measures in the coming years to effectively manage the anticipated increase in PW production, injection and disposal operations (Ali et al., 2013).

Failure to manage PW appropriately and sufficiently may cause the company lots of loses and lead KOC to reach a threshold level in its efforts to increase oil production (Al-Fadhli *et al.*, 2020). Moreover, in terms of renewable water resources, Kuwait ranks last among Middle East and North African countries (Roudi-Fahimi, Creel and De Souza, 2002). In addition, currently Kuwait sources all of its potable water exclusively from desalinated seawater (Darwish, AlAwadhi and Darwish, 2008). Therefore, Kuwait's lack of freshwater resources makes the large volume of PW produced by KOC's activities an asset for the country if it is managed appropriately (Aledan and Erfani, 2023).

It is therefore becoming mandatory in Kuwait to reuse treated PW in order to meet the needs of the population (Al-Jarallah, 2013). Hence, in this research, KOC's current PW management practices are considered in terms of supply chain costs, impact of emissions generated during PW treatment and reuse methods.

1.2. Research gap

Here are some potential research gaps that have opportunities for further study, the gaps that can be considered in this research are as the following:

1. Oil and gas industry stakeholder engagement and preferences: study the role of stakeholder engagement in the development of the optimisation model’s objectives and constraints. Use techniques to integrate stakeholder preferences and priorities to enhance real-world applicability.
2. Oil and gas industry multi-stakeholder conflicts: Engage multiple stakeholder opinions from different gas and oil industries and analyse potential conflicts between different interests in the management of PW.
3. Scalability and transferability of optimisation solutions: Assess the ability of optimisation solutions to be scaled and transferred across geographical locations, taking into account the effects of environmental conditions, regulations, and economic factors.
4. Data availability and data quality: Identify the challenges associated with data availability and data quality in PW management optimisation and investigate methods to deal with data gaps and uncertainties.
5. Incorporating social and community aspects: Explore the integration of social and community aspects as an objective in the multi objectives optimisation model. This can include constraint like community acceptance of reuse PW management for livelihood purposes.

1.3. Scope of research

The scope of this research encompasses a thorough investigation into the economic and environmental sustainability of PW management within the context of the oil and gas industry. Specifically, the study focuses on KOC as a representative case. The research includes the comprehensive analysis of multiple facets, such as the quantification of environmental impacts, the assessment of economic costs, and the identification of potential risks associated with PW management supply chain. The scope further extends to the development and application of a multi-objective mixed integer linear programming model to optimise the trade-off between economic cost and environmental impact. Also, in this thesis the purpose is to identify the potential for beneficial reuse and complications that may arise as a result of oil production operations. In summary, this research aims to offer a holistic understanding of the interplay between economic considerations and environmental concerns in the management of PW, ultimately contributing to sustainable decision-making practices within the oil and gas sector. The area of PW management is still a largely unexplored and this thesis cannot afford to cover it in its entirety. Instead, the purpose of this thesis is to fill the gaps that exist in the current literature about a few key issues in PW management at the decision level. Figure 2. provides an overview of the main topics covered in this thesis.

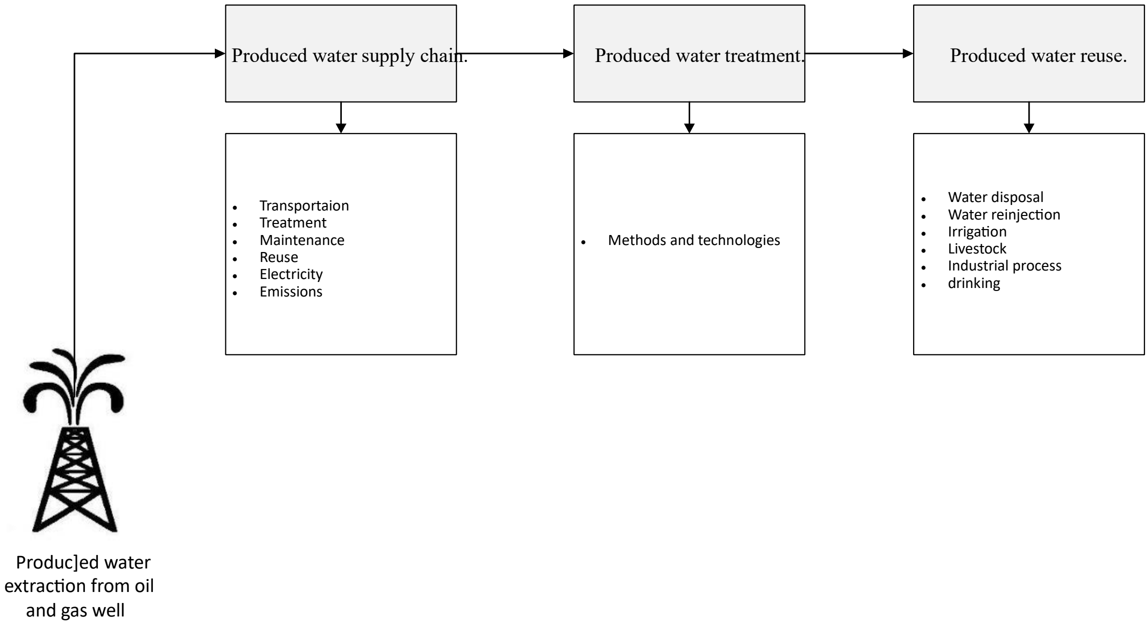


Figure 2. The main topics discussed in the thesis.

1.4. Research questions and objectives

The methodological framework in this research supports analysis of the current PW management system and identification areas for improvement in the presence of economic, operational and environmental constraints. This research approach is used to address the key questions and objectives listed below. The principal research questions that have been addressed by this research are as follows:

1. What are the economic, operational, periodical and environmental impacts of PW management systems in the oil and gas industry, including that of KOC?

2. Which global regulations for PW management leads to optimal environmental outcomes that contribute to health, safety and wellbeing?
3. Which determinants are needed to effectively control a PW management system?
4. How can a PW management system be optimised through the use of a mathematical model?
5. What are the PW recycling options that can be implemented in Kuwaiti oilfields?
6. What are the risks associated with the options of recycling PW?

In line with the above-mentioned research questions, the main goal of this research is to model PW management supply chain systems as decision support tools that policy makers can use when designing regulatory frameworks and improving decision-making in the oil and gas industry. And to provide effective and sustainable solutions for PW management that can consequently be implemented.

To achieve this, the following objectives have been defined.

- To review the literature related to PW management systems that consider capacity, storage, containment, treatment and recycling options.
- To define the global regulations for PW reuse, particularly its impact on the environment, health, safety and wellbeing
- To investigate the status and impact of PW management systems in the oil and gas industry, including in KOC.
- To develop a mathematical multi-objective optimisation model to study the trade-off between environmental and economic dimensions and apply it to KOC as a case study.
- To explore the determinants that are needed to effectively control PW management systems in the oil and gas industry, including in KOC.
- To identify PW recycling options and the associated risks.

1.5. Research methodology

In this Research, a comprehensive approach is adopted to address the complex challenges surrounding the economic and environmental sustainability of PW management and reuse. For the purpose of addressing the objectives defined in section 1.4 of the research, it is necessary to employ a variety of research approaches. present research employs four methodologies to provide a thorough and holistic analysis, including multi-objective mixed integer linear programming (MO-MILP), life cycle assessment (LCA), global sensitivity analysis (GSA), and risk assessment (RA).

Firstly, the application of MO-MILP forms the backbone of the research. This mathematical optimisation technique is employed to optimise the trade-off between conflicting objectives, specifically focusing on economic cost and environmental impact over 5, 10 and 20 years. Test period of 20 years is selected in alignment with the 2040 KOC strategic plan, which provides a comprehensive timeframe for assessing the long-term economic and environmental sustainability of the PW management system. Furthermore, recognising the need for more immediate insights, smaller timeframes of 5 and 10 years are investigated. This approach allows to capture both short-term and long-term implications of the multi-objective optimisation model and evaluate the robustness of the findings across various planning horizons. Selecting two objectives, namely environmental impact and cost, for PW MO-MILP is a practical and focused approach that allows for a more manageable and interpretable analysis for the KOC case study. By limiting the number of objectives, it can be concentrated on the most critical factors that align with the main goals of this research and allows to explore the best compromise between these two conflicting criteria, finding solutions that strike a balance between economic feasibility and environmental responsibility.

Secondly, LCA is employed in this research to quantitatively evaluate the environmental footprint of the PW treatment process. LCA helps in assessing the environmental sustainability of PW management, including its impact on CO_2 emissions. This is crucial for understanding the environmental implications in this research. The use of LCA in this research allows for a comprehensive evaluation of the environmental impacts of PW management in KOC, aligns with sustainability objectives and provides a data-driven foundation for the presented assessments. It enhances the rigor and relevance of this research in addressing both environmental and economic aspects.

Furthermore, and since this research focuses on multi-objective optimisation, GSA can provide insights into how changes in parameters affect the trade-off between the economic and environmental objectives. This is critical for finding optimal solutions that balance both dimensions effectively. GSA is used in this research to improve the understanding of parameter sensitivities and provides valuable insights for optimising PW management in KOC while considering environmental and economic objectives. It enhances the overall quality and applicability of the research findings, making them more relevant for decision-making in the oil and gas industry.

Lastly, a comprehensive RA methodology related to PW reuse is incorporated, identifying potential risks associated with different PW reuse options. The multi-objective optimisation model aims to find the balance between economic and environmental sustainability. RA included in this research is to provide an additional dimension to this balance. RA is an integral part of this research, helping to evaluate the potential consequences of different PW reuse options. RA allows in this research to assess the risks associated with different reuse way, helping decision-makers make informed choices that not only optimise economic and environmental objectives but also minimise potential negative impacts.

The integration of diverse methodologies, such as multi-objective optimization, life cycle assessment, and global sensitivity analysis, demonstrates the versatility of this research. It not only addresses the needs of the oil and gas industry but also contributes to the broader field of applied research methodologies. Furthermore, the amalgamation of these methodologies offers a comprehensive framework for decision-making, effectively optimizing both economic viability and environmental sustainability in the management and reuse of produced water.

Listed below are the details of the methodologies that are used in this research:

1.5.1. Multi-objective mixed integer linear programming (MO-MILP)

MO-MILP is an optimisation technique used to solve problems with multiple objectives, some of which involve discrete decision variables. In MOMILP, the goal is to find the optimal solutions that simultaneously optimise multiple conflicting objectives subject to linear constraints and considering that some decision variables are restricted to discrete (integer) values (Jabarzadeh *et al.*, 2020). The nature of multi-objective mathematical programming is that conflicting objectives must be optimised simultaneously, and no one optimal solution is capable of achieving all objectives simultaneously (Cui *et al.*, 2017). These solutions are known as the Pareto optimal solutions and are obtained using a scaling method. The Pareto optimal solutions generated by MO-MILP offer decision-makers a range of feasible alternatives. This can lead to more informed and robust decision-making, as it helps in understanding the best possible outcomes under different scenarios (Wang *et al.*, 2020). MO-MILP offers several benefits in addressing real-world problems with multiple conflicting objectives and discrete decision variables. It provides decision-makers with a deeper understanding of the problem landscape and empowers them to make informed, efficient, and balanced decisions that align with their objectives and constraints (Singh and Goh, 2019).

The MO-MILP model involves the locations of crude oil gathering centres, a treatment facility, disposal and reinjection wells and a water reuse site. In this research, the mathematical formulation is solved using the GAMS program 36.1.0/CPLEX 20.1.0.1. By utilising the results of the model, KOC can improve the management of PW supply chains. Moreover, the optimum method for monitoring and utilising PW for different uses in the oil and gas industry is determined. The research results and expected outcomes enable KOC to balance economic profitability with environmental responsibility, promoting a more sustainable and resilient approach to PW management.

1.5.2. Life cycle assessment (LCA)

The aim of conducting the LCA developed in this research is to quantify, evaluate the ecological impacts of the PW treatment performed by KOC. The current regulatory framework for LCA is defined by ISO 14040 and ISO 14044. The LCA analysis was performed using the SimaPro LCA software, with a characterisation model of the midpoint approach that provides different results for impacts and comprehensively covers many possible environmental interventions (Dong and Ng, 2014).The midpoint approach uses midpoint indicators that focus on single environmental problems, such as climate change or acidification, while endpoint indicators show the environmental impact on three higher aggregation levels, including the effect on human health, biodiversity, and resource scarcity (Bare et al., 2000). The appropriate unit process was selected from the eco-invent 3.4 database available in SimaPro (version 8.5, Pré Consultants, The Netherlands) to perform the inventory analysis. The LCA described in this research is based on data from the Eco invent database, actual data from KOC and similar LCA studies conducted by Vlasopoulos *et al.* (2006), Piemonte *et al.* (2017), Torp,(2014), Wang et al. 2018 and Kuraimid et al. 2013.

The functional unit (FU) used for PW LCA is one m3 of PW; this is a typical unit of measure used for PW in KOC treatment plants based on the studies of Vlasopoulos et al. (2006), Piemonte et al. (2017), Torp, (2014), Wang et al. 2018 and Kuraimid et al. According to KOC's data sheet on the PW treatment facility included in appendix 1, approximately 100,377 m^3 of PW are processed each day.

When defining the system boundaries in LCA, it is essential to include all the phases that could affect the overall interpretation or ability of the conducted LCA to address the issues for which it is being performed. The system boundaries encapsulate the treatment operations including chemical additives and the electricity consumption by KOC’s treatment facility. The energy, and chemical additives used throughout the treatment operations are included. All the factors included in the analysis are shown in the grey-shaded box in Figure 3.

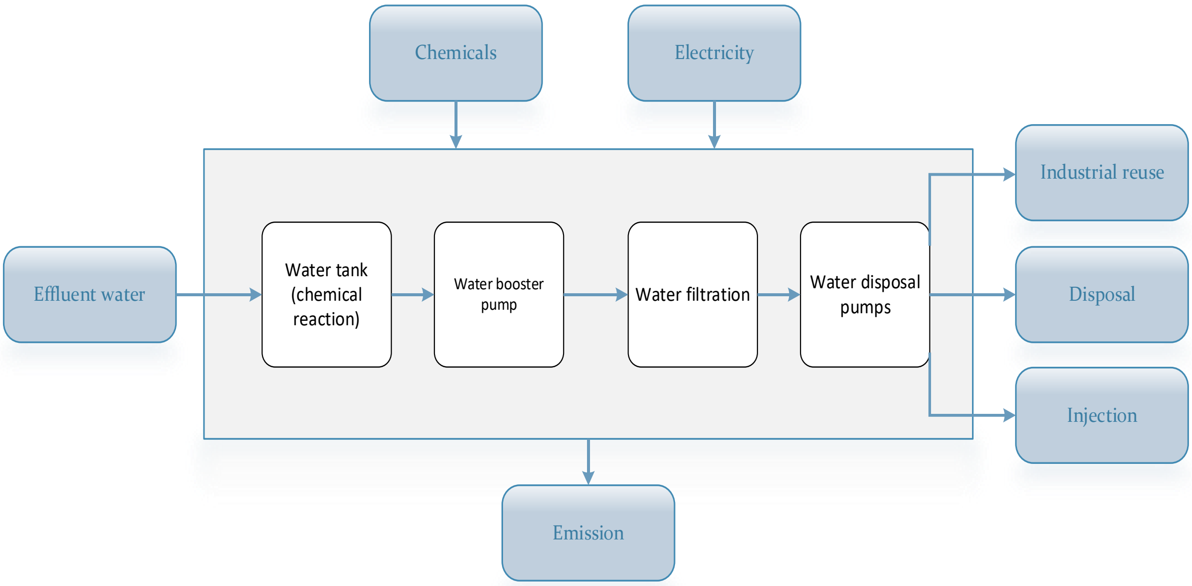


Figure 3. Process flow diagram showing the components of and operations within the effluent water disposal plant. The factors analysed in the life cycle assessment (LCA) conducted in this study are shown in the grey-shaded boxes. The blue arrows represent the flow.

The PW production operations and utilisation scenarios are not included in the system boundaries; the studied system ends at the treatment plant's gate, where the evaluation of the PW is completed. The disposal scenarios, as individual entities, and their environmental impacts are excluded from the system boundary due to lack of information and since they vary greatly depending upon local conditions and regulations. Hence, different disposal scenarios have different environmental impacts.

The selection of chemical additives and electricity consumption as key parameters for CO_2 eq emissions in the research LCA can be justified by two primary reasons:

1-Lack of facility-specific information: obtaining detailed and accurate facility-specific data for every aspect of PW treatment can be challenging. However, chemical additives and electricity consumption tend to have a significant impact on CO_2 emissions and are widely applicable across PW treatment facilities.

2-Significant environmental impact: Chemical additives play a vital role in the treatment process, affecting not only the efficiency of treatment but also generating emissions during production and usage. Similarly, electricity consumption, especially for power-intensive processes like pumping and filtration, contributes significantly to CO_2 emissions.

The life cycle inventory (LCI) is generated in accordance with the system boundaries described in Figure 3. Inventory data related to the process line were collected from the company based on the design of a real treatment facility; more information is available in Section 2 and 3 Appendix.

The construction of the treatment facility has not been considered in this research, as previous studies have demonstrated its weight to be less than 5% of the total environmental impact (Vlasopoulos *et al.*, 2006). An average of approximately 100,377 m^3 of untreated PW reaches the treatment facility daily (KOC report in Section 1 Appendix).

In KOC treatment facilities, PW is placed in a balance tank designed for primary treatment with specific chemical. Table 1. shows the amounts and types of chemical additives used in PW primary treatment.

Table 1. Chemical additives and the amounts used in the primary treatment of produced water (PW)

Additives	**Chemical formula**	**Amount g/m^3**
Sodium chloride	NaCI	188217
Calcium chloride dihydrate	CaCl2·2H2O	55480
Magnesium chloride hexahydrate	MgCl2·6H2O	38090
Potassium chloride	KCl	3820
Iron(III) chloride tetrahydrate	FeCl2·4H2O	1070
Sulphuric acid	H2SO4	408
Sodium hydroxide	NaOH	120

Source: (Kuraimid et al.,2013)

PW treatment involves the use of a large amount of electricity to power filters, which significantly contributes to the total environmental impact of PW treatment facility. The total daily average consumption of electricity inside KOC's treatment facility is 20,2562 kWh (KOC report in Section 2 Appendix). The datasheet containing this information includes all the underlying data used to calculate the electricity and heat energy consumed by the PW treatment facility. Table 2 shows the distribution of energy among to the different processes in the PW treatment facility.

Table 2. Produced water (PW) capacity and energy consumption data included in the inventory.

Element name	Capacity (m^3)	Energy (kWh)
Booster Pumps	510	560
Filters	116,667	185,000
Disposal Pumps	858	16,780

Note: '-' indicates that the data are not available.
Source: KOC report/appendix 3

1.5.3. Global sensitivity analysis (GSA)

Global sensitivity analysis (GSA) is performed in this research to obtain more representative results from the optimisation model. GSA is a mathematical technique that has become increasingly important in the development of environmental models and assessments over the past decade (Ye and Hill, 2017). In the context of this research, it plays a crucial role in understanding the impact of uncertainty and variability in various factors on the results of the MO-MILP.

When conducting the GSA, four independent parameters are taken into account including discount rate, treatment cost, electricity cost and water Capacity (amount of pw that can be treated). Multiple linear regression (MLR) has been used to conduct a GSA in which the influence of different PW supply chain parameters on the total operations cost and environmental impact are assessed. Moreover, MLR has been used to assess the impacts of the model's inputs on each of its outputs (Sin et al., 2011; Pianosi et al., 2016).

In the oil and gas sector, where investment cycles are long and project timelines reach 20-30 years, the discount rate is carefully considered. Several academic studies have demonstrated the importance of accurately determining the discount rate over long planning periods for projects (Komzolov et al., 2021). The use of discount rates in the oil and gas sector allows decision makers to assess the change in the value of expenses over the course of several years (Harden, 2014). Costs associated with PW treatment are also important, as large volumes of oil production wastewater are incapable of being discharged directly into the environment (Lynn E. Katz, R.S. Bowman, 2003). The development of a cost-effective treatment process is therefore essential (Liden et al., 2018). The cost of PW treatment is closely related to the price of electricity and the quality of the PW (Al-ghouti et al., 2019).

In experiments that require multiple parameters to be analysed, a factorial design is commonly used (Hribernik, Bauman and Lobnik, 2009). In practice, the 2k factorial design is considered for implementing the GSA in our analysis. This is because it can be used to investigate multiple parameters at once (Lu, 2016). Therefore, the GSA conducted in this study utilised a 2k factorial design. A total of 48 simulations are performed for four parameters over 5-, 10- and 20-year periods.

The results of the PW management optimisation model are expressed in terms of the MLR model and represented by Equation (1), as follows:

$$yi = \beta 1x1 + \cdots + \beta nxn + \cdots + \beta n+1x1x2 + \cdots + \beta pxnxn-1 + C, \tag{1}$$

where y is the dependent parameters representing different impacts including transportation, treatment, maintenance, reuse and electricity costs, as well as CO_2 eq from chemical additives and electricity usage. A vector of independent parameters, including discount rate, treatment expenditure, electricity expenditures and water capacity is represented by β_n. Interactions between these parameters are considered in Equation (1), such as x1x2. Here, the regression coefficient of each independent parameter reflecting the influence of each independent parameter on the dependent parameter. C is the intercept of the equation, and reflects external variables not considered in the model. To verify the validity of the optimisation model results, the robustness of dependent values is evaluated.

GSA helps identify which parameters have the most significant influence on the model's outcomes. This information is essential for decision-makers as it guides them on where to focus their efforts on refining and improving the model. Additionally, GSA enhances the robustness and reliability of the research outcomes by offering insights into which parameters might need more accurate data or further investigation. Figure 4. outlined the case study flowchart modelling process.

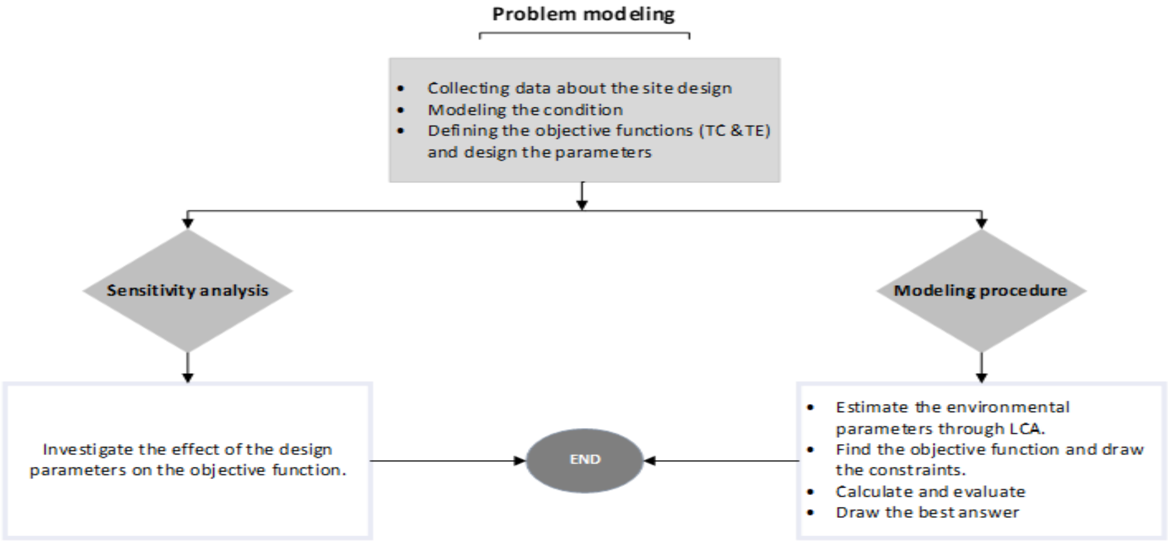
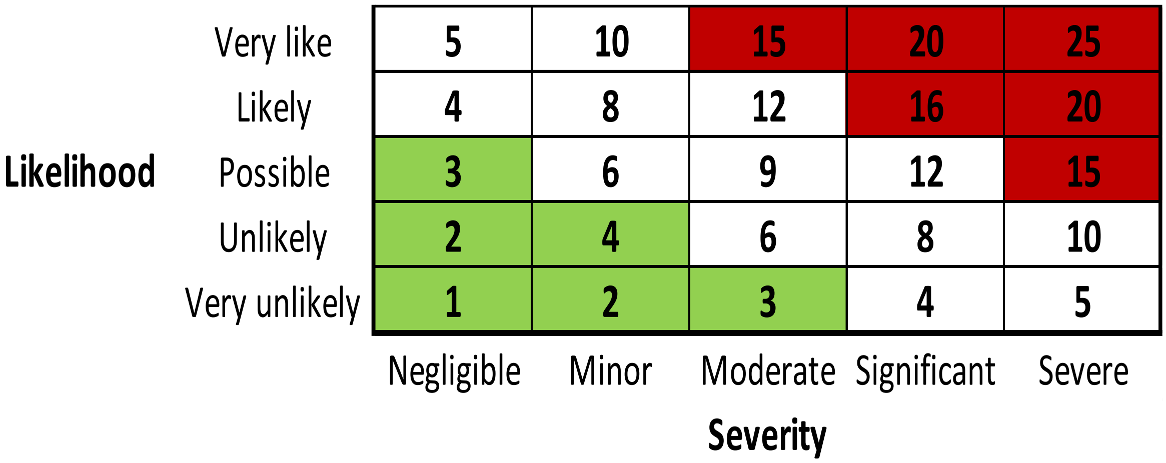


Figure 4. Flowchart of the modelling procedure used in this research.

1.5.4. Risk Assessment

Risk assessment (RA) is employed in this research to comprehensively evaluate the potential uncertainties, and hazards associated with the decision-making process regarding PW utilisation options. Risk assessment is a technique for identifying potential risks and their magnitude, both quantitatively and qualitatively (Torres, Yadav and Khan, 2016). It is imperative that valid information is collected prior to the application of any risk assessment method (Kovačević, Stojiljković and Kovač, 2019). For this study, information has been obtained from different of research studies and case studies related to PW management. In this research, a risk assessment matrix is used to assess and prioritise risks according to their likelihood and impact. Risk assessment matrix involves identifying the risks, defining the likelihood and severity, creating the matrix (Bartram J *et al.*, 2009). To create a risk matrix, clear definitions of likelihood and severity categories (e.g. likely, moderate) need to be developed (Fjeld, Eisenberg and Compton, 2007). Figure 5 presents two-dimensional grid that categorises risks into different levels of severity and shows a 5 × 5 matrix that combines the consequence “severity” in columns (scores 1 to 5) and the probability “likelihood” in rows (scores 1 to 5).



		Severity				
		Negligible	Minor	Moderate	Significant	Severe
Likelihood	Very like	5	10	15	20	25
	Likely	4	8	12	16	20
	Possible	3	6	9	12	15
	Unlikely	2	4	6	8	10
	Very unlikely	1	2	3	4	5

Figure 5. Risk assessment matrix.

The intersection of these two axes forms different cells in the matrix, each representing a combination of likelihood and impact. These cells are then assigned a risk level or priority based on previous and similar studies and case studies. The 5 X 5 matrix displays the joint components of risk that are presented in chapter 7. Multiplication of the scores of consequences by the probability equates to a risk score with a range of values from 1 to 25. The high-risk category (red colour zone) indicates that the risk is intolerable, and an adequate control measure should be established to bring the risk level to at least ‘medium’ before the activity is resumed. The medium risk category (orange colour zone) indicates that the activity should be performed with extreme caution and that additional mitigation or control measures should be established. The low-risk category (green colour zone) indicates that the risk is tolerable and no additional control measures are required. With the determination of the risk score, it is possible to identify, analyse, and prioritise the various risks that may affect the economic, technical, and environmental sustainability of different PW reuse outcomes. This information is vital for oil companies as it assists them in making informed decisions that minimise potential negative consequences and enhance overall operational resilience for PW utilisation. In addition, A risk assessment for the disposal of PW used in this research provides a framework for quantifying the uncertainties associated with the reuse of PW. Moreover, a variety of potential benefits for PW are discussed in this research in accordance with the RA presented in chapter 7.

The risk assessment matrix in chapter 7 is used to assess and categorise potential risks affecting a PW reuse. It is based on two intersecting factors: the likelihood of the risk event occurring and Its severity and the potential impact it may have. The method risk assessment matrix for disposal of PW involves the following steps:

- Define Objectives.
- Identify Risk Factors from related literature review.
- Risk identification.
- Risk analysis of an evaluation of the likelihood and impact.
- Risk prioritisation.

The outcomes of such assessment help to minimise the probability of potential risk to optimize project performance.

Chapter 7 describes the above steps in more detail.

1.6. Research approaches

In this study, a potential trade-off between the economic objective of cost optimisation and the environmental impact of different gases in oil and gas industry case study is examined. by developing and formulating a mixed-integer mathematical model for the optimal design and operations of PW management. Further, using life cycle assessment to determine the number of emissions consumed during the treatment of PW. The goal of developing the mathematical model is to minimise the cost and environmental impact associated with a PW supply chain network in oil and gas industry. The presented multi-objective optimisation model provides design and operation alternatives that can be implemented to enhance control of PW management in general, and in KOC specifically. It also provides alternatives for PW recycling outcomes and for the optimal design and operation of PW supply chain networks.

To develop the case study model, the following main decision variables are considered for PW management: the transportation of PW from two oil-gathering centres to a treatment facility, the treatment of PW inside an effluent water-treatment facility, the transportation of treated PW to different disposal locations and other methods of PW handling. Greenhouse gases (GHG) resulting from PW treatment have significant environmental consequences that must also be considered in the context of PW management. Figure 6 shows the process flow of PW supply chain management.

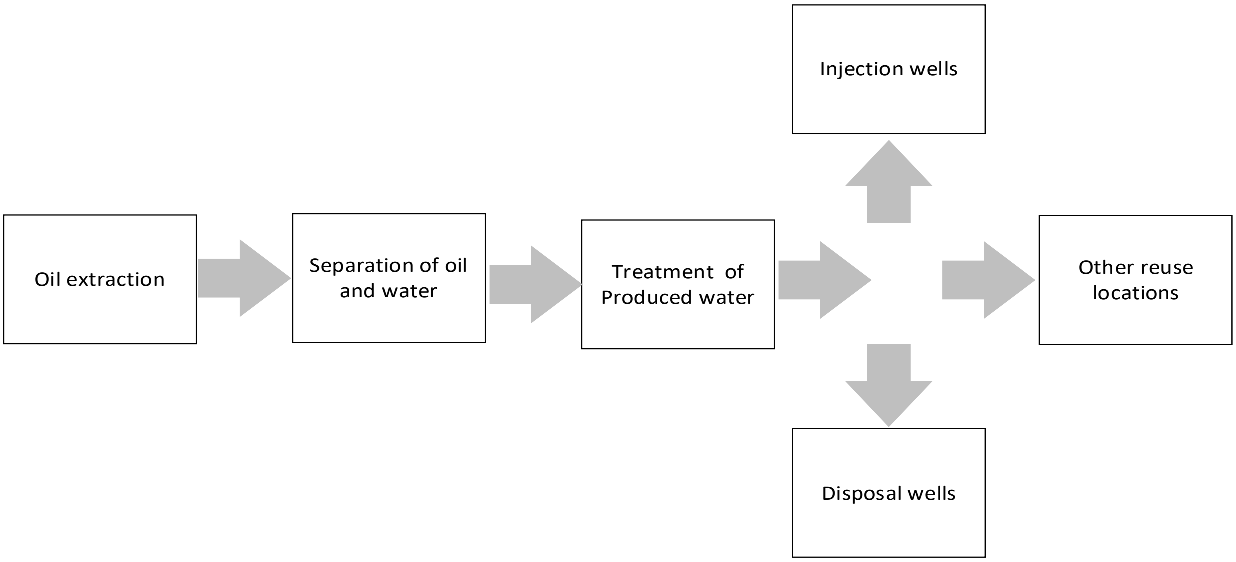


Figure 6. The process flow of the produced water (PW) supply chain.

1.7. Research overview

This thesis consists of eight chapters that discuss different aspects of PW management. The content of and topics presented in each chapter are as follows:

- Chapter 1: Describes the global problem of PW management. This is followed by discussion of the relevance of the study to Kuwait and the reason for selecting KOC for the case study. Also, a description of the research objectives, questions, and approaches is provided.
- Chapter 2: Provides a literature review of the sources, characteristics, environmental impact and economic perspectives of PW and the treatment technologies utilised to generate reusable PW.
- Chapter 3: Presents a case study related to KOC's PW supply chain management with different operational and regulatory constraints. This is combined with a short overview of Kuwait's demographic and economic background.
- Chapter 4: Provides the proposed formulation for the linear multi objectives-mixed integer linear programming (MO-MILP) framework for the PW management system model.
- Chapter 5: Describes the data analysis and major findings emanating from the optimisation model in relation to the research objectives.

- Chapter 6: Details a global sensitivity analysis (GSA) used to validate and test the PW management optimisation model.
- Chapter 7: Presents a range of possible PW reuse approaches, global reuse regulations and a PW reuse risk assessment.
- Chapter 8: Details the study's conclusions, recommendations and future research.

Chapter 2

2. Literature review

2.1. What is produced water (PW)?

The production of oil and gas generates various waste streams, including PW, which is brought up with the oil and gas from the reservoir (Pinheiro *et al.*, 2022). In most cases, PW refers to the type of water that is associated with fossil fuel extraction activities. It is also known in the oil sector as brine water, and saltwater (Alkhudhiri, Darwish and Hilal, 2013). PW is mainly derived from formation water (trapped underground) and injection water, condensed water from gas and oil production and chemical waste from the treatment process (Dudek et al., 2020; Salem and Thiemann, 2022). PW also contains formation water that is trapped in an oil reservoir in different amounts. Formation water is acidic water that exists naturally in the rock before drilling, usually within a layer below the crude oil layer (Renpu, 2011).

PW represents one of the most significant waste streams in the oil and gas industry (Simões *et al.*, 2020). At the beginning of the life of an oil well, the concentration of hydrocarbon in PW is relatively low, and as an oilfield maturates and oil production activity increases the water to-hydrocarbon ratio increases (Clark and, Veil, 2009). Currently, the volumetric ratio of PW to oil is 3:1, meaning that more PW is produced than oil worldwide, and the ratio is expected to reach 12:1 by 2025 as a result of the ageing of oil wells (Pinheiro *et al.*, 2022; Salem and Thiemann, 2022). In 1990, the production rates for crude oil and PW were approximately 10 and 30 million m^3 per day, respectively. Today, approximately 83 million barrels of crude oil and 300 million barrels of PW are produced globally on a daily basis. In view of this, and the ageing of wells, it is anticipated that the PW-to-oil ratio will increase by 2030; therefore, it is important to strengthen the market for PW management (Jiménez *et al.*, 2018; Dudek *et al.*, 2020; Coha *et al.*, 2021). The quantity of PW is influenced by a wide range of factors throughout the lifecycle of the well, including well location, type of drilling operation, type of methods used for enhanced oil recovery, subsurface fractures and weak mechanical structure (Nallakukkala and Lal, 2021).

With the growth of the oil industry and consequently the production growth of PW, comes the economic and environmental concerns about the treatment and management of this type of effluent. Recently, in terms of market size, it was estimated that the worldwide market for PW treatment reached USD 8.1 billion in 2020, with an expected compound annual growth rate of 4.8% over the period of 2020 to 2027 (Dawoud *et al.*, 2021).

At present, the majority of PW is either reinjected or disposed of after it has been primarily treated. After PW treatment, around 65% of the treated PW obtained from oil production is reinjected, 30% is disposed underground, and the remaining treated PW is discharged to the surface (Murray-Gulde *et al.*, 2003). However, treating PW for further beneficial reuse such as agricultural and industrial reuse is increasingly becoming a matter of interest (Alhumoud, Behbehani and Abdullah, 2003). Considering that PW is a chemically complex solution, it cannot simply be discarded in the environment; rather, it should be appropriately treated and managed (Simões *et al.*, 2020).

2.2. Characteristics of PW

It is becoming increasingly apparent that PW has a significant impact on the environment. Approximately 70% of the volume of PW extracted by the oil and gas industry is contaminated by toxic substances (Ekins, Vanner and Firebrace, 2005). It is therefore vital to gain a deeper understanding of its composition and chemistry to optimise its control and management (Dudek *et al.*, 2020). The composition of PW differs widely and is influenced by factors such as geological formation, reservoir lifecycle, and type of hydrocarbon produced (Simões *et al.*, 2020). In addition to the geological formation with which the formation water has been in contact, the field location and the regional climate can also influence the composition of PW that has been present in a formation for thousands of years (Alkhudhiri, Darwish and Hilal, 2013). The composition of PW also depends on whether the water is associated with oil, gas, or coal production (Coha et al., 2021). For example, PW extracted with gas production is more saline and toxic than PW extracted with crude oil production due to the higher contents of flow molecular weight (Saeed Hamed H.; Al-Haleem, Abdulah and Saeed, 2010). PW that has been trapped in various quantities in underground formations can accumulated high levels of TDS as a result of its long residence time and low flow rate (Gao and You, 2015).

PW has several primary components, including suspended particulates and colloids, salts and hardness, organic matter, heavy metals, and radioactive species (Luek and Gonsior, 2017; Coha et al., 2021). Table 3 summarises the main components of PW.

Table 3. Content of oilfield produced water.

Parameter	Concentration (mg/L)
Total dissolved solids (TDS)	100–400,000
Total suspended solids (TSS)	1.2–1,000
Chloride	0–270,000
Sodium	0–150,000
Iron	.1–1,100
Sulphate	2–14,900
Total oil and grease	2–560

Source: (Clark and, Veil, 2009; Fakhru'l-Razi et al., 2009; Jiménez et al., 2018; Al-Ghouti et al., 2019; Ahmad et al., 2020; Dudek et al., 2020; Salem and Thiemann, 2022)

This section presents information about PW composition, where different contamination metrics to assess the quality of PW which based on various studies are identified (Conrad et al., 2020; Dudek et al., 2020; Haneef et al., 2020, Hoek et al., 2022) namely TDS, total suspended solids (TSS), scale, hardness, iron, sulphate, dissolved minerals, dissolved gases, heavy metals, organics, and bacteria.

The major PW contaminants are listed in the following subsections.

2.2.1. Total dissolved solids (TDS)

The major TDS in PW are sulphate and sodium, followed by chloride and calcium. Upstream oil and gas companies usually refer to salinity associated with increasing inorganic on concentrations as TDS (Clark and, Veil, 2009; McDevitt et al., 2020). The majority of PW has higher salinity than seawater, with TDS concentrations exceeding 400,000 ppm compared to 35,000 ppm for seawater (Ahmad et al., 2020; Nallakukkala and Lal, 2021). As for drinking water, the maximum contamination level is 500 ppm, as set by the Environmental Protection Agency (EPA). Livestock, however, can tolerate water with TDS concentrations of 7,000 ppm

(Hoek et al., 2022). The higher TDS and oil content in PW increases soil salinity and blocks the soil pores, destroys the soil aggregate structure, affects the normal metabolism of soil organisms and eventually causes the weakening of the soil ecosystem (Li et al., 2021; Hoek et al., 2022).

2.2.2. Total suspended solids (TSS)

Production solids consist of many particles, such as clays waxes, precipitated solids, bacteria, carbonates, sand, corrosion and scale products, formation solids and other suspended solids (Fakhru'l-Razi *et al.*, 2009). Depending on the nature of the oil reservoir the concentration of the solid materials varies and could cause damage during oil production. For example, the flowline can be blocked by scales, oily sludge, and emulsions. Similarly, bacteria cause corrosion of equipment and pipelines (Veil *et al.*, 2004). A certain amount of solids control can be achieved by applying production chemicals or treating the injection water in a manner that prevents bacterial growth or scale formation (Dudek *et al.*, 2020).

2.2.3. Heavy metals

The most common heavy metals found in PW are lead (Pb), nickel (Ni), chromium (Cr), cadmium (Cd), arsenic (As), mercury (Hg), zinc (Zn) and copper (Cu) (Masindi and Muedi, 2018). These are most often found as hydroxides, oxides, sulphides, sulphates, phosphates, silicates and organics. Heavy metals enter PW as they leach out of source of rocks, from dissolving source rocks or from solid particles carried by fluids that flow from the oil reservoir (Igunnu and Chen, 2012, 2014).

The heavy metal concentration is influenced by the oil well formation geology and age (Azetsu-scott et al., 2007; Igunnu and Chen, 2012). The presence of heavy metals in PW has a direct impact on the environment and human health. Thus, it is difficult to control the number of heavy metals in PW, and more environmental regulations are needed to mitigate their adverse effects (Fu and Wang, 2011; Dudek et al., 2020).

2.2.4. Dissolved gases

PW includes dissolved gases that naturally results from bacterial activities or chemical reactions in the formation. The major dissolved gases in PW are carbon dioxide, oxygen and hydrogen sulphide (Hansen and Davis, 1994). Post-treatment is usually required for the separation of precipitated solids, biomass, and dissolved gases (Al-ghouti *et al.*, 2019). Nevertheless, when separation is performed at higher pressures, the dissolved gases may cause flow assurance problems, leading to the release of free gases or the formation of hydrates (Dudek *et al.*, 2020).

2.2.5. Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are contaminants found in several wastewater streams, including PW (Haneef *et al.*, 2020).There has been reference to their presence as one of the most contaminating and highly persistent elements that cause environmental pollution. PAHs are a large group of organic compounds with multiple fused aromatic rings that affect different biological processes (Karac *et al.*, 2009). The major components in PAHs are naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenz(a,h) anthracene, indeno(1,2,3-cd)pyrene, and benzo(ghi)perylene (Burritt, 2008). PAHs commonly occur in nature alone and in combination (Wilcke, 2007). The natural sources of PAHs include volcanic eruptions and forest fires; however, many are produced by human activities. It is worth noting that people can be affected by PAHs that are consumed or present in food (Rubin, 2001; Mellendorf *et al.*, 2010; Bakke, Klungsøyr and Sanni, 2013). Therefore, removing PAHs prior to PW discharge is crucial (Haneef *et al.*, 2020).

2.2.6. Dissolved minerals

Dissolved inorganic species (i.e., ions, compounds, or minerals) are found in high concentrations in PW and include heavy metals, cations, anions and naturally occurring radioactive materials (NORM). Cations and anions significantly affect the chemistry of PW (Fakhru'l-Razi *et al.*, 2009). Due to the high heavy metal content of PW, certain cations and anions may occur and cause inorganic scale to form on production equipment and reservoirs.

Thus, the high heavy metal content of the PW is crucial for both operational and environmental reasons and can lead to the toxicity of discharged PW (Dudek *et al.*, 2020).

2.2.7. Production chemicals

As part of crude oil production, various chemical additives (e.g., biocides, scale and corrosion inhibitors, emulsion and reverse-emulsion breakers) are mixed to separate the oil from the water. The purpose of injecting these chemical additives is to ensure that the production process is maintained, assisted, and protected from degradation. Furthermore, production chemicals are used in exploration to inhibit corrosion, hydrates formation, scale deposition, foam production, wax deposition, bacterial growth and gas dehydration (Stephenson, 1992; Mackay, 2009; Kuraimid *et al.*, 2013). There is a significant amount of production chemicals in PW, and it is difficult to estimate the type and concentration many of these chemicals since most dissolve during production (Igunnu, 2014).

2.3. PW management

Due to the increasing amount of PW that must be managed, an integrated approach is required for oil recovery, PW treatment, and reservoir management. For this to be achieved, a deeper understanding of the behaviour of PW in the reservoir and at various stages of production and processing is required (Dudek *et al.*, 2020).

PW poses significant environmental, health, and safety risks. Thus, adequate PW treatment systems are essential for generating PW that can be reinjected, reused, or discharged back into the environment at acceptable condition (Coha et al., 2021). As crude oil demand continues to grow, an increase in PW treatment capacity is required and consequently great deal of expenses are incurred. It is therefore likely that this will result in a bottleneck that prolongs the oil and gas production process. Moreover, PW treatment processes are determined by economic and operational factors, reuse options, discharge regulations, and disposal costs. The quality of the treated water must meet stricter environmental regulations and reservoir specifications (Dudek et al., 2020; Hoek et al., 2022). In addition to protecting the environment, treating PW so that it meets appropriate water quality criteria could be reused for different applications such as irrigation, livestock watering, aquifer storage, and municipal and industrial uses (Jiménez et al., 2018).

PW has been subjected to unsteady management attempts over the past two decades because of its high volume of production (Muñoz *et al.*, 2020). There have been a number of previous studies that have attempted to control the financial costs of managing PW. The authors Gao and You (2015), for example, sought to reduce the cost of the PW supply chain network for oil and gas operations while reducing freshwater consumption. Such a problem was formulated as a mixed integer linear fractional programming (MINFP) models problem. Also, they developed stochastic mixed integer linear fractional programming (SMILFP) model to optimise the levelised cost of energy generated from oil and gas operation.

While Bartholomew and Mauter (2016), focused on his study on the trade-offs in financial costs and human health and environmental (HHE) impacts associated with various PW management strategies during different schedules to quantify the private and public costs of various PW management strategies. For their optimisation model, Bartholomew and Mauter (2016) used mixed integer linear programming (MILP). Additionally, Bartholomew and Mauter (2016), examine the trade-offs associated with potential regulatory or policy changes that might affect company decisions regarding PW management.

Yang, Grossmann and Manno (2014), developed mixed integer linear programming (MILP) and mixed integer nonlinear programming (MINLP) investment optimisation and scheduling models for minimising the financial costs of freshwater acquisition, transportation, treatment, storage, and disposal cost while accounting for the revenue from gas production.

There has also been considerable work conducted on quantifying the HHE externalities of the gas production industry. There have been many studies that have examined the lifecycle greenhouse gas emissions associated with the transition from coal to natural gas (Burnham *et al.*, 2012; Bartholomew and Mauter, 2016). Furthermore, numerous of studies explained the lifecycle greenhouse gas emissions associated with the drilling, completion, production and power plant operations related to gas operations (Dale *et al.*, 2013; Laurenzi and Jersey, 2013)

Previous studies of criteria air emissions were limited in their ability to compare alternative water management scenarios and estimate their costs. Furthermore, the majority of studies that measure air emissions impacts on PW tends to refrain from articulating the impacts on human health and the environment in relation to factors such as illness rates, equipment damage, soil pollution and agricultural output.

In the case of GSA, information about output sensitivity is obtained from the statistical analysis of the input/output dataset generated through regression analysis. GSA conducted in this research is based on Pianosi et al., (2016) as well as Wagener and Pianosi, (2019). Their studies have explained how the variation in the output of a numerical model can be attributed to variations of its input factors.

Information about the risk to human health posed by Fjeld, Eisenberg and Compton, (2007),. They employed a risk assessment matrix to draw the first sight of probability and severity or likelihood and impact risk matrix.

There are, however, a number of pros and cons associated with these studies. Gao and You's (2015) study effectively target the reduction of costs in PW management while considering freshwater conservation, aligning with sustainable practices. The utilisation of the MINFP model offers a robust mathematical framework for optimisation, which can provide precise solutions. The incorporation of probabilistic elements through SMILFP demonstrates a commitment to handling real-world uncertainties in decision-making. Yet MINFP and SMILFP models can be complex, making them computationally intensive and potentially challenging to implement. their complexity can make them computationally intensive and potentially challenging to implement, especially for organisations with limited computational resources. Additionally, while the study aims to reduce costs, the environmental and health aspects might not be as extensive.

While Bartholomew and Mauter (2016) focused on quantifying trade-offs between financial costs and human health and environmental (HHE) impacts, offering a balanced approach. The MILP method is a well-established method of optimisation that can be applied in a variety of practical cases. This study explores the potential impacts of regulatory changes on PW management decisions, which is of oil and gas sector policy importance. However, the focus on financial costs and HHE impacts might overlook other dimensions of sustainability, such as long-term environmental effects. Also, the study mainly looks at private and public costs without delving into externalities beyond HHE impacts.

Yang, Grossmann, and Manno (2014) show in their study that the investment optimisation and scheduling models developed cover a broad spectrum of financial cost components in PW management. The utilisation of both MILP and MINLP offers flexibility in addressing complex optimisation challenges. Accounting for revenue from gas production shows a holistic economic approach. But the combination of MILP and MINLP implies a high level of complexity, which could be computationally demanding and while focusing on financial costs. Since the study primarily focuses on financial aspects, at the expense of giving equal attention to environmental sustainability. This emphasis on cost reduction might overshadow long-term ecological considerations.

As for the GSA based on Pianosi et al., (2016) and Wagener and Pianosi, (2019) studies, they provide a methodological foundation for conducting GSA, offering a systematic approach for understanding the sensitivity of a model to its input parameters. This helps to explain how GSA can assist interpret the sources of variability in model outputs, allowing for a deeper analysis. Following established methodologies like those presented in these studies enhances the transparency and reproducibility of GSA results in any research. Yet, depending on the complexity of the model and input parameters, applying GSA can be computationally intensive and require substantial resources. The success of GSA is dependent on the validity of the assumptions made during the analysis, which may not always capture the full complexity of the presented case. Conducting GSA may require large datasets, and data collection can be resource intensive. This might present challenges in situations where data availability or resources for data collection are limited.

RA Employed by Fjeld, Eisenberg, and Compton (2007) imply that the RA matrix offers a structured approach to assessing and categorising risks, providing a clear visual representation. It helps organisations prioritise risks based on factors like probability, severity, and potential impact. RA matrix can be a useful tool for communicating complex risk information to stakeholders, including non-experts. Still, the assignment of probabilities and impact scores in RA matrices can be subjective and may vary based on individual judgments. Risk matrices simplify complex risk relationships and may not capture all nuances in each risk scenario. Reliable RA requires high-quality data, which may not always be available or may have limitations. The quality of data available may influence the accuracy of the risk assessment results. In cases of complex and interrelated risks, a RA might oversimplify the actual risk landscape.

In summary, these studies collectively contribute to the understanding of various facets of PW management and environmental impacts. However, they each have specific scopes and methods, leaving gaps in terms of comprehensiveness and a well-rounded approach to balancing financial, environmental, and health considerations. Integrating these diverse approaches could lead to more holistic decision-making in PW management.

It is essential to adhere to some of the major contributions to this research, demonstrating everyone’s role and responsibility. Table 4 illustrates the contributions of various authors to this research.

Table 4.Author contribution table

Author(s)	Multi-objective model	Global sensitivity analysis	Risk management	Economic data	Environmental data	Operational data	KOC Background
(Abusam and Shahalam, 2013)						X	X
(Al-Abdullah *et al.*, 2019)				X		X	
(AlAnezi *et al.*, 2018)						X	X
(Al-Ballam *et al.*, 2018)							X
(Al-Fadhli *et al.*, 2020)							X
(Alfarhan and Duane, 2012)							X
(Al-Ghouti *et al.*, 2019)						X	
(Alhumoud, Behbehani and Abdullah, 2003)					X		X
(Ali *et al.*, 2013)							X
(Al-Qallaf, Owayed and Rao, 2017)							X
(Azapagic, 1999)					X	X	
(Bartholomew and Mauter, 2016)	X				X		
(Bartram J *et al.*, 2009)			X				
(Chang *et al.*, 2019)						X	
(Chen *et al.*, 2017)					X	X	
(Dahm *et al.*, 2014)					X	X	
(Elaila *et al.*, 2017)				X			
(Fakhru’l-Razi *et al.*, 2009)						X	
(Fjeld, Eisenberg and Compton, 2007)			X				
(Gao and You, 2015)	X						
(Jiang *et al.*, 2021)						X	

(Jiménez *et al.*, 2018)						**X**	
(Karapataki, 2012)				**X**			
(KOC, 2018)				**X**		**X**	**X**
(Kuraimid et al., 2013)					**X**	**X**	
(Laurenzi and Jersey, 2013)					**X**	**X**	
(Li *et al.*, 2015)						**X**	
(Li *et al.*, 2017)						**X**	
(Liang *et al.*, 2018)						**X**	
(Liu *et al.*, 2021)					**X**	**X**	
(Lu, 2016)		**X**					
(Mukhopadhyay and Akber, 2018)							**X**
(Nabzar and Jean-Luc, 2011)							**X**
(Naffakh, Qassab and Makhzoomi, 2021)							**X**
(Pianosi et al., 2016)		**X**					
(Scanlon *et al.*, 2020)						**X**	
(Senthilmurugan *et al.*, 2021)							**X**
(Vlasopoulos et al., 2006)					**X**	**X**	
(Wagener and Pianosi, 2019)		**X**					

The research presented here has been enriched by the diverse contributions of various scholars, each bringing their unique expertise to the table. These multifaceted insights have helped shape the research, leading to a more comprehensive understanding of the complex domain of produced water management. By integrating various optimisation methodologies, environmental assessments, and global sensitivity analyses, this study reflects the result of extensive contributions that have extended the knowledge in the field. Through their collective work, this research gained the ability to study the oil and gas industry's management practices, particularly within Kuwait, with heightened sensitivity to sustainability concerns. The findings have far-reaching implications, influencing policy decisions and industry practices. The work of these researchers has significantly influenced the research's direction, offering a foundation for a balanced analysis of economic and environmental considerations in PW management. Their collective impact lies in the cultivation of a holistic approach that has the potential to redefine practices in the oil and gas industry, particularly in Kuwait and beyond, fostering sustainability and improved decision-making.

As a result, the influence of these contributors reverberates well beyond the boundaries of this research, potentially making a shift towards more sustainable practices in managing PW, which is of dominant significance in a world increasingly focused on environmental responsibility and economic viability.

2.4. PW reuse

In the oil and gas industry, current goals are focused on internal reuse of PW to increase hydrocarbon production via processes such as hydraulic fracturing and enhanced oil recovery (EOR) or disposal. Reuse of PW could potentially close the water cycle for drilling and fracturing operations, thus alleviating strains on freshwater withdrawal, minimising water transportation activities, and mitigating environmental contamination risks. Recycling, or 'beneficial reuse' is based on using PW for an alternative purpose (Echchelh, Hess and Sakrabani, 2018b; Entrekin *et al.*, 2018; Conrad *et al.*, 2020).

The management of PW via Internal reuse (i.e., water reinjection into the source oil zone) or disposal is considered an acceptable, practical environmental option compared the disposal of PW into the sea or in desert evaporation ponds, which is environmentally harmful. These pits allow PW to evaporate, leaving behind concentrated waste that contain various contaminants. Such contaminants can pollute the surrounding soil and groundwater, affecting local ecosystems and potentially posing health risks to nearby communities (Wei et al., 2019).

Considering the global water shortage, the large quantities of PW represent potential water sources. However, it is important to consider both the quality and quantity of PW when selecting specific schemes of management. For its effective management, it is most important to select the right treatment method and disposal method. When handled improperly, PW can damage seawater, aquifer water, soil, aquatic animals and plants, the atmosphere, and even human health (Li et al., 2021).

In most cases, PW management strategies are traditionally based on minimising costs and environmental impacts. They typically involve gravity-based separation and discharging the treated PW into the environment from offshore platforms or injecting it underground for production enhancement or direct disposal from onshore platforms. To utilise PW in other applications, such as industrial applications, PW must be dealt with according to the end-user's requirements (Fakhru'l-Razi et al., 2009; Saad, Rayes and Pactor, 2016; Jiménez et al., 2018).

Figure 7 describes the basic strategies for managing PW.

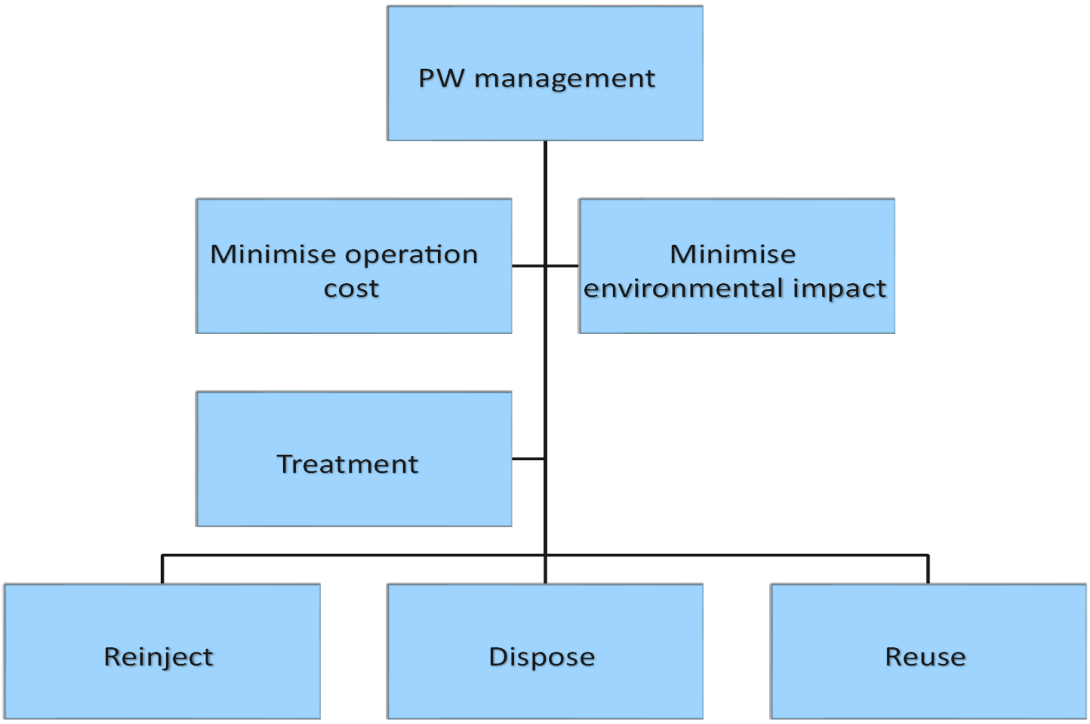


Figure 7. Produced water (PW) management strategies in oil & gas sector industries.

2.5. Treatment methods for generating reusable PW.

To treat large quantities of PW in a cost-effective manner, primary, secondary and tertiary treatment processes must be combined. In addition, to achieve different treatment objectives, a combination of physical, chemical, and biological treatment methods should be employed. This section provides an overview of a typical PW treatment train currently used in industry.

The selection of the appropriate treatment depends primarily on two factors: (1) the quality of the input water or feed water, particularly its salinity and other inorganic and organic constituents, and (2) the quality of the water that is generated relative to the requirements for beneficial use. Treatment of PW is a multistage process in which every stage is designed to separate specific constituents from the PW, such as solid salts, oils and gases (Davarpanah, 2018; Jiménez *et al.*, 2018).

In most PW treatment systems, suspended solids and non-aqueous substances are removed first, followed by the removal of suspended and dissolved organic matter and, if necessary, a final desalination step. Most PW treatment processes currently focus on the removal of dispersed oil as discharge limits are based on the amount of dispersed oil in the water (Dudek et al., 2020). Previous studies have shown that many techniques, including adsorption, membrane filtration and chemical precipitation, have removal efficiencies of over 90% for a variety of constituents of PW (Al-Ghouti *et al.*, 2019).

To select the best treatment options for a specific PW sample, it is prudent to first determine its major components. The following constituents are of particular concern in PW:

- TDS
- Oil and grease (O&G)
- Benzene, toluene, ethylbenzene and xylenes (BTEX)
- PAHs
- Organic acids
- Phenol
- Inorganic and organic compounds
  Chemical additives used in oil and gas operations (Jiménez *et al.*, 2018)

When the components have been identified, the treatment method can be determined (Jiménez et al., 2018). The concentration of each component is also an important consideration and can greatly increase treatment costs (Scanlon et al., 2020). The levels of PW treatment required must also be considered (e.g., primary, secondary, and tertiary levels), as well as the desired use of treated PW (Nijhawan and Myers, 2006). Primary-level treatment entails removing suspended matter, iron, and microbiological contaminants using skim tanks and an oil–water separator.

In secondary-level treatment, softening and PW clarification are performed (i.e., removal of hardness ions) using one or more technologies, such as reverse osmosis, oxidisation, chemical precipitation, and flotation after the primary treatment.

Tertiary-level treatment consists of a polishing step and is usually employed to remove ultrasmall droplets and particles, step gases and dispersed hydrocarbons. Tertiary treatment is optional and applied for surface discharge or beneficial uses (Rodriguez 2019; Munirasu, Haija and Banat 2016; Al-Ghouti et al. 2019).

There are a number of technologies that are used at each stage of the PW treatment, Figure 8 shows the technologies most commonly used for each level of treatment.

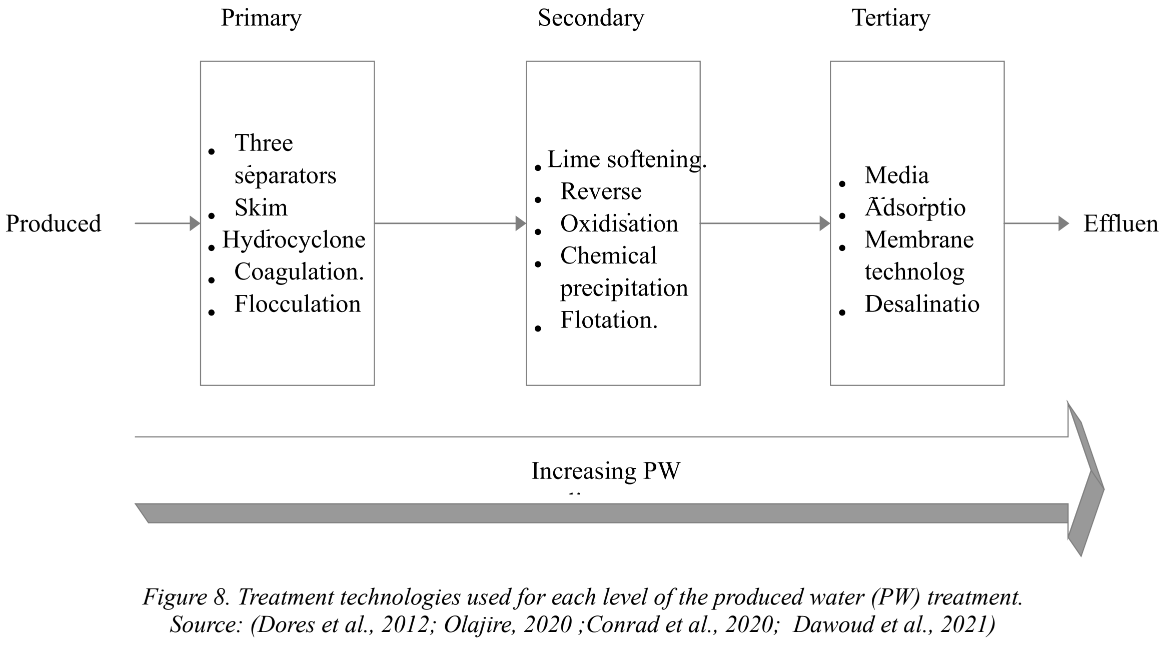


Figure 8. Treatment technologies used for each level of the produced water (PW) treatment. Source: (Dores et al., 2012; Olajire, 2020 ;Conrad et al., 2020; Dawoud et al., 2021)

Furthermore, treatment of PW involves the use of specific physical, chemical and biological methods. A physical method such as filtration, can be used at the beginning of PW treatment to remove solids and biomass without the use of chemicals. In the secondary stage, a chemical treatment can be applied to remove specific dissolved chemicals and suspended particles that cannot be eliminated using physical methods. Biological methods can be used in the tertiary stage; for example, bacteria can be used to remove biodegradable material (Dawoud et al., 2021).

A description of the three methods” of ’W treatment is presented in Table 5.

Table 5. Produced water (PW) treatment levels and methods (physical, chemical, and biological).

Treatment level	Method of treatment	Reference
Primary	Removal of inorganic and organics, including oil and grease, suspended particles and sand, hydrocarbon gases, carbon dioxide, and hydrogen sulphide.	(Nijhawan and Myers, 2006; Dores et al., 2012; Conrad et al., 2020; Dawoud et al., 2021)
Secondary	<u>Chemical treatment</u> Removal of remaining suspended oil dissolved organic pollutants , excess water hardness and bacterial control. Reduction of scaling, salinity and total dissolved solids (TDS)	(Nijhawan and Myers, 2006; Dores et al., 2012; Conrad et al., 2020; Olajire, 2020; Dawoud et al., 2021)
Tertiary	<u>Biological treatment</u> Polishing and removal of any remaining soluble organic compounds, finely suspended solids, turbidity and radioactive material	(Nijhawan and Myers, 2006; Liden et al., 2018; Dawoud et al., 2021)

The current practices for PW treatment are targeted to removing heavy metals, oil and grease and suspended solids which often lead to the generation of large volumes of secondary waste. For instance, heavy metals are removed as sludge using current treatment technologies (Igunnu and Chen, 2014). Figure 9 illustrates the PW treatment types and the possible uses of the resulting products.

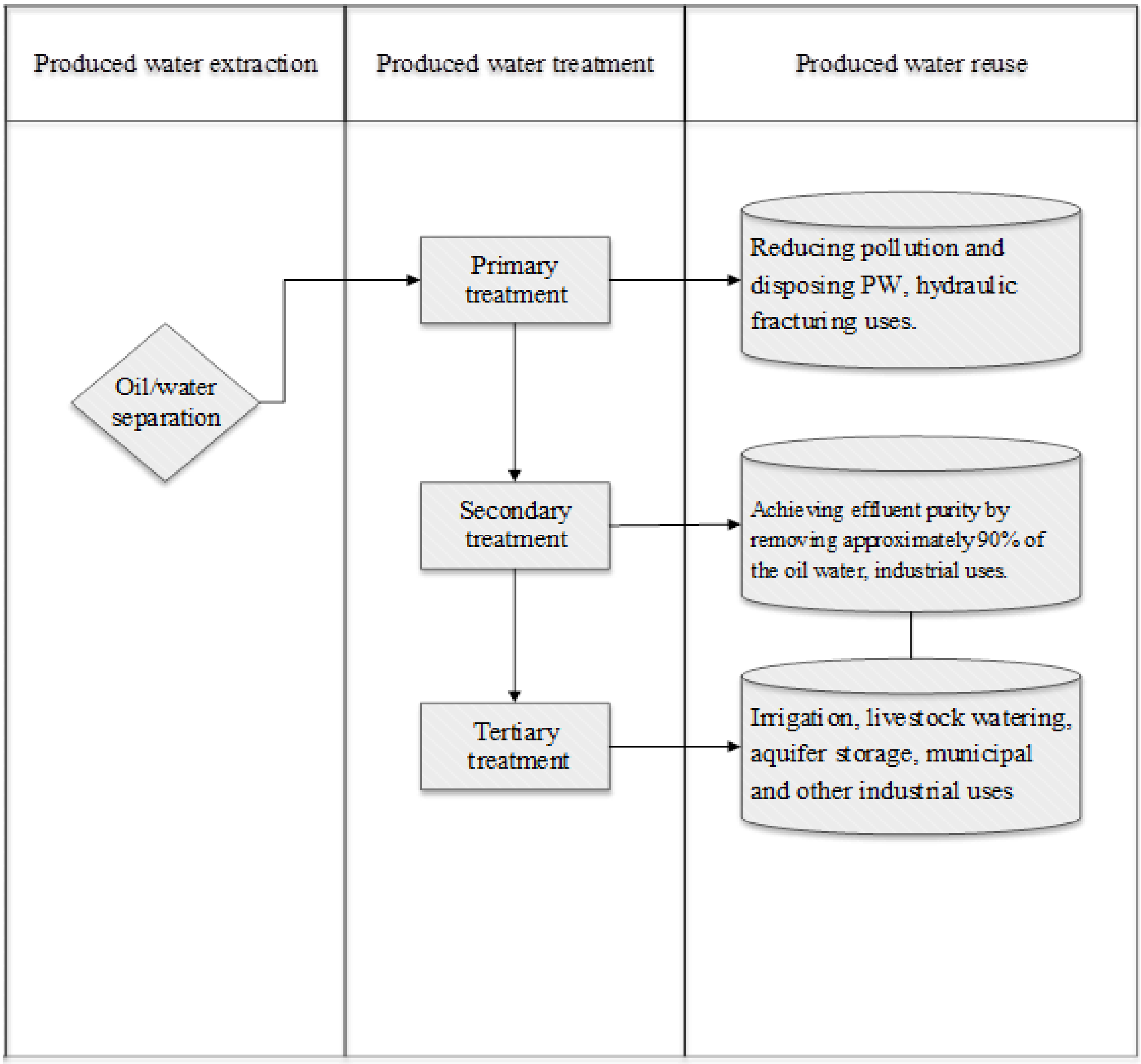


Figure 9. Produced water (PW) treatment levels and the resultant PW reuse options .
Source: (Stewart and Arnold 2011; Munirasu, Haija and Banat, 2016; Jiménez et al., 2018; Scanlon et al. 2020; Amakiri et al., 2022).

It is imperative to note that, treatment techniques that utilis only one type of technology are not sufficient for treating PW and generating treated PW that meets global environmental standards. Therefore, to generate useable treated PW and prevent environmental pollution, multiple treatment processes must be applied (Dawoud et al., 2021). PW treatment is, however, considered feasible if it cost effective (Plumlee et al., 2014).

2.6. Regulation of managing PW

The high volumes of PW generated necessitate the implementation of regulations to control the treatment level and minimise the discharge of this wastewater into the environment (Wu *et al.*, 2021). In response to the difficulties associated with the treatment, reuse and discharge of PW, many countries have implemented strict quality standards and instructions for these activities (Hernández, 2021). In the past, crude oil extraction from the subsurface required little effort and a straightforward process to manage the PW due to the small quantity involved. It was common practice in the oil and gas industry to discharge PW after basic treatment into pits or underground wells as a way to control the small amount of PW generated at the time. Today, it is difficult and costly to manage the high volumes of PW using only basic treatments, especially in light of the environmental impact associated with the release of PW (Fakhru'l-Razi et al., 2009).

Global environmental impacts are addressed through international agreements and principles, but the implementation and enforcement of environmental laws vary from country to country (United Nations and the Rule of Law, 2023). International environmental law, which encompasses agreements and principles, guides the world's collective effort to manage environmental challenges, including climate change, ozone depletion, and wildlife conservation. Many countries, including Kuwait, are signatories to international environmental agreements. Law No. 21/1995 established the Kuwait Environment Public Authority, granting it jurisdiction and regulatory powers over environmental matters. This law reflects Kuwait's commitment to environmental governance and aligns with international principles. Discussing global environmental law can help elucidate how these international commitments impact Kuwait's environmental regulations (Kuwait Environment Public Authority, 2019). Furthermore, exploring global environmental regulations can provide insights into best practices that could be adopted or adapted to enhance country's environmental regulatory framework (United Nation, 2019).

In this section, the current legal, regulatory, and operational frameworks governing PW management in five countries (USA, Kuwait, China, Qatar, Australia) with major PW production are briefly discussed.

Figure 10 shows the percentage of PW production in USA, Kuwait, China, Qatar and Australia.

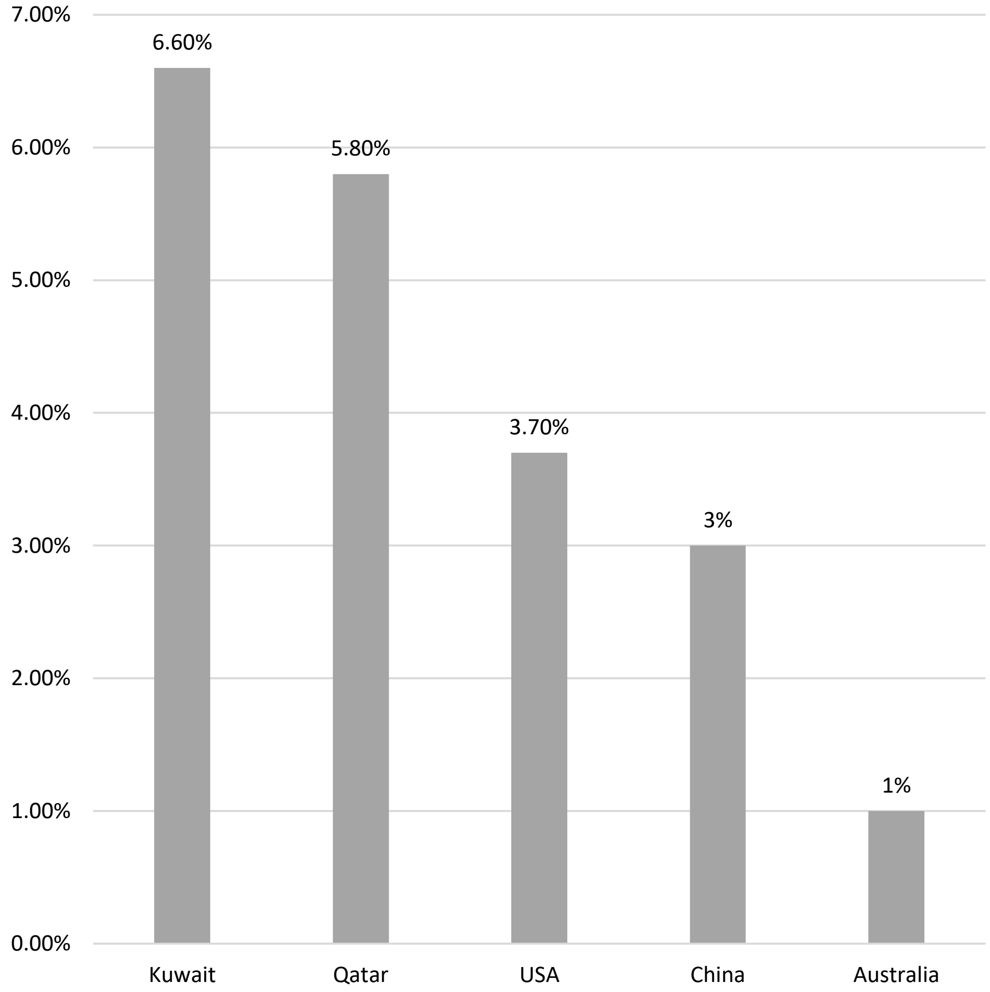


Figure 10. Global distribution of PW.
Source: (Jones et al., 2019)

2.6.1. United States of America (USA)

In the USA, the first major federal law addressing water pollution—the Federal Water Pollution Control Act—was enacted in 1984. Prior this, due to increasing public awareness of and concern about water pollution, sweeping amendments were made to the law in 1972 with the introduction of the Clean Water Act. An effluent restriction policy was established in 1973 as part of efforts to consolidate the many environmental responsibilities of the federal government under a single agency, the U.S. Environmental Protection Agency (EPA).

To comply with the EPA regulations, decision makers must treat waste in the most effective manner throughout the lifecycle of a project (EPA, 2022c). Several EPA regulations clarify known risks and provide guidance on how to protect against known risks.

Among these risks are the potential impacts on surface water and groundwater supplies caused by oil and gas operations, contamination of underground and surface waters and improper well construction, as well as the risk of ecological pollution caused by the release of gas into the environment (EPA, 2016). An important component of the EPA's role is the regulation of PW discharge and treatment. According to EPA regulations, new sources of discharged water must make use of the most advanced technology available. In addition, the EPA issues permits to facilities that discharge and treat PW in an approved manner. These permits include specific limits, monitoring requirements, and reporting requirements for discharges, as well as the related measures that must be taken to protect the environment. However, it should be noted that although zero discharge is a goal, it is not a legal requirement (EPA, 2022a).

The injection of PW into wells represents 80% of the reuse activities in the USA. According to EPA regulations, the process of injecting PW into oil and gas wells must be authorised by permit or by rule. It is the responsibility of the operators of the wells to comply with all applicable requirements, which include strict construction and conversion standards, as well as regular testing, inspection, reporting, and closure of the requirements (EPA, 2022b). The EPA has also implemented pollution control programmes, which include wastewater standards for industry and national water quality criteria recommendations for surface water pollutants. Moreover, discharge to surface water from industrial, municipal, and other facilities is only allowed with permit (EPA, 2016).

Regulations have been promulgated in Oklahoma and New Mexico that restrict the disposal of PW in certain units, such as the Arbuckle in Oklahoma and its geological equivalent in New Mexico, the Ellenburger, to reduce actual or potential induced seismicity (Lemons et al., 2019; Scanlon et al., 2019). Additional adverse impacts of subsurface disposal include contamination, with a recent analysis suggesting that disposal wells may impact overlying aquifers in some. basins (Ferguson et al., 2018). Previous studies have addressed a variety of risks related to PW management, including pollution from spills and leaks and casing failures (Meng, 2017; Torres et al., 2016).

Furthermore, New Mexico developed a Memorandum of Understanding with the EPA to assess regulatory frameworks for PW reuse within and outside the energy sector, including discharge to surface water (Scanlon *et al.*, 2020).

2.6.2. Kuwait

The Kuwaiti Environment Public Authority (KEPA) was established in 1995. It is led by the council minister and honoured by the higher council for the environment. The KEPA has a general control over the environmental affairs of Kuwait and responsibility for all projects and sponsor activities pertaining to environmental protection in Kuwait. More specifically, the KEPA's responsibilities include the following:

- Establishing the general environmental policy of Kuwait.
- Planning and implementing strategies to protect the environment.
- Applying the required regulations for the conservation of natural resources.
- Monitoring environmental activities and actions.

  Preparing laws, lists, regulations and requirements concerning environmental protection and following work completion (KEPA, 2022).

In compliance with Kuwait's environmental regulations, the KEPA and KOC have developed guidelines for disposal of wastewater in safe and protected locations. As part of its waste management, KOC has initiated a waste minimisation initiative to reduce or eliminate waste at the source as opposed to managing waste after it has accumulated (AlAnezi *et al.*, 2018). In the past, KOC disposed of PW into seepage pits and left it to evaporate. Given that this practice may cause the soil and groundwater to become contaminated with naturally occurring radioactive material (NORM) and hydrocarbon particles and residues present in the disposed water, dispose of PW into sealed pits is no longer feasible (Abusam and Shahalam 2013 ; Mahmud 2022). Due to the negative effects of such evaporation pits on the environment, and under Law No. 98, the KEPA has prohibited their use. Hence, KOC has decommissioned all its evaporation pits and instead treats PW before its re-injecting it into deep disposal wells (Mahmud, 2022). To enhance Kuwait's ability to treat and reuse industrial wastewater, the country's wastewater reuse standards must be refined. The KEP"s regulations must be adapted and implemented to protect the environment and provide more alternatives for reusing water. Considering these regulations will encourage the development of alternative water resources that can be utilised effectively to augment the already scarce supply of water (Abusam and Shahalam, 2013). It is the responsibility of oil and petroleum companies operating in Kuwait to comply with the environmental and engineering standards set by the KEPA in Environmental Law No. 2 of 2017 (Salem and Thiemann, 2022).

2.6.3. China

There has been a lack of effort on the part of the Chinese government in implementing environmental regulations and more operational regulations specific to the oil and gas industry. This has resulted in the poor environmental record of the oil and gas industry in China. Particularly in Yanan, Shaanxi Province, oil and gas exploration and development have a significant impact on the environment. The oil and gas industry generated over 10 million tons of wastewater during 2004, and of that amount, more than half was discharged without any treatment at all, leading to the severe pollution of several rivers in Shaanxi and Gansu as a result of these practices (Li and Liu, 2009). In addition, China's National Groundwater Pollution Prevention Plan for 2011-2020 indicated that there had been a negative impact on the quality of groundwater in China as a result of intense oil and gas operations (Krupnick, Wang and Wang, 2014).

However, some provinces (such as Gansu, Hebei, Heilongjiang, Liaoning, Shaanxi, Shandong, and Xinjiang) that produce significant quantities of conventional oil and gas have taken steps to improve environmental protection by enacting environmental regulations for oil exploration and production. It should be noted that even though these regulations include an abundance of principles, execution control guidelines are lacking. Moreover, in the abovementioned provinces there seems to be a lack of environmental regulations or standards that are applicable to the oil and gas industry at the provincial level.

It is possible that oil and gas activities in China may result in significant environmental burdens, particularly in terms of water pollution and water quantity, due to inadequate or non-existent environmental regulations and the highly ambitious oil and gas plan promoted by Chinese government agencies (Krupnick, Wang and Wang, 2014). According to the Chinese Environmental Protection Law of 1998, PW can be managed in two ways. First, industries can dispose of PW in suitable disposal wells or reuse it to produce steam. Second, the injected water must be characterised and meet specific requirements. However, several countries including China have failed to meet the commonly agreed upon discharge thresholds or, in some cases, have ignored the regulations entirely (Hoek et al., 2022).

In several country, including China, the general practice has been to implement a zero-tolerance policy for the discharge and disposal of PW. Towards this goal, China has implemented its own independently developed onshore regulations for discharge.

2.6.4. Qatar

Qatar's first water law was Decree No.7, which was adopted in 1963 and governs water tariffs. Since that time, with the goals of organising, managing and protecting its water resources as efficiently as possible, Qatar has enacted and implemented additional environmental laws and decrees as part of its development plan (Abdallah, 2021).

Qatar ranks as one of the top producers of PW and is responsible for 5.8% of global brine production. To minimise the environmental impact and cost of disposal of brine in Qatar, improved brine management strategies should be implemented, thereby encouraging further development of desalination facilities to protect water supplies (Jones *et al.*, 2019).

To ensure that the PW is cleaned prior to discharge, several physical treatments are employed in addition to meeting the regulations imposed by law on contaminants levels. Hence, due to

Qatar's environmental regulations, Qatar Petroleum and other producers have made new commitments, including a 50% reduction in wastewater injection volumes in the North Field (Salem and Thiemann, 2022).

As part of the Ministry of Municipality and Ministry of Environment and Climate Change's efforts to control and regulate PW generation in Qatar, several regulations related to PW have been put in place. Hence for Qatar petroleum companies to comply with the requirements of these regulations, and to ensure the long-term disposal of PW on a sustainable basis, a technology was developed to de-oil PW. It is a primary objective of environmental monitoring efforts in Qatar to evaluate the degree of protection provided by the discharge regulations (Dawoud *et al.*, 2021).

2.6.5. Australia

The Queensland government in Australia considers PW a strategic asset and released a series of guidelines for the approved beneficial use of PW, which are promoted within the existing regulatory framework (Ford, Steen and Verreynne, 2014).

Prior to conducting any activity related to PW reuse, field operators must be authorised under the Environmental Protection Act 1994. The government's policy has been designed to outline the government's views on the management and reuse of PW, assist field operators in managing PW according to the government's regulations and inform the community about the government's preferred approach to managing PW.

As a consequence of government policy, the oil and gas industry in Australia is expected to provide high-quality social and environmental outcomes (Department of the Environment and Heritage Protection, 2012). It is essential that decision-makers account for and plan the use of PW over a project's lifetime to effectively manage all PW. It is also necessary to ensure that trends in the volume of water being produced are observed and analysed and that the success of management solutions is measured in a proactive way (Queensland Government, 2022). The Queensland policy focuses on beneficial reuse rather than treatment and disposal of wastewater. Accordingly, the government supports the development of PW that can be reused rather than discarded (Department of the Environment and Heritage Protection, 2012).

It is anticipated that future regulations will be more focused than current regulations on protecting human health and the environment from the risks associated with PW utilisation and the development of zero emission and discharge frameworks (Hernández, 2021). By examining global environmental laws in comparison to Kuwait's laws, you can provide a more comprehensive understanding of how Kuwait's regulations fit into the global context. This can help highlight strengths, weaknesses, and areas for improvement. Analysing how Kuwait's environmental laws align with global standards can offer policymakers insights into the country's position on various environmental issues and its role in international efforts. In addition, if there is a lack of comprehensive research on Kuwait's environmental law, comparing it with global standards can fill a gap in the literature and provide a more robust analysis.

Chapter 3

3. Kuwait oil company’s PW supply chain management case study

3.1. Overview of the Kuwait macro-economic environment

Kuwait is a small country geographically and has a population of approximately 4.5 million. This country covers an area of 17.81 km^2 and is located in a desert region. Kuwait has a continental climate characterised by long, dry, hot summer and short, cold winters with infrequent rainfall (Kuwait Central Statistical Bureau, 2020). In terms of its economy overview, Kuwait is known for its huge production of hydrocarbon resources and its large crude oil reserves. It is a member of the Organisation of the Petroleum Exporting Countries (OPEC) and has the sixth-largest oil reserves, which equates to about 102 billion barrels – covering approximately 8.2% of world reserves, as shown in Figure 11 (U.S. Energy Information Administration, 2016).

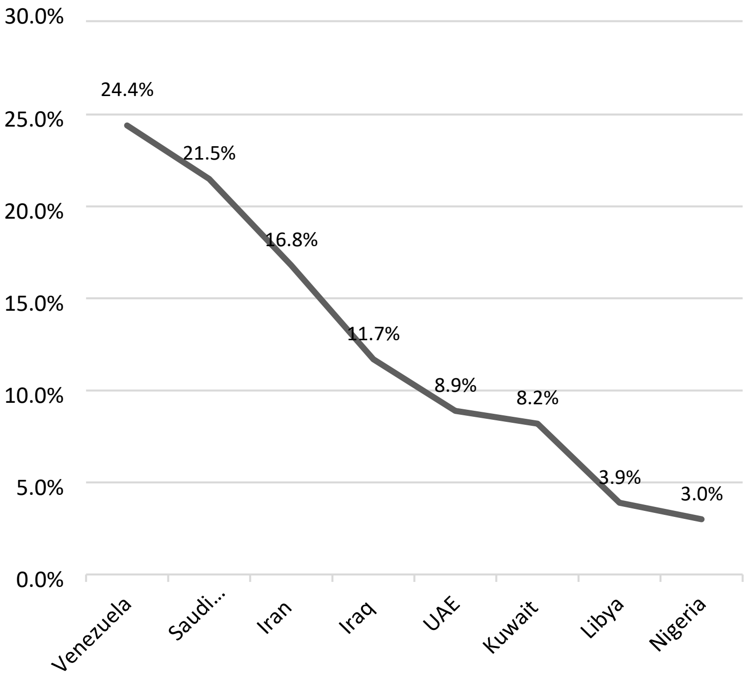


Figure 11. World crude oil reserve
Source: (OPEC Annual Statistical Bulletin, 2022)

Kuwait meets its energy needs through the use of hydrocarbon products, including crude oil, natural gas and fuel oil. Kuwait's government receives most of its income from petroleum exports, which account for a large portion of its economy. It is estimated that petroleum exports accounted for 89% of Kuwait's total export revenues (Siderius et al., 2020).

A primary macroeconomic objective of the country is to maintain a low inflation rate, and this is being achieved in part through a monetary policy tied to a stable currency attached to a basket of reserve currencies (Shehabi, 2020). Kuwait has recently attempted to divert its economy away from its sustainable position; furthermore, the Kuwait government has developed a plan for economic development that aims to increase non-oil revenues and develop the private sector to reduce reliance on oil production profits (Alotaibi, 2019).

3.2. The oil and gas industry in Kuwait

In Kuwait, the daily crude oil production rate is around 3 million barrels per day (OPEC, 2019). Oil revenue is accounts for nearly half of the country's GDP and around 90% of the government's income (U.S. Energy Information Administration, 2016). The fast-growing global demand for energy sources increasing the demand for crude oil production. Therefore, in Kuwait, oil production is increasing to keep up with industry requirements (Ali, 2015). In 1975, the Kuwaiti government took control of KOC, which has since responsible for the exploration, drilling and production of oil and gas, for the storage of crude oil and for export services in Kuwait. All oil sector operations and production are now owned and controlled by the Kuwaiti government (Kaufman et al., 2002; U.S. Energy Information Administration, 2016).

According to KOC, oil fields operations are based on geographical locations i.e., South & East Kuwait (S&EK), West Kuwait (WK) and North Kuwait (NK). Burgan oil field is the oldest oil producing field situated in S&EK area (Hanif and Al-ghawas, 2017). The Greater Burgan is also the largest oil field in Kuwait and the second largest in the world after Ghawar in Saudi Arabia. The production has undergone change over the last 70 years and currently there are approximately 75 billion barrels of oil recoverable from the Greater Burgan field. To achieve integrated operational excellence, the Greater Burgan field in Kuwait links multiple wells, pipeline networks and processing facilities. Burgan field includes 5 large reservoirs, 14 oil gathering centres and 2 centralised effluent water disposal plants (Al Jadi et al., 2019; Desai et al., 2019).

Figure 12 shows the Greater Burgan field.

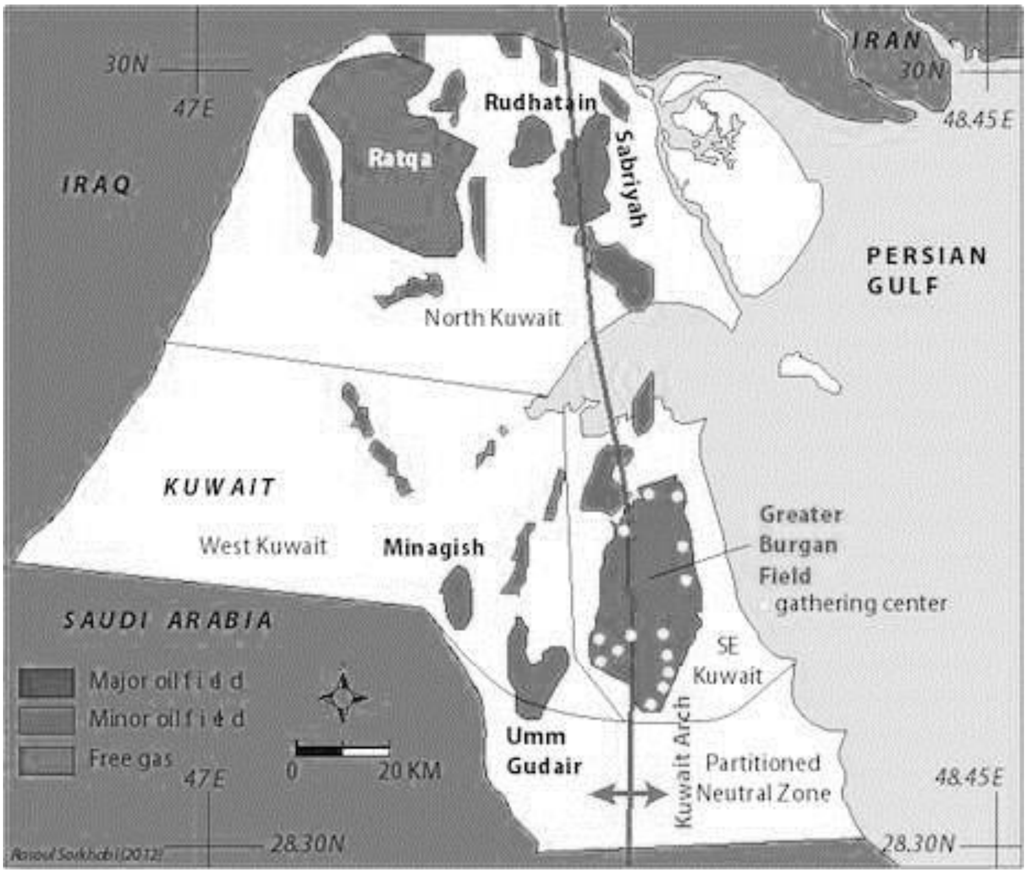


Figure 12. The Greater Burgan fields.
Source:(Rasoul Sorkhabi, 2012)

KOC is expecting a high production rate of oil in the coming years, and it is policy is to continue making investments in the development of its oil and gas production facilities (Alsayegh, 2021). As Kuwait's oil fields contain approximately 40% water, KOC produces close to 2 million barrels per day of PW, as opposed to approximately 3 million barrels per day of oil daily. With an increase amount of PW in Kuwait's oil fields, KOC faces the challenging problem of managing the supply chain of PW as the rest of the world (AlAnezi *et al.*, 2018). It is becoming increasingly difficult for KOC to cope with the amount of PW that is being produced. PW associated with oil production in KOC is exceeding the design specifications of the oil gathering facilities capacity (Al-Hubail and El-Dash, 2006; Hanif and Al-ghawas, 2017; AlAnezi et al., 2018; Alsayegh, 2021).

When compared with typical PW samples from around the world, a typical sample from the Burgan field shows high concentration of salinity (TDS ≅ 200,000 mg/L) with high sodium, and chloride contents. Notably, high salinity restricts the options available for treating PW (Salem and Thiemann, 2022).

The characteristics of the PW generated in Kuwaiti oilfields are listed in Table 6.

Table 6. Characterisation of produced water (PW) in Kuwait oil fields.

Parameter	Concentration mg L
Total dissolved solids (TDS)	171,337
Chloride	151,354
Sodium	74,726
Iron	.17
Sulphate	385
Lithium	5
Calcium	13,056
Magnesium	2,563
Potassium	2,398
Strontium	371
Barium	3
Silicon	9
Boron	29
Bicarbonate Alkalinity	217
Hardness	43,151

Source: (AlAnezi et al., 2018; Salem and Thiemann, 2022.)

In addition, since the treatment methods used by KOC are limited to the primary level, only well reinjection and well disposal are available for generated PW. Reinjection of PW into wells in Kuwait oil fields is performed to stimulate oil production and maintain reservoir pressure, while underground discharge of PW into disposal wells is used to dispose of excess PW and meet environmental regulations (Ali, 2015; AlAnezi et al., 2018).

Countries with renewable water reserves below 1000 m^3 per capita are classified as 'water scarce'. It is estimated that Kuwait has the world's lowest level of renewable freshwater resources, with a total renewable water supply of less than 5 m^3 per capita per-year (Siderius et al., 2019). With the impact of climate change, rapid growth of the population and increasing urbanisation and agriculture, the demand and the availability of freshwater resources in the country is becoming a problem (Freyman, 2014).

Aquifers and desalination are the two main sources of water in Kuwait. There is potential for PW to be an important water source in Kuwait, at least as an irrigation water source, and it should not remain an unutilised resource. The reuse of PW could reduce pollution to the environment while also reducing the need to supply fresh water to the population (Alhumoud, Behbehani and Abdullah, 2003). Hence, in Kuwait, control and reuse of treated wastewater is becoming mandatory to meet the population demand and the local water shortage (Al-Jarallah, 2013; Salem and Thiemann, 2022).

As a consequence, there is now a need for KOC to pay attention to and make efforts towards PW management to identify any potential for beneficial reuse and complications that may arise as a result of oil production operations. KOC is dealing with an increasing amount of PW in a daily basis, and this has elevated the level of concern towards dealing with PW. As KO"s Burgan field is the primary contributor to overall production and the increasing volume of PW, it has been selected for study in order to determine how to monitor and utilise PW at the Burgan field in the most effective and efficient manner.

Also, as part of this study, PW supply chain management at KOC is evaluated. The focus in this research is on the constraints related to PW quantity, facilities' capacity, pipeline capacity, operational cost and environmental impacts. Also, the focus in this research is to explore the main opportunities that may arise from treating PW in terms of different utilisation options. In the case study, the major drivers for decision making are minimisation of the operating costs related to facilities management and minimisation of the environmental harm caused by KOC's PW supply chain.

KOC's PW supply chain consists of two gathering centres (g_1 and g_2), one effluent water treatment facility (*wp*), one disposal well location (j_1) and one reinjection well location (j_2). The case study involves the delivery of treated PW from *wp* to j_1 and j_2 via pipelines. To reflect the prospect of expanding the reuse sources within KOC, a third reuse location (j_3) is added, without indicating its nature. A truck is selected as the transport mode for delivery to j_3. In this study, 50% of the treated PW is to be transported to j_1 by pipeline, 45% is to be transported to j_2 by pipeline and the remaining 5% is to be transported to j_3.

Figure 13 illustrates the superstructure of the case study's PW supply chain system.

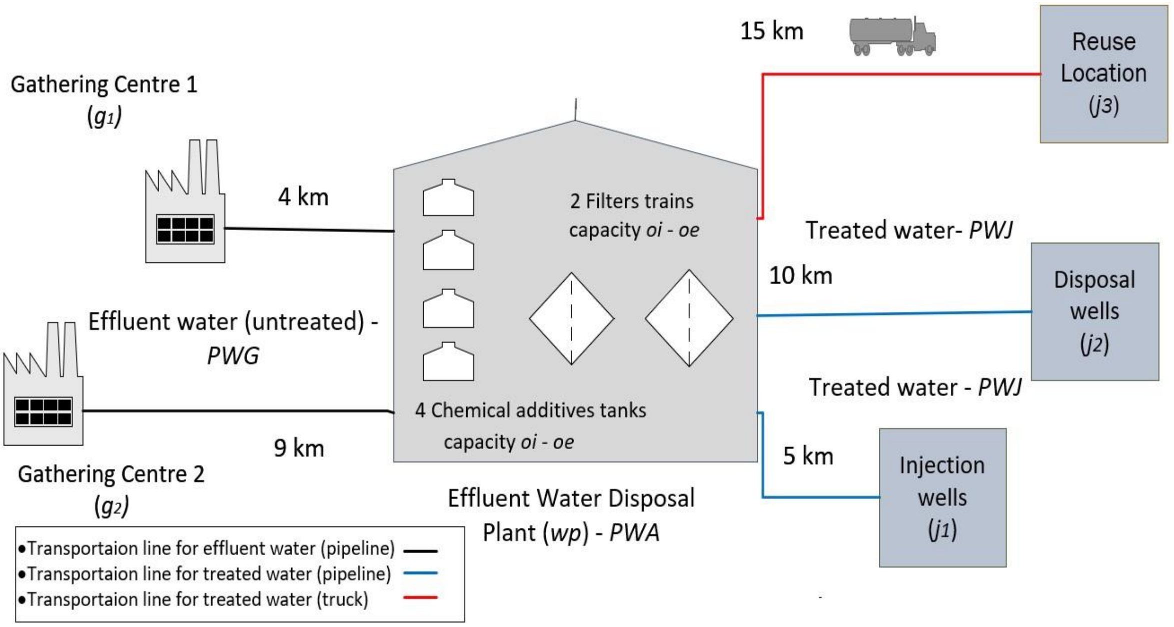


Figure 13. detailed diagram showing the superstructure of KOC's PW supply chain.

Following KO's water handling system, this research makes its considerations on the basis of the following assumptions:

1. PW supply chain consists of two gathering centres (gc_1, gc_2) and one treatment facility (wp), one injection point (j_1) that is 5 km away from wp, one disposal point (j_1) that is 10 km away from wp, and one reuse point (j_3) 15 km from wp.

2. The distances are measured between buildings in accordance with the actual locations of KOC facilities.
3. 100% of PW is transported from the gc_1 and gc_2 to wp by pipelines.
4. PW is placed in the water tank, pumped to the filters, and finally disposed for reuse purposes.
5. Water treatment, facility maintenance, facility operations, electricity, and disposal operations are included in the model operational cost.
6. Water treatment cost includes chemical additives and filtration cost.
7. Pipelines and truck are included in the model transportation cost.
8. Pipelines includes two types: carbon steel and plastic.
9. Reinjection operations all the cost associated with treatment operations including chemical additives and filtration costs.
10. The cause of emissions in the treatment facility comes from two sources only: electricity consumption and chemical usage.
11. 95% of treated water is sent to disposal and reinjection sites by pipeline.
12. Remaining 5% of treated water is sent to the reuse site by truck.
13. To reflect the prospect of expanding the reuse sources within KOC a third reuse location j_3 without indicating its nature is added.
14. To expand the options for transportation in the PW model, a truck is selected for delivery to j_3.

The PW supply chain decision variables are as follows: PW quantity ($PWG_{g,t}$, $PWK_{h,t}$, PWA_t, $PWI_{i,t}$ and $PWJ_{j,t}$), emissions from chemical additives and filters. In addition, the parameters that are considered are as follows: building capacity (o_i and o_e), pipeline capacity, distance between facilities in kilo-meters (km), transportation capital cost in Kuwaiti Dinar (KWD), chemical additives cost in KWD, injection and disposal costs in KWD, electricity cost, emissions associated with chemical additives in carbon dioxide (CO_2) and emissions related to electricity usage in CO_2 eq.

Chapter 4

4. Kuwait oil company produced water supply chain model formulation.

4.1. Introduction

In this research a mathematical programming technique to perform a MO-MILP model has developed. This section presents a detailed description of the mathematical formulation of the MO-MILP model, including the constraints and the objective functions. In this section, MO-MILP model is developed in the form of a multipurpose formula designed to address different PW supply chain activities including costs, CO_2 emissions, capacity, water handling and pipeline constraints, providing optimal PW supply chain management solution. The objective of this model, in addition to minimising the total cost, it is also minimising environmental performance based on CO_2 eq emissions.

By considering MO-MILP in an optimisation model, it promotes integrated decision-making, considering the interplay between different constraints. MO-MILP model designed in this research can be used to achieve Pareto-optimal solutions for trade-offs between two different objectives (cost and environment) of sustainability in KOC's PW supply chain network. The existence of Pareto-optimal solutions confirms the validity of this model. This model allows decision-makers to achieve the optimal PW management design.

In this research, the economic data were collected from KOC and driven from the data and analysis of selected case studies, AlAnezi et al., 2018, and other oil and gas fields of a similar nature (Karapataki, 2012; Elaila et al., 2017; Al-Abdullah et al., 2019), ensuring consistency and accuracy in the assessment of financial implications.

By using the same nature case studies for economic evaluation, a standardised approach and enable meaningful comparisons of cost-related factors across different scenarios is maintained.

This approach enhances the reliability and validity of the economic analysis, making the findings more robust and applicable to real-world decision-making. The emissions values were estimated using LCA. LCA is used to calculate the emissions associated with the chemical additives and the electricity consumption of the treatment facility. The assessment of LCA is limited to CO_2 eq in this study.

In the appendix, information about the case study is provided, including LCA, financial and operational details.

In this chapter, all the parameters are denoted by lower-case symbols, and all the variables are denoted by upper-case symbols. The parameters and variables used in this model are listed in the nomenclature section. The following mathematical model formulation illustrates the relationship between different parameters and the two objectives. The components are detailed below according to each type of constraint.

4.2. Objective function

The proposed mathematical model has two objectives in the case study: total costs (TC) and total CO_2 emissions (TE). The *TC* and *TE* shall be optimised, subject to satisfying the equality and inequality constraints.

Objective function (Z) is to minimise $\{f_1, f_2\}$, where:

$Z_{PW\ supply\ chain} = \min\ (f_1 + f_2)$

f_1 and f_2 are the objective functions to reduce the cost and emissions defined as follows:

$f_1 = TC,$
$f_2 = TE,$

where:

$TC = \sum_{i=1}^{9} TC_i$, and
$TE = \sum_{i=1}^{2} TE_i,$

where, TC_i and TE_i are defined next.

The objective function is subject to a different set of constraints including cost constraints in equation (1) through (9), environmental constraints in equation (10) to (11), capacity constraints in equation (12) through (20), water handling constraints from equations (21) to (22) and pipeline constraints from equations (23) to (25).

4.3. Cost constraints

In the calculation of total PW system costs, transportation, treatment, chemicals, maintenance, injection, disposal, and electricity prices are included.

The transportation cost from node g_1 and node g_2 as shown in Figure 1. includes the capital cost of pipeline icy_g, as shown by constraint (1):

$TC_1 = \sum_{g \in G} \sum_{t \in T} (icy_g \times dg_g \times YG) + (icg_g \times dg_g \times PWG_{g,t}) /(1 + dr)^t$, (1) where icg_g denotes the unit variable transportation cost for transporting PW, and icy_g is the pipeline capital cost coefficient based on the distance dg_g.

The PW transport to the disposal locations includes the capital cost of transportation, as shown in constraints (2) and (3):

$TC_2 = \sum_{j \in J} \sum_{t \in T} (icp_j \times dp_j \times YD) + (icd_j \times dp_j \times PWJ_{j,t})/(1 + dr)^t$, (2) where icd_j denotes the unit variable transportation cost for transporting PW, and icp_j is the pipeline capital cost coefficient based on the distance dp_j.

Constraint (3) is as follows:

$TC_3 = \sum_{j \in J} \sum_{t \in T} (ict_j \times dt_j \times YT) + (icc_j \times dt_j \times PWJ_{j,t})/(1 + dr)^t$, (3) where icc_j denotes the unit variable transportation cost for the truck transporting PW, and ict_j is the truck capital cost coefficient based on the distance dt_j.

The PW treatment cost is estimated using the treatment cost coefficient C_i, and the total PW treatment cost is shown in constraint (4):

$$TC_4 = \sum_{t \in T} (C_i \times PWI_{i,t})/(1 + dr)^t. \tag{4}$$

The chemical tank chemical unit price in the *wp* maintenance cost is estimated using the cost coefficient f_h. The total chemical cost is estimated using constraint (5):

$$TC_5 = \sum_{t \in T} (f_h \times PWK_{h,t})/(1 + dr)^t. \tag{5}$$

The *wp* maintenance cost is estimated using the cost coefficient *d*. The total maintenance cost is estimated using constraint (6):

$$TC_6 = \sum_{t \in T} (d \times PWA_t)/(1 + dr)^t. \tag{6}$$

The water injection and disposal cost are estimated using the respective cost coefficients ij_t and id_t. The *TC* of treated water reinjection and disposal are shown in constraints (7) and (8), respectively:

$$TC_7 = \sum_{t \in T} (ij_t \times PWJ_t)/(1 + dr)^t. \tag{7}$$

$TC_8 = \sum_{t \in T} (id_t \times PWJ_t)/(1 + dr)^t$. (8)

The TC of electricity used in wp is explained in constraint (9), where the electricity cost is estimated using the cost coefficient *er*:

$TC_9 = \sum_{t \in T} (er \times PWA_t)/(1 + dr)^t$. (9)

4.4. Environmental constraints

As for the total environmental impact, the CO_2 eq emissions from wp, are mainly generated by the chemical additives added to the water storage tank. These emissions are estimated using the onsite treatment air emission coefficient, *ea*, based on the amount of wastewater treated in *wp* as shown in constraint (10).

The emissions from onsite chemical treatment ($TE_{1,}$) are calculated using the following equation:

$TE_1 = \sum_{t \in T} ea_h \times PWK_{h,t}$. (10)

The CO_2 eq from *wp* are due to electricity consumption for operations inside *wp* facility. These emissions are estimated by the onsite operations air emission coefficient, *ee*, based on the amount of wastewater treated in water treatment facility as shown in the following constraint.

The emissions from electricity consumption, (TE_2), is given by:

$TE_2 = \sum_{t \in T} ee_i \times PWI_{i,t}$. (11)

4.5. Capacity constraints

The total flow of pw from node 1 g_1 to node 2 g_2 is represented by $PWG_{g,t}$ and PWA_t denotes the total amount of PW inside *wp* facility. This amount of water inside the treatment facility is less than the total amount of PW received, and this is stated in constraint (12):

$PWA_t \leq \sum_{g \in G} PWG_{g,t}$. $\forall t \in T$ (12)

In Equation (13), PWA_t denotes the total amount of treated PW inside wp at less than its capacity oc. YO is a binary variable that is equal to 0 when PWA_t is more than the facility capacity and 1 when PWA_t is less than its capacity oc:

$$\mathrm{PWA_t} \leq oc \times YO. \qquad \forall \ \in tT \qquad (13)$$

In equation (14), PWA_t denotes the total amount of treated PW inside wp and more than its demand ou. YO is a binary variable that is equal to 0 when PWA_t is less than the facility demands and 1 when PWA_t is more than its demands ou:

$$\mathrm{PWA_t} \geq ou \times YO. \qquad \forall \ \in tT \qquad (14)$$

The treated amount of PW from wp, $PWJ_{j,t}$, cannot exceed its capacity cwd_j in j_i sets of locations such as j_1, j_2, and j_3. This constraint is given by:

$$PWJ_{j,t} \leq cwd_j. \qquad \forall t \in T, \forall j \in J \qquad (15)$$

When the treated amount of PW from wp facility $PWJ_{j,t}$ is greater than or equal to its demand dwd_j, the following constraint applies:

$$PWJ_{j,t} \geq dwd_j. \qquad \forall t \in T, \forall j \in J \qquad (16)$$

The amount of PW that is centrally treated in wp by filters i is presented by the continuous variable $PWI_{i,t}$. $PWI_{i,t}$ cannot exceed the capacity oi of filter i, this constraint is explained as follows:

$$PWI_{i,t} \leq oi. \qquad \forall t \in T \qquad (17)$$

When $PWI_{i,t}$ is greater than the demand oe of filter i, this constraint is stated as follows:

$$PWI_{i,t} \geq \mathrm{oe}. \qquad \forall \ \in tT \qquad (18)$$

The amount of PW that is placed in h tanks is presented by the continuous variable $PWK_{h,t}$. $PWK_{h,t}$ cannot exceeded the capacity ok of tank h, and this constraint is explained as follows:

$$PWK_{h,t} \leq ok. \qquad \forall t \in T \qquad (19)$$

When $PWK_{h,t}$ is greater than the demand ow of tank h, this constraint is stated as follows:

$PWK_{h,t} \geq ow.$

$\forall t \in T$ (20)

4.6. Water handling constraints

When the amount of PW inside *wp* is greater than the total amount for reuse $PWJ_{j,t}$,This relationship is modelled using the following constraint:

$$PWA_t \geq \sum_{j \in J} PWJ_{j,t}. \qquad \forall t \in T \qquad (21)$$

When the amount of PW inside *wp* is equal to the amount of treated water inside the tanks h and filters i, this relationship is modelled using the following constraints:

$$PWA_t = \sum_{h \in H} PWK_{h,t} + \sum_{i \in I} PWI_{i,t}. \qquad \forall t \in T \qquad (22)$$

4.7. Pipeline constraints

Constraints (23) ensure that the amount of produced water transported by pipeline from g_1 and g_2 locations to *wp* is bounded by the capacity of pipelines:

$$PWG_{g,t} \leq fcpg_g. \qquad \forall t \in T, \forall g \in G \qquad (23)$$

The amount of treated produced water transported by pipeline is bounded by the capacity of pipelines, given by constraints (24):

$$PWJ_{j,t} \leq fcpw_j. \qquad t = 1,2, \forall j \in J \qquad (24)$$

The amount of treated produced water transported by truck is bounded by the capacity of truck, given by constraints (25):

$$PWJ_{j,t} \leq fcpt_j. \qquad t = 3, \forall j \in J \qquad (25)$$

In this study, the mathematical formulation is solved using the GAMS program 36.1.0 /CPLEX. 20.1.0.1.

Chapter 5

5. Kuwait oil company case study results and discussion

5.1. Introduction

In the preceding chapters, theoretical foundations, methodological frameworks, and formulations that support the aim of this research have explored. A major objective of this study is to is to develop a multi-objective optimisation model that strikes a balance between economic and environmental sustainability in PW management.

This pivotal section of our research is dedicated to the exposition of results obtained through the application of multi-objective optimisation model, complemented by LCA. These empirical findings emerge against the backdrop of KOC case study. The selection of KOC as our case study serves as a poignant representation of the multifaceted challenges confronting the oil and gas industry at large. Kuwait, a prominent player in the global energy landscape, offers an ideal microcosm for the broader narrative of the sector. Consequently, the results unveiled in this section possess both localised significance and broader international relevance.

This approach is driven by the need for sustained cost and environmental impact control. Within this empirical discourse, PW management is systematically examined across distinct time horizons: 5, 10, and 20 years. These selected periods are aligning with KOC's strategic planning horizon. The forthcoming section, comprising results and discussions related to the implementation of this multi-objective optimisation model.

5.2. Life cycle assessment results

A comprehensive set of 18 environmental impact categories is included, at the mid-point level. There is no consensus on how to aggregate the different environmental impacts into a single environmental impact function, nor on whether such aggregation is conceptually and philosophically valid (Azapagic, 1999). The decision to prioritise and select an impact category is subjective and is based on the preferences and priorities of the decision-maker (Rogers and Seager, 2009). Since CO_2 eq is the focus of many oil and gas supply chain optimisation studies (Laurenzi and Jersey, 2013; Bartholomew and Mauter, 2016; Chen et al., 2017), the assessment of LCA is limited to CO_2 eq in this study. CO_2 emissions are often a key focus due to their significant contribution to climate change (Tillman, 2000). The global warming potential resulting from the use of chemical additives and electricity usage is found to be the main contributor to the PW facility's environmental impact.

Here, the results of the LCA performed for the KOC PW treatment facility are reported. Kuwait's electricity grid has been used to analyse electricity section in the study. The chemical additives input including those associated with NaCI, NaOH and CaCl2 are modelled based on the study of Kuraimid *et al.*, (2013).

In this research, a set of six categories that cover the following three areas of protection commonly addressed in LCAs: use of resources, impacts on human health, and impacts on ecosystems. Moreover, the selected categories represent the most common indicators used in the literature described in this chapter. The impact categories included in the study have the following description:

1. *Global warming potential (GWP ; kg CO_2 eq.)*: Reflects the contribution of the various emissions to the increase in the effect of global warming.
2. *Stratospheric ozone depletion (ODP ; kg CFC11 eq.)*: Thinning of Earth's ozone layer by the release of chemical compounds containing gaseous chlorine or bromine from industry and other human activities.
3. *Fossil depletion potential (FDP ; kg oil eq.)*: Refers to a group of resources that contain hydrocarbons. The group ranges from volatile materials (like methane) to liquid petrol, to non-volatile materials (e.g., coal).

4. *Ionising radiation potential (IRP ; kg U235 to air)*: indicates the damage to human health related to the routine release of radioactive material into the environment.

5. *Terrestrial acidification (TP ; kg SO_2 eq.)*: Reflects the contribution of substances that produce H_2SO_4 when in contact with water. When these substances are present in the environment, they produce acid rain, causing terrestrial and aquatic species degradation.

6. *Mineral resource scarcity (RS ; kg Cu eq.)*: Metal ores started to become scarce during industrialisation, when demand for metals sharply increased.

The resultant environmental impacts are assessed by identifying the outputs of the primary treatment method, including the effects of chemicals used and the energy consumed. The direct emissions are estimated using the data available on chemicals used in PW treatment and the electricity consumption of the booster pumps, filters and disposal pumps. The environmental impact categories are selected due to their significance and relevance in terms of evaluating the environmental performance of the PW treatment practices at the KOC treatment facility. Table 7 summarises the environmental impact assessment results, which are calculated based on FU 1 m^3 of PW.

Table 7. The environmental impact assessment results.

Impact Category	Unit	Chemical additives	Electricity
Global warming potential	kg CO_2 eq.	29.44	6.18
Ionising radiation potential	kBq Co-60 eq.	0.44	0.66
Terrestrial acidification	kg SO_2 eq.	0.03	0.02
Stratospheric ozone depletion	kg CFC11 eq.	1.23E-05	2.04E-06
Mineral resource scarcity	kg Cu eq.	0.08	0.00
Fossil depletion potential	kg oil eq	7.98	2.01

Figure 14 shows the process tree of the PW treatment process components that contribute to global warming potential by 1m^3 of PW.

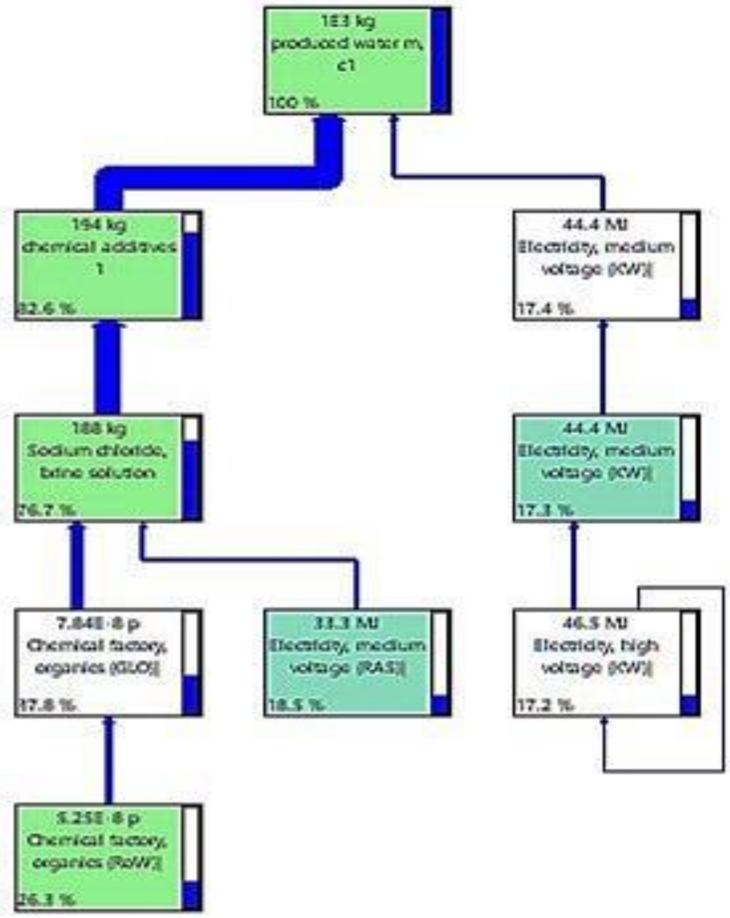


Figure 14. Process tree of the produced water(PW) treatment process components that contribute to global warming potential.

Furthermore, the LCA results suggest that the KOC treatment facility’s electricity consumption has a lower overall environmental impact than its use of chemical additives on the generation of global warming potential. However, the results reported in this work can be useful only to draw first considerations about the environmental reliability of PW treatment processes of PW treatment processes in KOC.

Following the LCA in this research, the environmental impacts are then formulated into a linear MILP mathematical model that constrains the emissions associated with the system.

5.3. Results of the model

The solutions for three different PW management strategy lifetimes (i.e., 5, 10 and 20 years) is developed. Based on the linear nature of the model, the obtained outcomes are comparable in both scenarios. These solutions allow decision-makers to select strategies based on their priorities. A convex Pareto front is observed, suggesting that significant reductions in environmental impact require more substantial economic investments. The multi-objective optimisation model produced a range of valuable outcomes, showing the trade-offs between economic cost and environmental impact in managing PW over different planning horizons (5, 10, and 20 years). The varying outcomes, in terms of cost and emissions, are discussed below.

The PW model indicates that operating PW supply chain for 20 years would cost KWD 262 million. PW management operates at a lower cost for 10-year and 5-year timelines by 46% and 72%, respectively. Moreover, the treatment aspect of PW management is responsible for 235 million kg of CO_2 eq emissions over the course of 20 years.

Over the 10-year and 5-year periods, the *TE* would be 46% and 72% lower, respectively. Overall, more than 90% of the *TE* is accounted for electric consumption, and over 50% of *TC* is for treatment costs.

Over the period of 5, 10 and 20 years, there is a negative correlation between financial cost and environmental impact. It is evident from this negative correlation that efficient operations could be more cost-effective and have a lower environmental impact.

Cost and emission results are presented in Table 8.

Table 8. The produced water(PW) management modelling results for the different periods and selected Pareto Points A, B and C.

Point A	**5 Years**	**10 Years**	**20 Years**
Total transportation cost (KWD-million)	26.77	53.13	60
Total treatment cost (KWD-million)	37.6	72.51	135
Maintenance cost (KWD-million)	1.3	2.5	4.65
Total reuse cost (KWD-million)	28	54	100
Electricity (KWD-million)	0.32	0.62	1.16
Emissions: water treatment (kg CO_2 eq-million)	3.2	6.47	12.94
Emissions: electricity consumption (kg CO_2 eq-million)	55.3	110	221
Point B	**5 Years**	**10 Years**	**20 Years**
Total transportation cost (KWD- million)	5.77	11.12	21
Total treatment cost (KWD- million)	37.42	72.22	134
Maintenance cost (KWD- million)	1.3	2.5	4.65
Total reuse cost (KWD- million)	28	54	101
Electricity (KWD- million)	0.32	0.62	1.16
Emissions: water treatment (kg CO_2 eq- million)	4.31	7.99	15.35
Emissions: electricity consumption (kg CO_2 eq- million)	54.74	109.72	218
Point C	**5 Years**	**10 Years**	**20 Years**
Total transportation cost (KWD- million)	2	8	17
Total treatment cost (KWD- million)	37	71.85	133
Maintenance cost (KWD- million)	1.29	2.5	4.65
Total reuse cost (KWD- million)	28	54	100
Electricity (KWD- million)	0.32	0.62	1.16
Emissions: water treatment (kg CO_2 eq- million)	5.92	11.84	23.69
Emissions: electricity consumption (kg CO_2 eq- million)	54.19	122	259

In the following, figures 15, 16 and 17 illustrate *TC* and *TE* over 5, 10, and 20 years. Point A indicates the lowest *TE* value (and the highest *TC* value). In contrast, Point C indicates the highest *TE* value (and the lowest *TE* value). In Point B, the balanced trade-off is achieved when both objectives are equally important. In any case, the stakeholder will have to decide which solution to consider based on their preferences and constraints (Al-Abdullah et al., 2019).

In figure 15 the emissions are shown to be relatively stable over the period of five years.

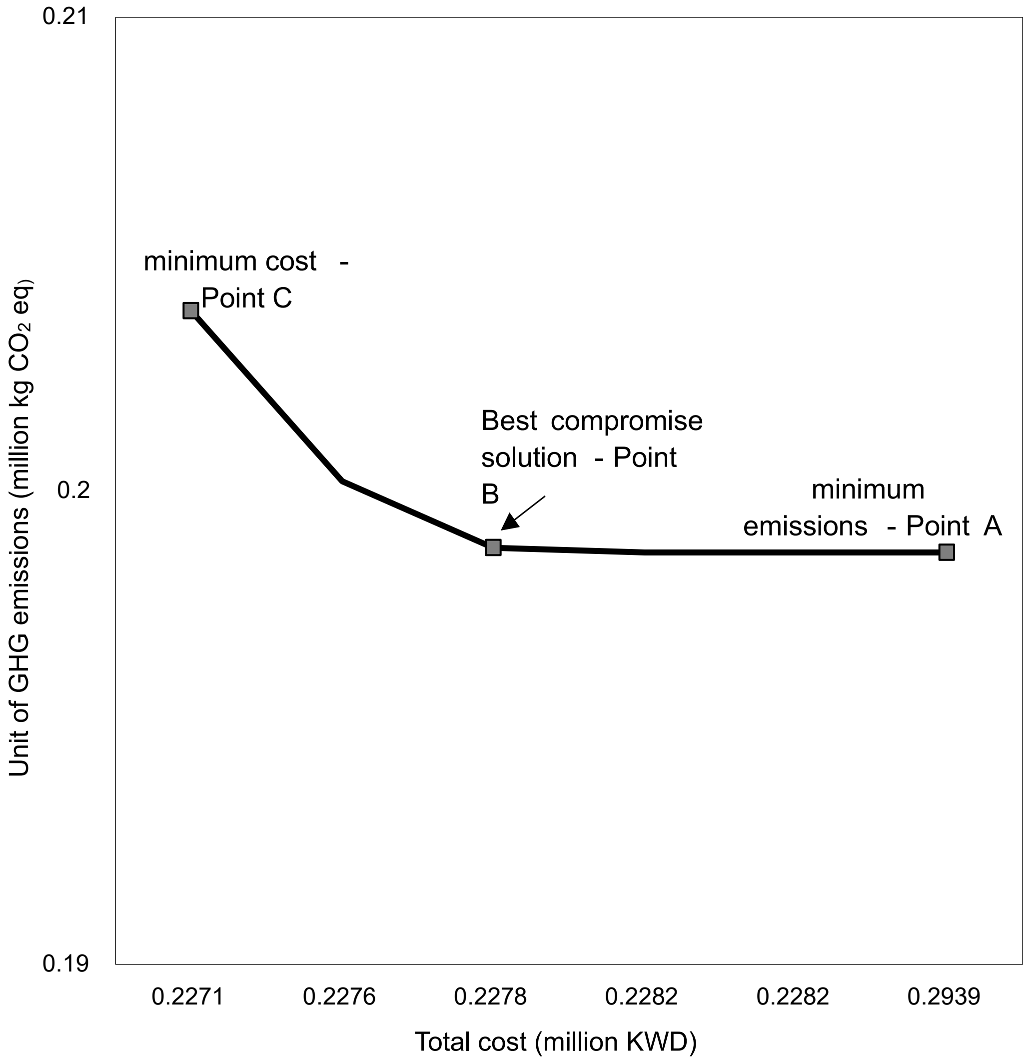


Figure 15. The Pareto set for the 5-year multi-objective produced water (PW) management model.

In contrast, the operational Point B indicates cost associated with managing PW is found to vary. At Point B, for a 5-year period, the *TC* is calculated to be KWD 73 million and the *TE* is calculated to be 59 million kg CO_2 eq.

The solution for managing PW over a 10-year period reflects concurrent changes in the economic and environmental objectives shown in Figure 16.

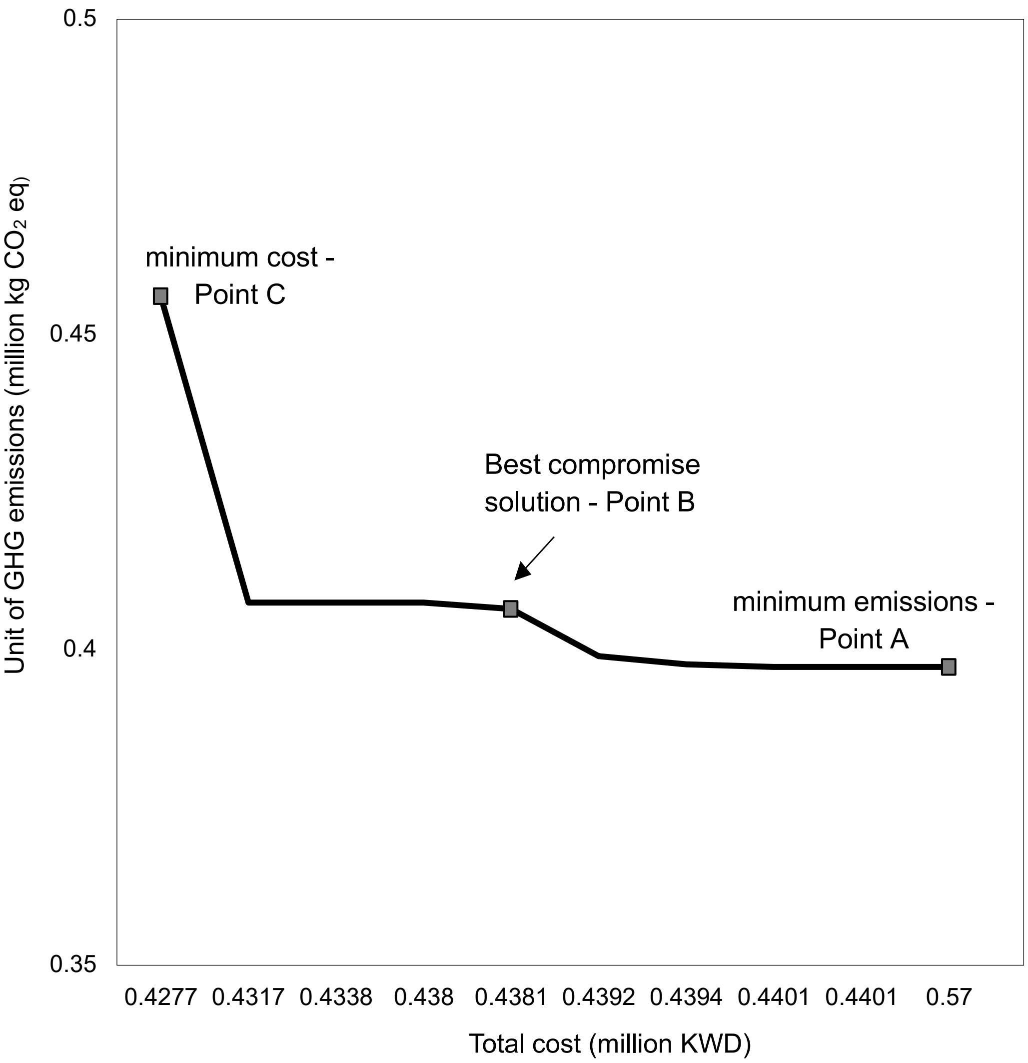


Figure 16. The Pareto set for the 10-year multi-objective produced water (PW) management model.

At Point A, the *TC* is KWD 183 million, but at Points B and C, the *TC* has been reduced significantly (KWD 141 million; 23% reduction and KWD 137 million; 25% reduction), respectively.

Comparatively, the *TE* at Point A is 117 million kg CO_2 eq, and they increased at Points B (118 million kg CO_2 eq ; 12.5% increase) and C (135 million kg CO_2 eq ; 12.9% increase).
For a 10-year period, the *TC* at Point B is calculated to be KWD 141 million and the *TE* at Point B is calculated to be 117 million kg CO_2 eq.

For the 20-year period, The *TC* is found to be highest at Point A (KWD 301 million) and it is 13% lower at Point B (KWD 261 million) and 14% lower at Point C (KWD 258 million).
Figure 17 shows the results for the 20-year period.

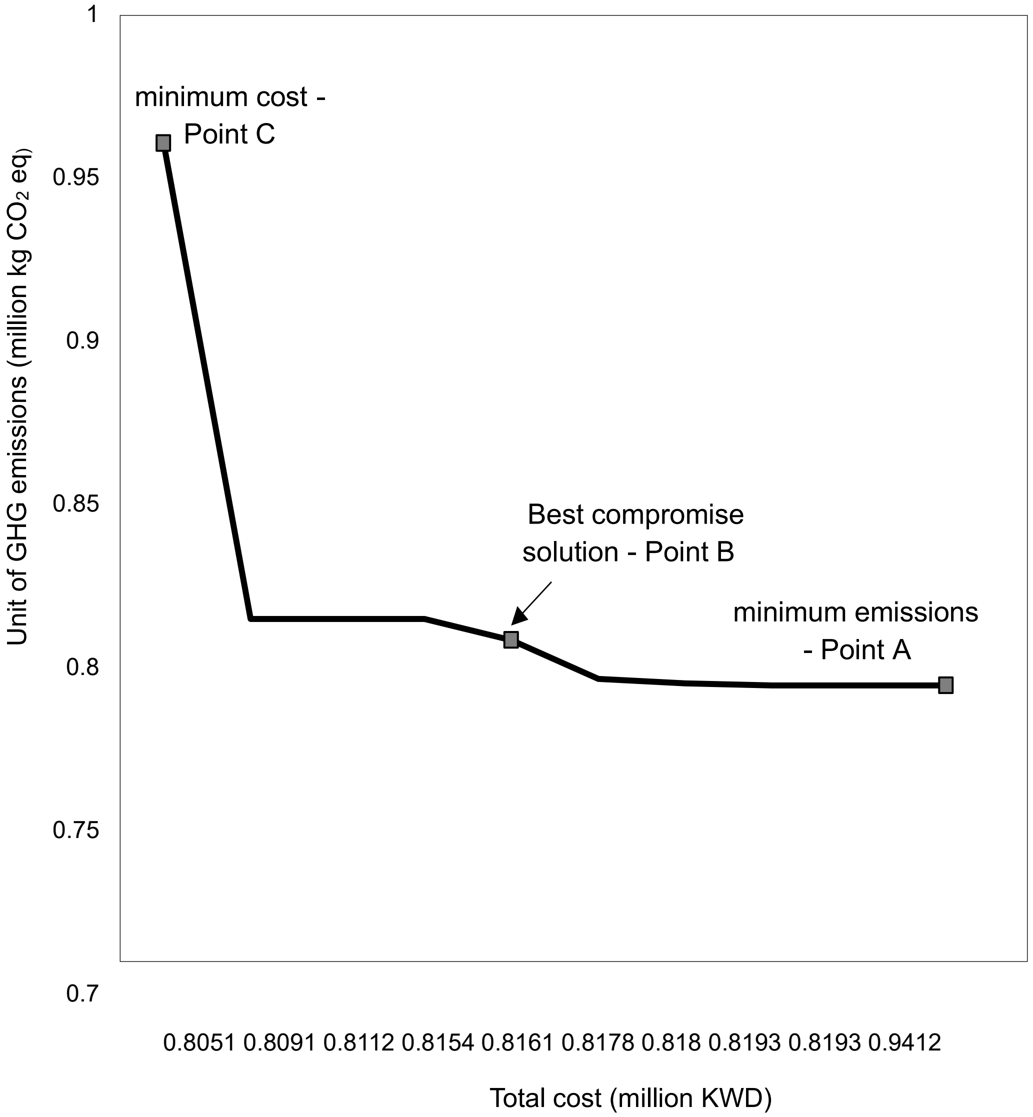


Figure 17. The Pareto set for the 20-year multi-objective produced water (PW) management model.

Conversely, in terms of *TE*, the values increase from Point A (234 million kg of CO_2) to Point B (235 million kg CO_2 eq ; 0.3% increase) and to Point C (283 million kg CO_2 eq ; 20% increase). At Point B, for a 20-year period, the *TC* is calculated to be KWD 262 million and the *TE* are calculated to be 235 million kg CO_2 eq.

Figure 18 shows that the cost of transportation through pipeline has increased by 50% over the 5 to 10 years period. Also, the emissions of electricity and the costs of maintenance and disposal are doubled in amount.

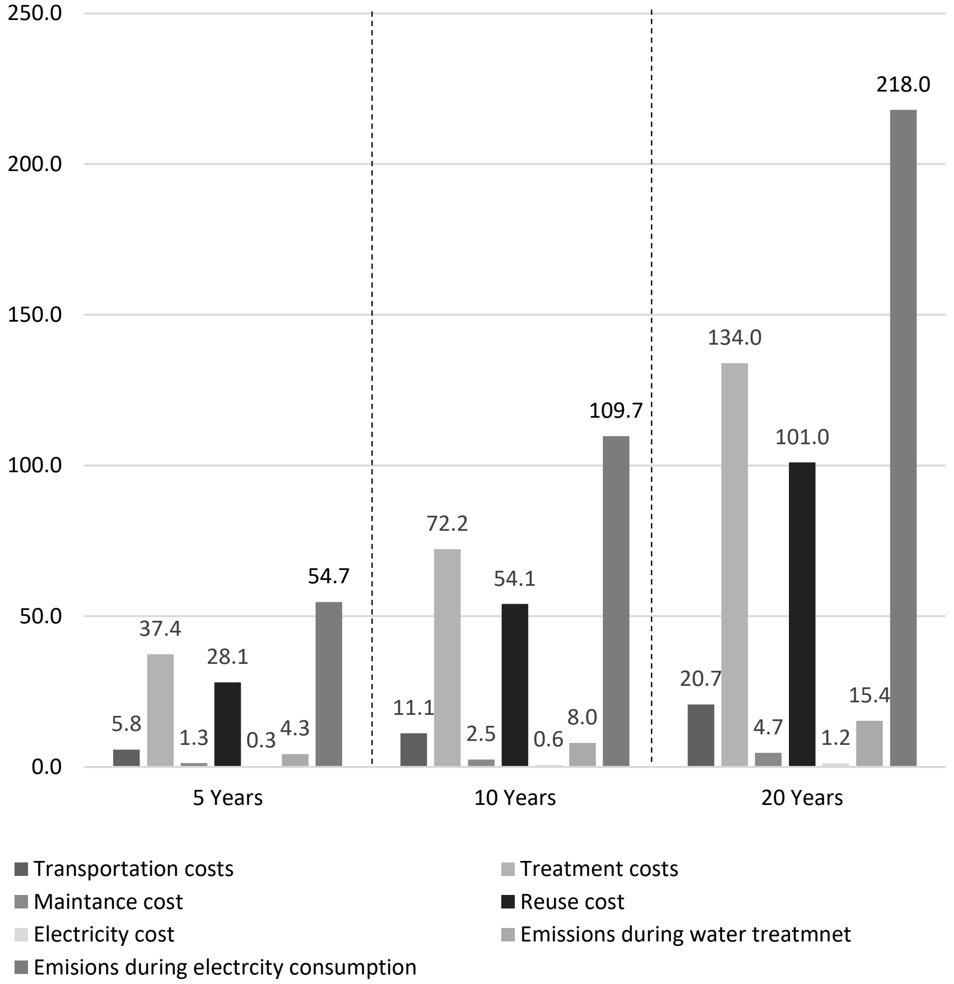


Figure 18. Comparison of the different impacts of PW supply chains over a range of time periods.

Over 10 to 20 years of operating, costs associated with the transportation through pipeline have risen over 40%. Moreover, the costs of maintenance and reuse have doubled in addition to an increase of 60% in electricity costs.

Figure 19 provides an overview of the major effects of parameters for the PW supply chain network. In general, the results of the PW model throughout different periods of time indicate that the highest impact is caused by emissions associated with electric consumption. Similarly, treatment costs and disposal costs are high in descending order of impact.

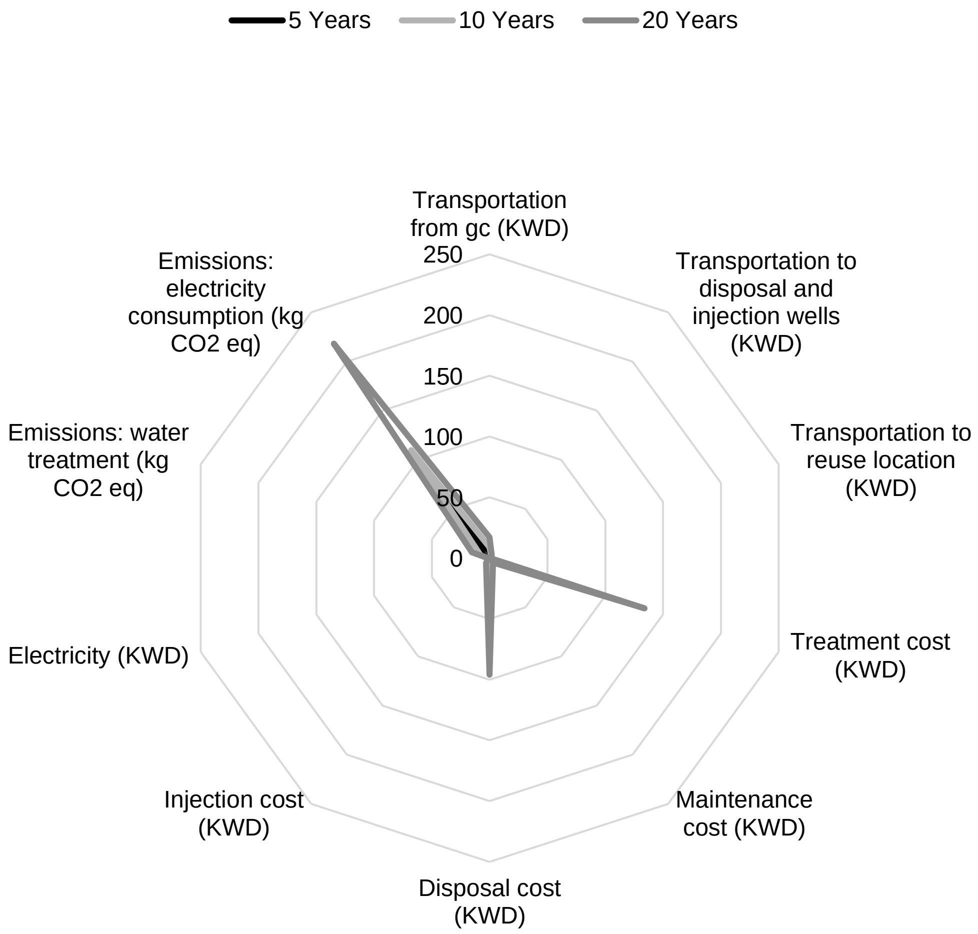


Figure 19. Comparison of the different impacts of PW supply chains over a range of time periods.

Also, results of the PW model indicate that there are comparable and economically low costs associated with transportation through pipelines, maintenance, and injection. The least economic impact of the PW supply chain network in KOC presented in this research comes from transportation costs through trucking, electricity costs. Besides, the least environmental impact in the PW supply chain comes from emissions caused by water treatment.

In Figure 20, the average *TC* and *TE* associated with the optimal solutions for each of the 5-, 10- and 20-year periods are compared. Most noticeably, the *TC* and *TE* for the 20-year period is found to be distinctly higher than that for the 10-year period and the 5-year period. This indicates that there could be a rising cost and emissions associated with time in KOC's sustainable PW management systems.

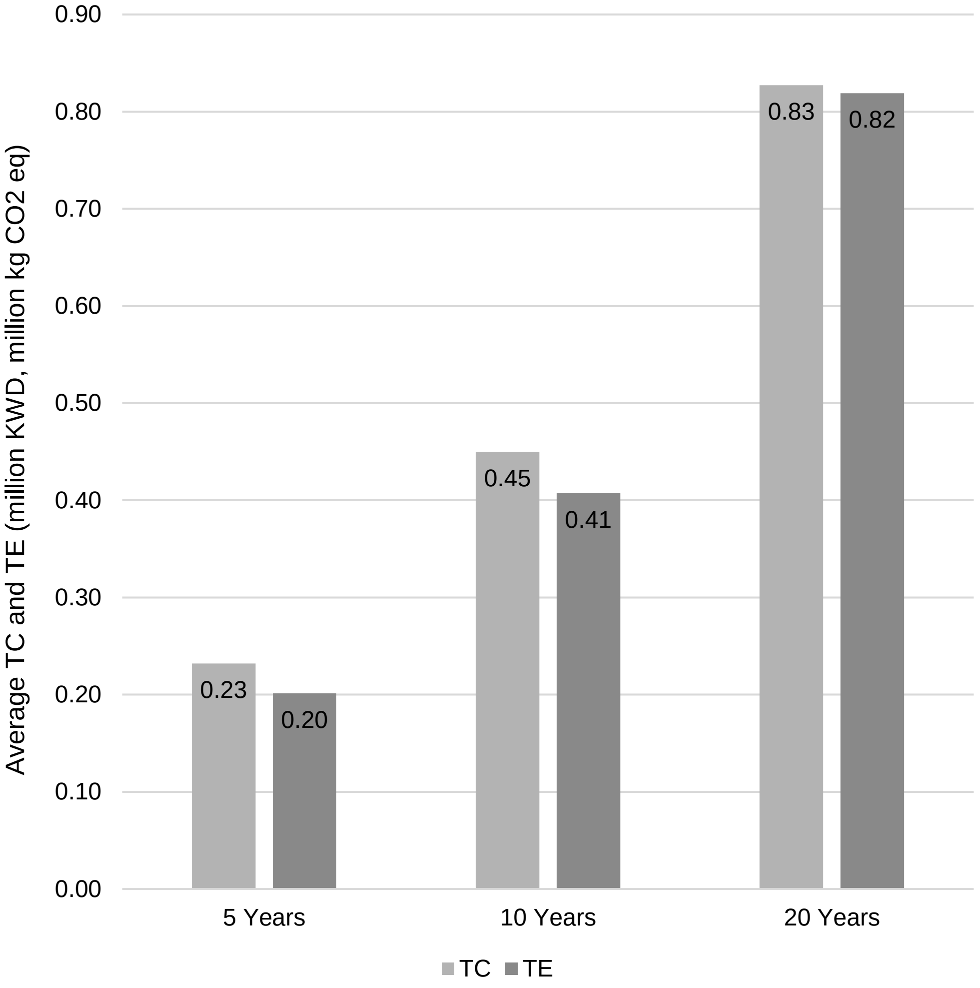


Figure 20. Comparison of the average total cost (TC) and total emissions (TE) associated with the modelled produced water (PW) supply chain network over 5, 10 and 20 years.

The multi objective optimisation model revealed several optimal solutions representing various strategies for PW management. Based on the optimisation model results and depending on the time period, costs and emissions associated with PW supply chain management vary.

For instance, in the 5-year planning horizon, a clear trade-off emerged. Opting for a more environmentally friendly strategy, involving advanced treatment methods and increased recycling, resulted in a moderate increase in economic cost. This illustrates that short-term economic gains are feasible but come at the expense of higher environmental impact. The total cost development in the PW supply chain is basically determined by the costs associated with treating and reusing PW, which are comparatively high compared to the short duration applied. For KOC, this often translates to solutions that focus on cost reduction, avoids implementation of costly emissions control technologies, delay upgrades of capital-intensive equipment and adopts lower cost treatment methods.

However, a 5-year horizon raises concerns about the environmental consequences of such short period. The model reveals that while different strategies might lower immediate operational costs, they lead to higher emissions and environmental risks. This could potentially harm KOC's environmental reputation and, in the long run, result in higher costs due to regulatory fines and ecological damage.

As for the 10-year planning horizon, KOC can still achieve notable economic savings while also has the opportunity to implement more sustainable practices. Investments in advanced treatment technologies and recycling options can show their benefits, as cost savings and environmental improvements become more balanced.

The 10-year scenario highlights the need for KOC to find the optimal balance between short-term financial objectives and long-term sustainability. It suggests that strategic investments that can be in infrastructure and technology can yield substantial cost reductions over this period. Meanwhile, adherence to environmental regulations and proactive measures help mitigate environmental impact.

A 5-year and 10-year planning horizon highlights the need for continuous improvement in the management of PW. The KOC should not view these periods as isolated events, but rather as stages within a broader sustainability strategy.

Extending the analysis to a 20-year planning horizon offers a unique perspective on PW management for KOC. Significant variation in the financial costs and emission impacts is observed across PW supply chain. It becomes clear that the trade-offs between economic cost and environmental impact shift significantly over this extended period. In the 20-year scenario, the model highlights that strategies emphasising long-term economic viability often involve adopting a more cautious approach in environmental measures.

Conversely, for KOC and other organisations committed to long-term environmental sustainability, the presented model demonstrates that substantial reductions in environmental impact can indeed be achieved. These solutions often require increased investment in advanced treatment technologies and robust PW recycling systems.

The 20-year planning horizon underlines the complexity of balancing economic and environmental objectives. KOC faces the challenge of aligning its strategic vision with practical implementation. This necessitates not only effective management but also a commitment to adapting strategies as technology evolves and regulations change. For example, implement energy-efficient practices and technologies to reduce emissions associated with energy consumption. Also, implement effective management plans to properly dispose of PW, which can reduce disposal costs.

It is important to note that there is no one-size-fits-all solution; instead, the optimal strategy depends on the organisation's economic and environmental goals. Decision-makers can choose from a range of solutions, each representing a different balance between economic cost and environmental sustainability.

Several limitations are acknowledged in the presented model, including simplifications in environmental impact modelling and the assumption of fixed parameter values. Future research can focus on refining these aspects for greater accuracy.

In summary, the stated multi-objective optimisation model offers a robust framework for PW management in the oil and gas industry. By recognising the inherent trade-offs between economic cost and environmental impact, it empowers organisations like KOC to make informed decisions that prioritise both financial viability and environmental stewardship.

Chapter 6

6. The validation of model independent parameters for Kuwait oil company case study

6.1. Introduction

During the course of this research, it is vital to take into consideration that the major drivers for decision-making at KOC about PW management is the cost associated with operating the PW supply chain (i.e., the goal is to minimise the cost). Thus, further investigate how the variations in inputs could impact the outputs of the PW model.

The aim of this chapter is to evaluate the input parameters (via GSA) and identify the most effective input parameter.

There is always a certain degree of uncertainty associated with model's input parameters due to spatial variability, financial constraints, or difficulties in obtaining data. Model uncertainties can impact the economic performance of the supply chain system and may result in a suboptimal design (Ebrahimi-Moghadam *et al.*, 2020). This results in a better understanding of the model behaviour and, thus, better estimates and reduced uncertainty (Wagener and Pianosi, 2019).

As a matter of definition and discrimination, local sensitivity analysis is the study of the output variability against variations of an input factor around a specific value x, while GSA is the study of the output variability within the entire space of input factor variability (Pianosi *et al.*, 2016). GSA is usually conducted as a preliminary step in model building as it is useful for identifying (1) components with a low-impact that may be converted to fixed values for simplifying the model and (2) components with high-impact that require further study to reduce the uncertainty of the model (Wang, Huang and Tang, 2020). Four independent parameters are considered when conducting the MLR analysis:

1. Discount Rate.
2. Treatment Cost.
3. Electricity Cost.
4. Water Capacity (amount of pw that can be treated).

In the oil and gas sector, where investment cycles are long and project timelines reach 20-30 years, the discount rate is carefully considered. Several academic studies have demonstrated the importance of accurately determining the discount rate over long planning periods for projects (Komzolov et al., 2021). The use of discount rates in the oil and gas sector allows decision makers to assess the change in the value of expenses over the course of several years (Harden, 2014).

Costs associated with PW treatment are also important, as large volumes of oil production wastewater are incapable of being discharged directly into the environment (Lynn E. Katz, R.S. Bowman, 2003). The development of a cost-effective treatment process is therefore essential (Liden et al., 2018). The cost of PW treatment is closely related to the price of electricity and the quality of the PW (Al-ghouti et al., 2019). While the capacity of a water treatment facility can affect its design, it may not necessarily affect the PW management cost in a significant way (T. Heberling *et al.*, 2015).

Data were collected on the tested independent parameters from existing case studies that had been conducted under similar conditions to the presented case study. More information about the tested independent parameters from exiting case studies are available in the supplementary file. The variations in the data obtained for each independent parameter are shown in table 9.

Table 9.The independent parameters that resulted from the 2k factorial design, bounded by lower and upper level.

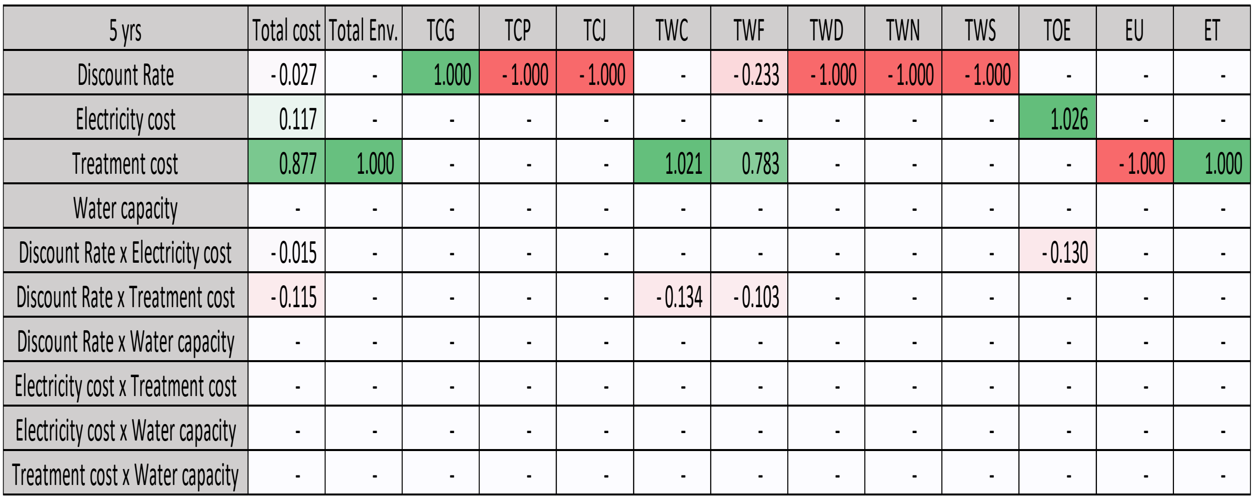
	Discount Rate	Treatment Cost	Electricity Cost	Water Capacity
Lower	0.0150	0.1000	0.0100	2,500,000
Upper	0.0300	22.0000	0.3000	80,000,000

6.2. Results of the model

Since the independent parameters have different units of measure, the model values were converted to dimensionless values by normalising them to values between 0 and 1. Then, the MLR results obtained for the different periods (5, 10 and 20 years) is used to illustrates the effects of the different independent parameters on the dependent parameters. The data resulting from the GSA conducted for the 5-, 10- and 20-year periods are presented in Figures 21, 22 and 23respectively.

The results show the importance and contribution of each of the selected independent parameters to the PW management model. They also show the effect of each of the independent parameters on each of the dependent parameters in the PW supply chain model.

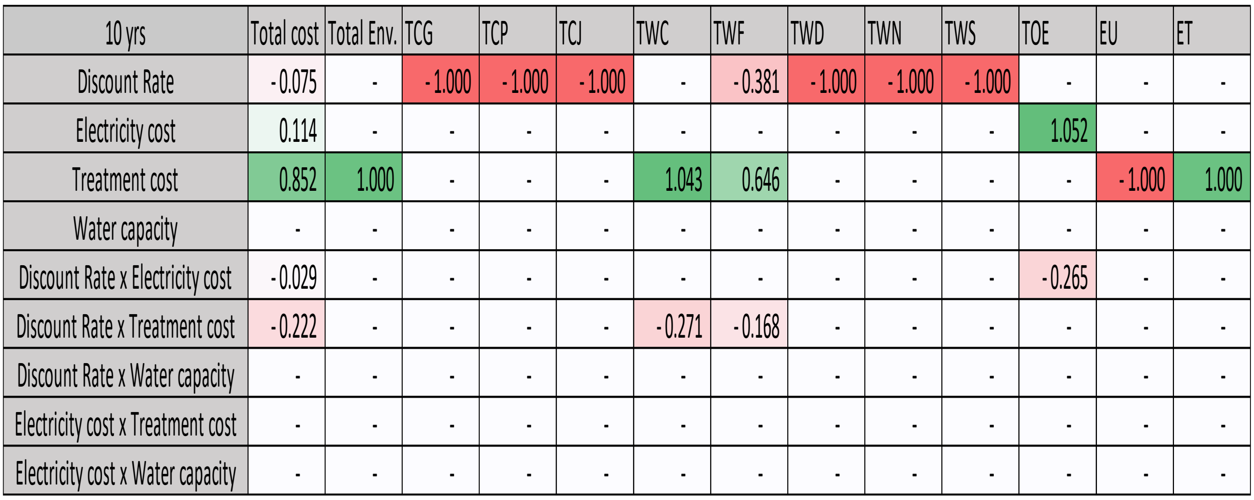
The independent parameters are listed in the first row, and the dependent parameters are listed in the first column in each table. The zero values indicate the situations in which the independent parameter does not affect the dependent parameter. In cases where a dependent parameter is found to be affected by an independent parameter, The coefficient is highlighted with a different colour as red indicates high negative correlation and green indicates high positive indication.



5 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Discount Rate	-0.027	-	1.000	-1.000	-1.000	-	-0.233	-1.000	-1.000	-1.000	-	-	-
Electricity cost	0.117	-	-	-	-	-	-	-	-	-	1.026	-	-
Treatment cost	0.877	1.000	-	-	-	1.021	0.783	-	-	-	-	-1.000	1.000
Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Discount Rate x Electricity cost	-0.015	-	-	-	-	-	-	-	-	-	-0.130	-	-
Discount Rate x Treatment cost	-0.115	-	-	-	-	-0.134	-0.103	-	-	-	-	-	-
Discount Rate x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricity cost x Treatment cost	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricity cost x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Treatment cost x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 21. Effect of independent parameters on dependent parameters: 5-year periods (note: “-“ indicates an insignificant correlation value of zero or less than .01)

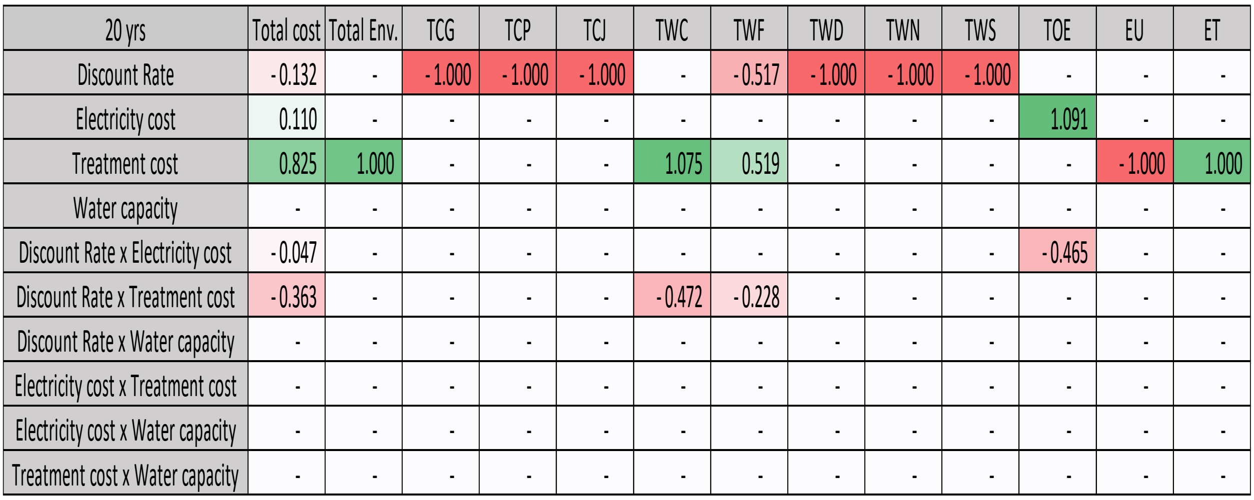
The coefficient values shown represent the rate of change in the dependent parameters when a unit change occurs in the independent parameters. For example, in Figure 21, -0.027 KWD is the average change in Total Cost (dependent parameter) when a unit change occurs in Discount Rate (independent parameter).



10 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Discount Rate	-0.075	-	-1.000	-1.000	-1.000	-	-0.381	-1.000	-1.000	-1.000	-	-	-
Electricity cost	0.114	-	-	-	-	-	-	-	-	-	1.052	-	-
Treatment cost	0.852	1.000	-	-	-	1.043	0.646	-	-	-	-	-1.000	1.000
Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Discount Rate x Electricity cost	-0.029	-	-	-	-	-	-	-	-	-	-0.265	-	-
Discount Rate x Treatment cost	-0.222	-	-	-	-	-0.271	-0.168	-	-	-	-	-	-
Discount Rate x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricity cost x Treatment cost	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricity cost x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 22. Effect of independent parameters on dependent parameters:10-year periods (note: "-" indicates an insignificant correlation value of zero or less than .01).

Similarly, in figure 19, 0.114 KWD is the average change in Total Cost (dependent parameter) when a unit change occurs in Electricity Cost (independent parameter). Moreover, in figure 24, 0.825 KWD is showing the average change in Total Cost (dependent parameter) when a unit change occurs in Treatment Cost (independent parameter).



20 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Discount Rate	-0.132	-	-1.000	-1.000	-1.000	-	-0.517	-1.000	-1.000	-1.000	-	-	-
Electricity cost	0.110	-	-	-	-	-	-	-	-	-	1.091	-	-
Treatment cost	0.825	1.000	-	-	-	1.075	0.519	-	-	-	-	-1.000	1.000
Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Discount Rate x Electricity cost	-0.047	-	-	-	-	-	-	-	-	-	-0.465	-	-
Discount Rate x Treatment cost	-0.363	-	-	-	-	-0.472	-0.228	-	-	-	-	-	-
Discount Rate x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricity cost x Treatment cost	-	-	-	-	-	-	-	-	-	-	-	-	-
Electricity cost x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-
Treatment cost x Water capacity	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 23. Effect of independent parameters on dependent parameters:20-year periods (note: "-" indicates an insignificant correlation value of zero or less than .01).

The interaction effects of the independent parameters on the dependent parameters shown in Figure 24 for the 5-, 10-, and 20-year periods. Only the parameters that are found to have an interaction effect shown in Figure 23. In each panel, the dependent parameters are listed on the x-axis, and the magnitude of the respective effects of the independent parameters are represented on the y-axis and the vertical line shows the effect of different parameters interactions.

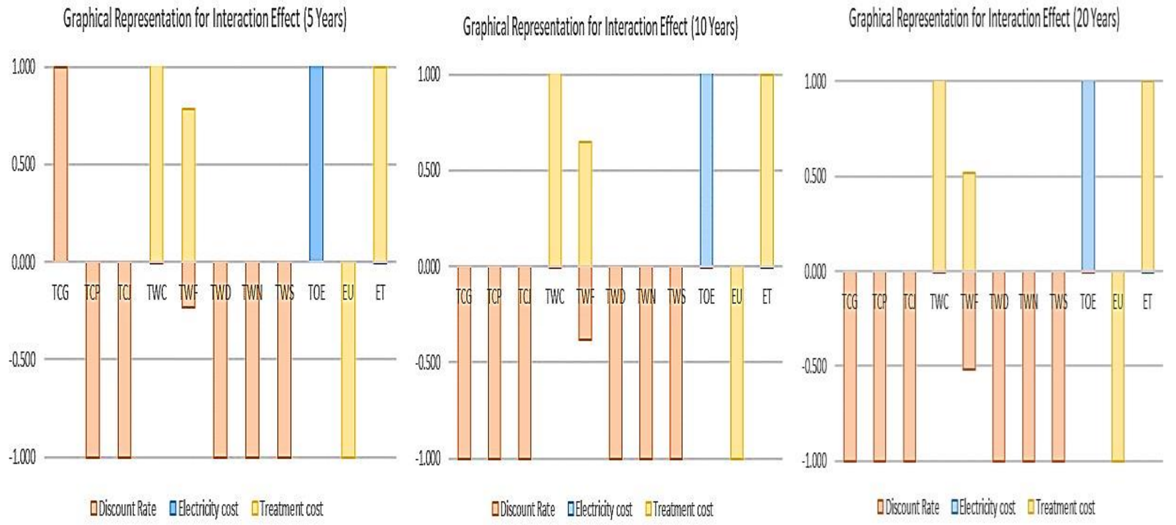


Figure 24. The interaction between the independent and dependent variables in the produced water(PW) supply chain model.

As shown in Figure 24, among the independent parameters (i.e., Discount Rate, Electricity Cost, Treatment Cost and Water Capacity), Treatment Cost is found to have the greatest impact on the two dependent parameters of Total Cost and Total Environment. It had the greatest impact on Total environment, with a value of 1, and Total cost the treatment cost is the highest among all. Total Environment is the highest value among individuals which is 1.

The displayed results indicate that PW treatment costs play a key role in determining the Total Cost and Environmental impact of PW management. Electricity Cost and Discount Rate have the second- and third- greatest impact, respectively. Water Capacity has zero effect on both Total Cost and Total Environment. The two categories of interactions that affect the dependent parameters are Discount Rate x Treatment Cost and Discount Rate x Electricity Cost. Figure 25 shows the interaction effect of Discount Rate x Treatment Cost and Discount Rate x Electricity Cost for the periods of 5, 10 and 20 years.

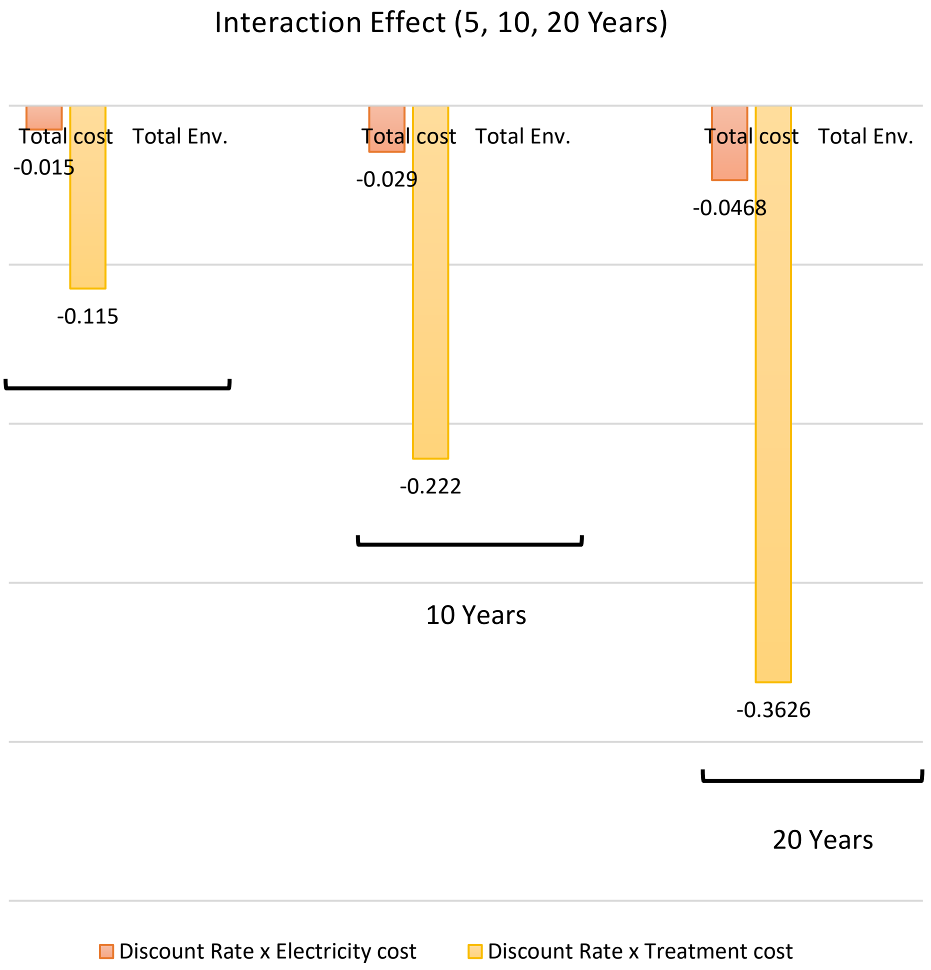


Figure 25. . The impact of two categories of interactions on the dependent parameters over the 5-,10- and 20- year periods .

It can be observed in Figure 26 that between the two categories examined (Discount Rate x Treatment Cost and Discount Rate x Electricity Cost), Discount Rate x Treatment Cost recorded the highest interaction in each analysis (5 years = -0.115, 10 years= -0.222 and 20 years = -0.3626). However, in terms of Total Environment, both Discount Rate x Treatment Cost and Discount Rate x Electricity Cost recorded values zero.

GSA findings show that all the investigated parameters significantly influence KOC's PW supply chain system, except Water Supply Capacity. A negative correlation exists between Discount Rates and Total Cost and Total Environment were also found, whereas Electricity Cost and Treatment Costs are found to positively correlate with Total Cost and Total Environment in KOC's PW management system. Various interactions occur among the independent parameters; specifically, interactions exist between the Electricity Cost and

Discount Rate, between Treatment Cost and Discount Rate, leading to an inverse relationship with Total Cost.

Notably, the GSA findings reveal that Water Supply Capacity does not significantly impact the system's performance. This might seem counterintuitive, but it suggests that within the examined range, the existing capacity is adequate to meet demand. Therefore, KOC may need to focus its optimisation efforts on other parameters that exhibit more sensitivity.

The negative correlation identified between Discount Rates and Total Cost and Total Environment is a key finding. This finding is essential for KOC's long-term planning because it highlights the role of Discount Rates in determining project feasibility over extended periods. Lower Discount Rates can lead to more sustainable and environmentally friendly PW management strategies. On the other hand, the positive correlation between Electricity Cost and Treatment Costs with Total Cost and Total Environment signifies their significant role in shaping KOC's PW management expenses and environmental footprint. Consequently, strategies aimed at optimising electricity usage and treatment processes can yield substantial economic and environmental benefits.

The sensitivity analysis for the 5-year and 10-year scenarios highlights the influence of factors like energy prices, discount rates and treatment cost. This emphasises the importance of mid-term adaptation. KOC must remain flexible in its approach, ready to adjust strategies based on emerging trends and new opportunities.

Based on the 20-year GSA findings, adaptive strategies are necessary. KOC should consider flexible strategies that can be adjusted to align with changing conditions while maintaining cost-effectiveness and environmental responsibility. Furthermore, GSA for the 20-year timeframe provided insights into optimal investment planning. It identified key parameters related to capital investments and expenditures, depreciation rates, and asset utilisation that strongly influence the financial aspects of the PW management system. These findings assist KOC in allocating resources effectively over the long term.

The conducted GSA further underscores the importance of considering time as a critical factor. It reveals that certain parameters, such as the discount rate and long-term environmental impact projections, exert more major influence on the optimal strategies in the 20-year scenario. This highlights the dynamic nature of decision-making over extended periods.

GSA revealed significant insights into the factors driving the outcomes of the presented multi-objective optimisation model. The findings confirm and emphasise the importance of conducting a GSA for parameters selection for gaining an understanding of the sensitivity of selected independent parameters. Stakeholder expectations and environmental regulations are likely to evolve over time. Understanding the sensitivity of the PW system to these changes allows KOC to engage with stakeholders and regulators proactively, reducing compliance risks.

In summary, there is significant uncertainty around which PW management practices minimise cost and environmental impacts damages. This chapter presents a framework for regulators and policy makers to evaluate alignment between cost and emission impacts minimisation for PW management scenarios in oil and gas sector.

Chapter 7

7. PW reuse and risk assessment

7.1. Introduction

Oil and gas production is increasing globally, and by 2030 global petroleum consumption is estimated to reach 106.6 million barrels per day with wastewater accounting for up to 95% of the volume in ageing oil fields (Igunnu and Chen, 2014). To meet the world's need for alternative freshwater supplies, there is a greater focus on reclaiming, reusing, and recycling of PW, rather than discarding it.

PW can be used for a variety of purposes, including drinking, irrigation, livestock watering, habitat and wildlife watering, fire control, industrial uses (e.g., dust control, cooling water, oil field uses) and power generation (Al-Ghouti et al., 2019). Despite these multiple potential uses that would alleviate water scarcity worldwide, reuse of treated PW to increase the quantity of available water and lower freshwater consumption is a hotly debated issue (Sadiq, Khan and Veitch, 2005).

A significant factor in determining the ability to reuse PW is the type of treatment used, and the selection of the treatment process is mainly driven by characteristics of the PW and the quality standards to be met prior to reuse (Chard and Saunders, 2019). Treatment cost is another significant factor in determining the treatment method and the amount of PW to be treated and reused (Bagheri, Roshandel and Shayegan, 2018).

PW must be adequately treated to make it suitable for its intended reuse, and attention must be paid to the environmental hazards that are associated with its technical operations, transportation and storage. There are hazards associated with the occurrence of spills and leaks, waste management, air emissions and the preservation of ecosystems. It is likely that more traditional practices will become more complicated as future regulations shift toward health and environmental protection and zero emissions frameworks (Hernández, 2021). In the petroleum industry, environmental and even social factors are changing the way PW is perceived. Nowadays, rather than being viewed as an operational liability, PW is being viewed more as a by-product of strategic value and importance. It is anticipated that this will allow PW to be undergo more extensive treatment, resulting in a product that with higher quality standards and that will enable greater recycling and reuse (Dores et al., 2012).

The amount and type of treatment varies and is based on the purpose for which the treated PW will be used. For example, higher levels of treatment are required for drinking and agricultural purposes as compared to reinjection and disposal (Al-Ghouti et al., 2019). Moreover, for the reuse of PW, the management approaches are based on production volume, targeted pollutants and environmental regulation and standards, which vary between oilfields (Zheng et al., 2016). If PW is not properly managed during the operation and the production stages, it can pose several risks and have a detrimental effect on the environment and pose a number of risks.

For instance, chemical additives used in PW treatment may contaminate surface water and/or groundwater, and exposure to such chemicals may cause health problems (Sun *et al.*, 2019).

The occurrence of spills and leakages during PW treatment and reuse is another possible risk, which could result in contamination of surface water and groundwater (EPA, 2016). For example, the inorganic contamination has been shown to persist for many years following a PW spill (Lauer, Harkness and Vengosh, 2016). Hence, contamination resulting from PW operations can have a significant negative impact on the environment (e.g., the soil ecology) and human health (Sun *et al.*, 2019).

There are also risks associated with injecting PW into wells. First, this practice could induce earthquakes and result in well-casing failures. Second, any failure in the well injection operation could result in fractures in the underground layers that could, in turn, create pathways for PW to enter water resources, along with its associated ions and organic compounds (Digiulio and Jackson, 2016).

Using PW for onsite operations or other beneficial purposes requires specific technical, economic, environmental and regulatory factors to be considered (Hernández, 2021).

Therefore, when the regional factors and regulations that apply at each site and within each region are known, the type of treatment method that can be applied and, consequently, the results of reuse can be determined (Hagström et al., 2016).

The purpose of this chapter is to provide a broad overview of the recycling options for PW and the challenges the oil and gas industry faces in recycling PW. Also, to assess existing PW utilisation methods and determine the challenges associated with the use of PW for various purposes in order to minimise uncertainty by identifying risks and assessing their occurrence and impact.

The risk assessment developed in this research considers the environmental, health, technical and economic risks that have been integrated into most studies related to PW management and treatment techniques. Despite the fact that the risk analysis is supplemented by references to other studies, a limited amount of research has been conducted that assesses the risks associated with PW reuse and how these risks are taken into account during the decision-making process (Kabyl et al., 2020).

Hence, in the following sections show the reutilisation options for PW and risk assessment for reusing PW are discussed.

7.2. Current produced water management practices

In the oil and gas sector, the majority of generated PW is disposed rather than reused (Hagström et al., 2016). Present practices include minor treatment processes and disposal of PW into deep wells underground, which can be harmful to the environment (Jiménez et al., 2018; Liden et al., 2018). In the oil and gas industry, water reinjection is a method of reusing PW, which involves injecting water into a reservoir to increase pressure, thus maximising oil recovery. To increase the viscosity of crude oil and restore the formation pressure, EOR is achieved by using thermal reclaiming, injecting chemicals, gas, or pressure waves. This is because reinjection of PW can help maintain reservoir pressure and improve oil recovery rates, leading to increased production and reduced environmental impact (Kabyl et al., 2020; Li et al., 2021).

Although reinjection of PW is generally considered to be an environmentally friendly and efficient method of disposal, it can also be one of the more expensive options depending on various factors such as the quality and quantity of the water, the location of the injection well, and the type of treatment required prior to injection (Echchelh, Hess and Sakrabani, 2018; Salem and Thiemann, 2022).

In summary, PW reinjection for EOR and PW disposal are two different methods of PW management with different associated risks. While PW reinjection can be more expensive, it is considered to be an environmentally friendly and efficient method of disposal that can improve oil recovery rates. PW disposal, on the other hand, can be damaging to the environment if not properly controlled and is considered to be a less environmentally friendly method of disposal compared to PW reinjection for EOR. In Figure 26, the two common practices of disposing and reinjecting of PW are shown with the associated risks.

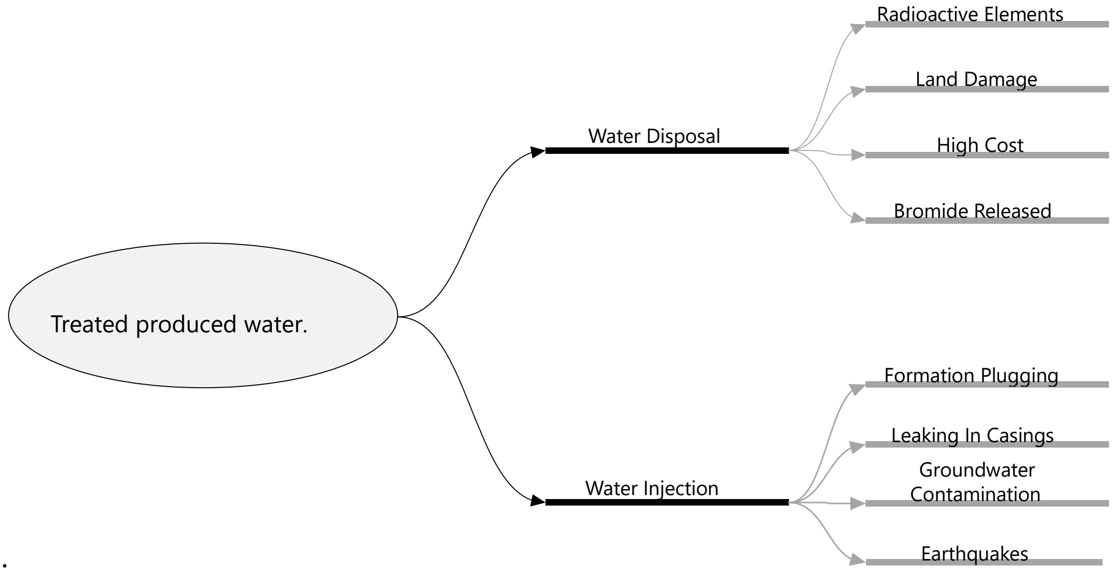


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Figure 26. Current7 ways of utilising of produced water (PW) and the risks associated with it in the oil and gas industry.

The current PW management practices in the oil and gas industry vary between countries. In the USA for instance, approximately 60% of PW is used for underground injection of EOR and 35% is sent for disposal, while the remaining 5% is discharged for beneficial use (Echchelh, Hess and Sakrabani, 2018b).

In China, reusing PW for industrial purposes specially for well fracturing operations which often occurs in the shale gas industry (Al-ghouti et al., 2019). While In Kuwait, most of PW is disposed of in underground disposal wells and injected into the subsurface via effluent injection wells for EOR (Salem and Thiemann, 2022).

It is likely, however, that in the future a greater fraction of PW will need to be extensively treated and ultimately recycled and reused for different purposes due to a variety of factors, including legislation, environmental restrictions, and local water scarcity. As a result, the petroleum industry will need to change its approach for managing PW and consider it as a strategic asset as opposed to an operational liability (Dores et al., 2012). It is essential to consider the fundamental factors that affect the PW management, such as the methods used to control it, the level of treatment applied, and the environmental impact of the process (Sadiq, Khan and Veitch, 2005). Despite the projected increase in PW volume, it is expected that the amount destined for non-beneficial uses (disposal and discharge) will decrease compared to the amount directed to beneficial uses (EOR and other beneficial reuses) (Mahmud, 2022).

7.3. Reuse of PW beyond oil and gas industry

Earth's terrestrial surface is largely covered by drylands, which are expected to expand as a result of climate change (Feng and Fu, 2013). With this reduction in available freshwater in mind, the reuse process of PW that would otherwise be discharged underground or wasted could therefore result in saving the same amount of freshwater for more critical uses, such as human consumption (Hernández, 2021).

PW reuse remains a minor practice although it is expected to develop and increase in the future. Several PW reuse scenarios have been identified, including using PW for the following: crop, rangeland and other vegetation irrigation; livestock watering; and augmentation of streamflow and natural wetlands (Hagström et al., 2016).

The petrochemical industry consumes large quantities of wastewater on a daily basis as part of its operations. PW is suitable for use in some of the petrochemical industry's operations, such as hydraulic fracturing, distillation and equipment cooling (Davarpanah, 2018). In addition to being used in industrial setting, PW can be discharged to the surface and used to recharge depleted aquifers; however, these options are not recommended because of the salty nature of PW and the presence of toxic particles that may negatively impact the environment (Scanlon et al., 2020).

Furthermore, treated PW can potentially be used as a water source for livestock unless there are concerns about supply and liability. However, livestock may experience diarrhoea when the treated PW contains high amount of TDS (Veil et al., 2004). In addition, the agricultural sector may be able to make use of PW after it has been appropriately treated and sufficient volumes are available. Treated PW can be utilised in platform washing, ship balancing, dust control on dirt roads, and fire control as needed. The scope of such practices, however, is generally limited to volumetric and treatment analysis (Kabyl et al., 2020).

Reuse of PW is well known as a best practice in the Middle East, the USA, North Africa and Australia, where there is a high demand for water and limited supply due to dry climates or restrictions on the development of additional water resources caused by environmental or health issues (Nijhawan and Myers, 2006).

For over 25 years in California (USA), Chevron/Cawelo has been managing a water reuse project in which a water supply system utilises treated PW for irrigation of more than 40 fruits, nuts and vegetables. This project supplies approximately 450,000 barrels per day of treated PW. A reserve of treated PW is also maintained by Chevron/Cawelo for the use in the that there is an increased demand (Nijhawan and Myers, 2006). In another example, in Weld County, Colorado (USA), PW is reused for agricultural irrigation following the application of appropriate treatment trains, including pre-treatment, considering the feed quality and the desired effluent quality (Cole et al., 2022). Despite these successes, using PW for irrigation may not be suitable in all cases due to the high ratio of irrigation water volume to PW volume. Also, the operational demand for water by oil and gas companies often exceeds available PW volumes and thus eliminates the use of PW for irrigation (Scanlon et al., 2020).

In Wellington, Colorado (USA), partially treated PW is provided the domestic sector for consumption (Alzahrani and Wahab, 2014). The San Ardo oil field in California (USA) treats

PW for beneficial reuse through surface discharge to the aquifer for recharging purposes (Webb et al., 2009).

New Mexico has changed its rules and regulations to prohibit landowners from using any other water source for hydraulic fracturing operations when PW is available (Scanlon et al., 2020). Pemex, the Mexican petroleum company, has established a wastewater treatment system the main goal of producing treated water that can be used within the plant, primarily for cooling tower operations. This system has achieved a recovery rate of 90% (Carbonate and Formation, 2005).

In Qatar, a minimal amount of treatment has been anticipated for enabling the reuse of PW in microalgae production and the microalgae play a role in removing certain metals from PW (AlGhouti et al., 2019). While in China, Sinopec Yanshan refinery has established a process for reusing PW as boiler feedwater in the refinery's operations (Wang, Tong and Aerts, 2011).
These examples demonstrate the possibilities associated with the treatment and reuse of PW. Given that reuse of treated PW could result in zero liquid discharge or at least a significant reduction in the amount of discarded PW, which would reduce pollution and increase environmental sustainability, it seems applicable to treat and reuse PW outside oil and gas industry (Jiménez et al., 2018).

7.4. PW reuse risk assessment

In the oil and gas industry, the concept RA has evolved since the 1960s with uncertain and limited data. In the early days, RA was primarily performed through effective safety management practices. It was not until the 1970s and 1990s that risk analysis became used for a method of supporting regulatory decisions, and safety management systems were established (Torres, Yadav and Khan, 2016).

Risk assessment is the process of identifying potential risks, based on quantitative estimations and qualitative expressions (Fjeld, Eisenberg and Compton, 2007). A risk is associated with the probability of exposure to a hazardous event and its consequences, and it is a combination of possible consequences and associated uncertainties. The process of managing risk involves establishing a risk model, assigning probabilities of events, identifying and assessing factors that influence risk and calculating specific probabilities. Through the use of well-developed and structured RA frameworks, decision-makers can obtain information regarding probable responses to hazards, which is in turn guides the identification, analysis, and evaluation of hazards, as well as the resulting risk (Müller, Avellán and Schanze, 2020). In addition, the potential risks are characterised and their magnitude (Guglielmi et al., 2015).

As part of this section, risks associated with the three PW reuse outcomes that are outlined in chapter 3, section 3.2, Figure 10 for detailed diagram of the superstructure of KOC's PW supply chain. The three PW reuse outcomes in the research's supply chain superstructure are 1) water injection, 2) water disposal and 3) water reuse. Various risks may arise during each PW reuse process. Therefore, an RA that involve the following two main tasks is conducted: (i) risk analysis (category, description, cause and consequences); and (ii) risk evaluation (likelihood, severity and score).

As shown in Table 8, 9 and 10 RA that illustrates the impact and challenges associated with using the three options of utilising PW involving water disposal, water injection and water reuse are presented. The matrix can be used to evaluate the risk associated with each PW outcome and to determine the level of impact by calculating the severity and likelihood score of each risk . This analysis builds on a previous study that focused on reuse of PW.

Developing a risk assessment matrix for the reuse of PW begins with the identification of the objective of the matrix, which is to determine the risks associated with recycling PW. According to the related literature review, the associated risk factors for PW recycling include corrosion of equipment, high costs, land damage, radioactive elements, leaks in casings, plugging of oil formations, earthquakes, contamination of groundwater, cooling water, hydraulic fracturing, and difficulty irrigation. Risk analysis of an evaluation of the likelihood and impact is shown in Table 10, 11 and 12. The following Tables 10, 11 and 11 outline the possible risks associated with PW recycling options, including the disposal of water, the injection of water and the reuse of water in same order.

Table 10. Possible risks associated with water disposal of produced water (PW).

Water disposal				
Risk Category	**Technical risk**	**Economic risk**	**Environment risk**	**Health risk**
Risks	Equipment corrosion and scaling.	High cost.	Land damage.	Radioactive elements.
Cause	Formation water with a high level of pyrite, fes2, can oxidize forming acidic conditions, which can be corrosive to equipment.	Disposal is difficult for regulatory or geological reasons.	Disposal to land#.	Dissolved in high concentrations from long periods of water-rock contact and also, from disposing massive amount of PW.
Consequences	Risk of contamination of underground drinking water sources.	PW must be treated and trucked for hundreds of miles at prohibitive costs.	Soil damage and pollution of watercourses or underground shallow aquifers is possible.	Potential accumulation in facility equipment. Also, effect human health due to exposure. And cause high and chronic doses, vomiting, depression, loss of muscle coordination and psychoses.
Likelihood	3	5	5	4
Severity	4	2	5	3
Score	🟥 12	10	🟥 25	🟥 12
Reference	(Liden *et al.*, 2018)	(Dores *et al.*, 2012)	(Allen and Robinson, 1993)	(Christie, 2012), (Torres, Yadav and Khan, 2016)

Table 11. Risks associated with water injection of produced water (PW).

Water injection				
Risk Category	**Technical risk**	**Technical risk**	**Environment risk**	**Environment risk**
Risks	Leaking in casings.	Oil Formation plugging.	Earthquakes cause well casing failure.	Groundwater contamination
Cause	Failure in the assessment of well internal and external integrity, failure in selection of impermeable layer and the absence of open faults or fractures surrounding the selected formation.	The number of plugging increases with time.	Performing injection operations on a regular basis and under high pressure. The slippage of fluids along critically stressed faults due to the release of stored elastic stress.	Pipeline spills and/or leaks.
Consequences	Affect formation permeability if the recycled PW is reinjected to the subsurface for HF.	Risk of hampering or stopping production.	Land effect and well condition effect, being critically stressed means that existing shear forces overcome natural friction.	High concentrations of different contaminants.
Likelihood	2	4	1	3
Severity	4	3	5	4
Score	8	12	5	12
Reference	(Hernández, 2021)	(Dores et al., 2012)	(Torres, Yadav and Khan, 2016)	(Torres, Yadav and Khan, 2016)

Table 12. Risks associated with water reuse of produced water (PW).

Water reuse				
Risk Category	**Technical risk**	**Technical risk**	**Environment risk**	**Health risk**
Risks	Cooling water for industrial processes	Hydraulic fracturing misusing	Difficult irrigation	Affect the health of livestock.
Cause	Complex logistical considerations and storing, water aviliability, and treatment method	Wrong practice for detecting, managing and overall minimising leaks along water management systems, as well as costly effective treatment technologies limit the compatible water compositions to minimise risks to operations.	Increase salinity, specific ion toxicity, and alkalinity which are magnified because of the lower produced water quality- higher SAR values than the standard values for irrigation use	PW treatment is inappropriate.
Consequences	Delay in operational process, impact equipment with the potential for corrosion and scale deposition	Less flow rate for fracturing which lead to delay in drilling operations, decrease pressure drop around the well and eventually increase sand production.	Very crucial to consider the crop type when using produced water for irrigation - NOT usable for irrigation.	Risk health and cause diarrhea.
Likelihood	5	5	2	1
Severity	3	5	3	2
Score	15	25	6	2
Reference	(Chard and Saunders, 2019)	(Wu et al., 2021)	(Echchelh, Hess and Sakrabani, 2018, Al-Ghouti et al., 2019)	(Al-Ghouti et al., 2019)

The risks associated in Tables 8, 9 and 10 can be prioritised based on every value of the impact assessments and controlled based on the defined negative consequences. For example, risk related to PW disposal shown in Table 8. According to Figure 5 in section 1.5.4 related to risk assessment methodology, the results that have the highest risk indices identified from different literature review are determined by the following three different reuse: risk of land damage (score = 25), risk of groundwater contamination (score= 12), and risk of Hydraulic fracturing misusing (score = 25). The lowest risk score is represented is the Affect the health of livestock (score = 2), followed by the risk of earthquakes cause well casing failure (score = 5) and the risk of high cost (score = 10). As land damage , radioactive elements, oil formation plugging, groundwater contamination, cooling water for industrial processes, hydraulic fracturing misusing have the highest risk impact, it should be carefully controlled, managed and mitigated in order to prevent its occurrence within the organisation.

While preparing this RA matrix, many challenges were faced including lack of data and information on PW reuse activities and their economic and human health effects. PW risks and uncertainties are easier to manage when identified. According to the analysis results, each type of PW reuse outcome involves several types of risks that can negatively impact health, technology, the environment and the economy. PW management can be improved by applying proper handling techniques, reducing transportation, and increasing inspection of storage tanks, pits/impoundments, and pipes. Finally, zero discharge wastewater techniques minimise the risk associated with improper treatment followed by stream discharge.

Chapter 8

8. Conclusion, recommendation and future work

Worldwide, PW is one of the largest waste streams in the oil and gas industry. PW management creates considerable economic and environmental challenges for the industry. Therefore, a sustainable, environmentally friendly, and cost-effective PW management methods are sought.

This research addressed a range of key objectives within the realm of PW management systems in the oil and gas industry. Through a comprehensive review of the existing literature, the study has explored the many factors related to PW capacity, storage, treatment, and recycling options. Moreover, a review of the global regulatory has been presented, shedding light on the profound impact of PW reuse.

This research yields a PW management system through a mathematical optimisation model for the optimal operations of PW supply chain networks in KOC. In this research a multi-objective optimisation problem of PW supply chain management is presented. The model considers the economic and environmental objectives associated with PW supply chain networks. The multi-objective optimisation model provides KOC with the tools to explore various strategies and find the most appropriate balance between economic and environmental objectives at each stage.

Using a real case study, presentation of comparable results of operational costs, treatment costs, and transportation costs as well as environmental impact results for PW management are facilitated to assess and guide managerial decisions. Along with that, short term, medium-term, and long-term plans for KOC’s PW management systems is tested to provide better solutions to the problems associated with PW supply chain management. Furthermore, this research has explored the determinants that contribute to the effectiveness of PW management systems. By identifying these determinants, the research offers guidance on how to establish robust controls to manage PW-related challenges in the oil and gas sector. Additionally, the exploration of PW recycling options and their associated risks has provided a comprehensive understanding of potential pathways towards sustainable and responsible PW utilisation.

According to the analysis of the modelling results, the most expensive component of KOC's PW supply chain is the PW treatment cost, which includes chemical additives and filtration costs. The second most expensive component in KOC's PW supply chain model is the cost of PW injection and disposal operations. As for the components contributing to PW's lower supply chain costs, pipelines and maintenance expenses are the major contributors.

Electricity prices have the least economic influence on KOC's PW management system, even though electricity consumption emissions have the greatest impact on the environment in KOC PW supply chain. In contrast to the factor most likely to have an environmental impact on PW supply chain, chemical additives are the least likely to have such an environmental impact.

The results of this study demonstrate the significance of air pollutants in relation to the financial costs of PW management, and therefore should be considered in the decision-making process related to the management of PW in KOC. Research findings also demonstrate that further investment in treatment and improved electricity use within the treatment facility may result in lower electricity-associated emissions. In addition, the results suggest that among other factors, the costs associated with PW treatment, pipelines and disposal are central to determining the total cost of PW control.

To reduce KOC's PW supply chain model uncertainties and assess the effects of different parameters used on the model's output, the proposed model is tested across four major parameters: i) discount rate, ii) cost of treatment, iii) cost of electricity and iv) water supply capacity. In this research, the sensitivity of the model's parameters is investigated using the GSA method. GSA in this study enhance the accuracy of the system, reduce uncertainty in the estimation of values and increase understanding of the system.

The GSA results provide an indication of the degree to which the specified parameters contribute to the PW supply chain system. All the investigated parameters significantly influence the PW supply chain system, except for water supply capacity. While water capacity may affect the design of a PW supply chain system, However, it may not have a significant impact on the PW supply chain cost and environment. Other parameters tested such as discount rate, treatment and electricity costs play significant roles in affecting the overall PW supply chain system.

A negative correlation also exists between discount rates and cost and environmental impacts, while electricity prices and water treatment costs are positively correlate with cost and environmental impacts within the PW management system. Various interactions occur among the dependent parameters, specifically, interactions exist between the electricity cost and discount rate, as well as between the treatment cost and discount rate, leading to an inverse relationship with the total cost.

the GSA findings provide a nuanced understanding of how various parameters affect KOC's PW supply chain system. While some parameters exhibit straightforward relationships with cost and environmental impact, others engage in complex interactions. This knowledge equips KOC with the tools needed to develop holistic, sustainable, and economically viable PW management strategies that align with their long-term objectives and regulatory compliance.

With respect to PW reuse, the utilisation of PW poses many challenges due to the immense volume of PW discharged. Hence, on the basis of this research model and analysis results, a thorough review of risk assessments is conducted. A major concern for the oil and gas industry is the possibility of environmental impact associated with PW reuse. In addition, there are other challenges related to the reuse of PW, including the development of effective and economically viable methods for its transport, storage and treatment.

Oil and gas sectors could create an important water source by increasing the reuse of PW generated in the oil and gas industry. It could also provide a viable alternative to disposal in underground injection wells. For this reason, it is essential that the methods used for managing PW meet the specifications for the targeted reuse scenarios, and this requires a thorough understanding of the nature and complex composition of PW. Hence, it is becoming increasingly important to explore different techniques for minimising the pollutants present in PW management so that they are suitably treated before discharge or reuse. In other words, the treatment type and level must be appropriate for generating the treated PW for the intended type of reuse.

With PW discharge and reuse regulations becoming increasingly stricter, it is necessary to apply innovative treatment technologies for PW treatment to meet both the regulatory criteria and the needs of various water applications. Environmental regulations generally prohibit the disposal of PW into onshore surface water unless it has been treated and is intended for injection into a well for disposal or production purposes. The regulatory standards governing PW vary from country to country, and failure to comply with regulations can result in serious consequences for both organisations and the environment.

Although it may seem intuitive that PW can be reused, the decision about whether it should be reused or discharged depends on a range of factors— such as regulations, technical, economics, health and environmental concerns—that affect decision-making. The common risks of PW reuse outcomes are mostly related to the risk of PW spills and an inadequate water treatment. Such risks can be avoided with proper handling and management techniques. PW management can be improved by applying proper handling techniques, reducing transportation, and increasing inspection of operations.

Solutions to PW pinch problems represent important technical challenges that are only practically solved by the industry. The results presented here are an example of how real applications can be resolved with multidisciplinary methods.

In the future, study for other uncertainties could also be factored into the same optimisation model established, such as exchange rates, pipeline costs and well locations. Besides, and based on the GSA framework of this study, future studies should consider the sensitivity of the different parameters including the pipeline material, pipeline length, salinity and electricity consumption level under different conditions.

Moreover, to perform a more detailed risk assessment, future studies require more significant data on PW utilisation. Utilising PW is a complicated process and there several associated uncertainties, such knowledge of the appropriate treatment level, the quality of the resultant water, operational sufficiency and environmental readiness. However, the existing sources of data are limited and the data that are available are mainly related to the treatment of PW.

Moving forward, when an oil and gas company is determining whether its PW should be treated and reused, its leadership team will need to weigh the risk of litigation and regulatory enforcement actions against the benefits of adding PW treatment protocols to its routine operations. Moreover, it is recommended to adopt the zero PW discharge concept, thereby eliminating any extra generation of contaminants and thereby minimising PW generation.
Generally, the oil and gas industries face a significant knowledge gap in terms of PW quality and management, a lack of appropriate regulations, suitable standards and economic factors that delay the beneficial reuse of this asset.

In this research, a significant variation in the financial and environmental impacts under different objective functions is observed, suggesting the need for collaboration between policy makers and operators in KOC when considering the regulation of the PW produced. The proposed model represents the first quantitative platform for assessing the trade-offs between the financial and environmental impacts of PW extracted from the Kuwaiti oil field. This research is designed to develop a realistic base model that could be expanded to a larger-scale investigation of other oil fields.

In summary, this research has significantly contributed to the understanding of PW management systems in the oil and gas industry. By addressing these diverse objectives, the study has offered a holistic view of the complexities, regulations, optimisation potential, and risk considerations surrounding PW management. The insights garnered from this research have the potential to inform both industry practices and policymaking, ultimately leading towards more environmentally responsible and economically viable approaches to PW management. Thus, the novel information generated in this research can be used to improve decision-making, planning and prioritisation in sustainable PW management within KOC. Besides, increase the company's profits in managing supply chain.

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APPENDICES

Appendix One – Life cycle assessment (LCA)- Different studies related to wastewater.

1. Introduction

LCA provides producers, consumers, policymakers and/or legislative authorities with a quantification of the environmental profile of a waste management system. These stakeholders can then use the information contained in the LCA to further broaden the practical applications, reduce the environmental insecurity, and eliminate the human health risks associated with the system (Sulistyawanti, Iswara and Boedisantoso, 2020).

The methodological framework adopted by both Society of Environmental Toxicology and Chemistry (SETAC) and ISO (14040), includes the following four main stages:

1. Goal and scope definition.
2. Inventory analysis (life cycle inventory LCI).
3. Impact assessment (life cycle impact assessment LCIA).
4. Improvement assessment interpretation.

The majority of LCA studies concerning wastewater have discussed different conventional treatment methods (Emmerson *et al.*, 1995) and different LCAs have compared several wastewater management systems (Dennison *et al.*, 1998; Mels *et al.*, 1999).

While some LCAs have been conducted to manage PW generated by the oil and gas industry, there is a need for a more comprehensive and systematic framework to improve the environmental performance of PW management through LCA implementation. (Vlasopoulos *et al.*, 2006). Therefore, an LCA of the treatment of PW inside KOC's treatment facility is conducted using information on chemical additives and electricity consumption. It should be noted, however, that the results of this analysis may be compromised by the use of average, outdated or inaccurate data.

The works in the current literature that describe how these elements have been addressed in LCAs of PW treatment are listed and discussed in the following sections.

2. Goal and scope

The most important phase of an LCA is the goal phase. This specifies the audience and includes the reason and need for the study. The scoping phase is usually performed to describe the system, its boundaries, the main hypothesis and the limitations (Tabesh *et al.*, 2019). Table 11 shows the different goal statements of PW LCA.

Table 13. The different goal statements of selected produced water (PW) life cycle assessment (LCA).

Literature	Goal	Country
N. Vlasopoulos et al., 2006	To investigate the environmental impact of 20 technologies suitable for PW treatment during the oil and gas extraction processes.	-
Jiang, Hendrickson and Vanbriesen, 2014	To estimate the life cycle water consumption and wastewater generation impacts gas well from its construction to end of life.	USA
S Sulistyawanti, 2020	To identify the environmental impacts that occur during the process of taking and producing oil	Indonesia
Muñoz et al., 2020	To determine whether or not the implementation of wastewater reclamation	Turkey
Wang et al., 2018	To evaluate the primary trade-offs, including the cotreatment process environmental, transportation impacts, and environmental benefits.	USA
El-Houjeiri, Brandt and Duffy, 2013	To analyse the gas emissions mitigation options by producers and to model the emissions from oil and gas production operations.	USA
Clark, Horner and Harto, 2013	To estimate the water consumed over the life cycle of conventional gas production, accounting for production and for flowback water reuse.	USA
Dale et al., (2013)	To perform an LCA in three oil and gas areas including greenhouse gas (GHG) emissions, energy consumption, and water consumption.	USA
Wilkins, Menefee and Clarens, (2016)	To perform an LCA of the using of either water or CO_2 for gas production.	USA
Mallapragada et al., (2018)	To estimate the life cycle of GHG emissions and of life cycle freshwater consumption.	USA
Piemonte et al., (2017)	To generate an LCA to highlight the importance of treating PW.	-

3. The functional unit and system boundaries

The term ‘Functional unit’ (FU) is used to definer the product being analysed in an LCA. The definition of FU for a product allows comparison of the environmental and other impact of different products (Laurenzi and Jersey, 2013). According to Dwyer and Mcdonald (2016), most studies conducted on wastewater management use and FU based on volume, such as m^3 or ML. Yet, using a volume of water as the FU can be deceptive because it does not reflect the water quality or treatment efficiency.

In many studies, the system boundaries of assessed wastewater treatment plants cover the complete wastewater system, including freshwater withdrawal, water production, distribution and use of water, generation of wastewater and transport to the wastewater treatment plant (Dwyer and Mcdonald, 2016). The different FUs and system boundaries included in selected LCAs related to wastewater management are shown in Table 12.

Table 14. The different functional units (FUs) and scopes (or system boundaries) of selected life cycle assessments (LCAs).

Literature	Functional unit	Scope/System boundary
N. Vlasopoulos et al., 2006	10,000 m^3/day for 15 years.	Combined stages technologies.
Jiang, Hendrickson and Vanbriesen, 2014	1 well of gas.	Well pad preparation, well drilling, hydraulic fracturing, well completion, gas production, gas processing, gas transmission and well closure.
S Sulistyawanti, 2020	Oil extraction: ESP skw 25 Oil processing: separator PV-99000 (gas).	2 separator units, 1 unit of column stripper, 1 unit of degassing boot, 1 unit of flares and 5 units of generator.
Muñoz et al., 2020	1m^3, with specific composition.	Refinery wastewater from the different separators, boiler feedwater, cooling water and fire water
Wang et al., 2018	1 m^3 treated water.	Produced water (PW) storage, rapid mixing of PW, flocculation, sedimentation, and sludge dewatering. The expanded system boundary included the transportation of PW to the cotreatment site.
El-Houjeiri, Brandt and Duffy, 2013	1 MJ of crude petroleum	Exploration, drilling, production and extraction, maintenance, waste disposal and crude transport.

Clark, Horner and Harto, 2013	Litres (L) of water per gigajoule (GJ) of gas, Litres of water per Litres of gasoline equivalent, and Litres of water per kilowatt hour (kWh)	Establishment of well infrastructure, fuel recovery, fuel processing, fuel use and transportation and distribution of fuels.
Dale et al., (2013)	-	Pad construction and drilling, fracturing and completions, production, and processing.
Wilkins, Menefee and Clarens, (2016)	Energy 1 GJ of natural gas	Marcellus Shale formation (transportation, storage, fracturing, flowback, and production).
Mallapragada et al., (2018)	1MWh of power generated at the power plant	Well pad to generation of electricity at a combined cycle gas turbine power plant, added operations associated with natural gas liquefaction, shipping, regasification, and gas pipeline transportation.
Piemonte et al., (2017)	3500 m^3-PW	From PW extraction to the final water treatment.

Note: '-' indicates that the data are not available.

5. Life cycle impact assessment (LCIA)

LCIA is used to analyse the impact of a product/process on the environment and human health. The LCIA is a consequence of the inventory analysis (Sulistyawanti, Iswara and Boedisantoso, 2020). 2). Table 14 shows some of the LCIA methods and impact categories discussed in various studies on wastewater LCAs.

Table 15. Life cycle impact assessment (LCIA) methods and categories used in selected life cycle assessment (LCA) studies.

Literature	LCIA method	Impact categories
N. Vlasopoulos et al., 2006	CML 2 baseline 2000 v2.1	Climate change/global warming, depletion of abiotic resources, acidification, eutrophication and photo-oxidant formation.
Jiang, Hendrickson and Vanbriesen, 2014	TRACI	Eutrophication potential freshwater ecotoxicity potential, carcinogenic potential, and noncarcinogenic potential.
S Sulistyawanti, 2020	Eco Indicator 99	Climate change, ozone layer depletion, respiratory inorganic effects, respiratory organic effects, fossil fuels, and land use.
Muñoz et al., 2020	CML-IA	Global warming, fine particulate matter pollution, aquatic eutrophication and marine ecotoxicity.
Wang et al., 2018	TRACI based on US impact data	Ozone depletion, global warming, smog, acidification, eutrophication, carcinogenic, noncarcinogenic, respiratory effects and fossil fuel depletion.
El-Houjeiri, Brandt and Duffy, 2013	bottom -up	GHG emissions from crude oil production
Dale et al., (2013)	TRACI based on 100year values	GHG emissions, energy consumption and water consumption. GHG emissions from Electricity Generation.
Wilkins, Menefee and Clarens, (2016)	Eco invent	Energy use, GHG emissions, and water consumption.
Mallapragada et al., (2018)	bottom-up process	GHG emissions, freshwater consumption and gas composition.
Piemonte *et al.*, (2017)	Gabi 6	Global warming potential, acidification potential, freshwater ecotoxicity, eutrophication potential, ecotoxicity and human health and quantifying the effect of emissions derived from the ecosystem and human exposure.

Appendix Two – Case study supporting documents.

Table 16. Effluent water disposal plant (EWDP-I) electricity consumption per day.

Facilities	**EWDP-I**	**EWDP-II**
Month	**Kwh**	**Kwh**
January	4,109,419	5,592,446
February	3,348,770	6,513,178
March	3,934,893	4,945,549
April	3,763,380	5,845,996
May	3,289,945	7,487,070
Total	18,446,407	30,384,238
Average	**3,689,281**	**6,076,848**
Minimum	**3,289,945**	**4,945,549**
Maximum	**4,109,419**	**7,487,070**

(Source: KOC report)

Table 17. Table 16. Produced water consumption inside Effluent water disposal plant (EWDP-I) for April and May 2021.)

Date	**Effluent Water (BBLS)**	**Effluent Water (m^3)**
01-APR-2021	161,076	25,609
02-APR-2021	144,368	22,953
03-APR-2021	157,597	25,056
04-APR-2021	159,730	25,395
05-APR-2021	160,081	25,451
06-APR-2021	160,665	25,544
07-APR-2021	167,550	26,638
08-APR-2021	172,033	27,351
09-APR-2021	158,252	25,160
10-APR-2021	177,137	28,163

11-APR-2021	146,242	23,251
12-APR-2021	147,553	23,459
13-APR-2021	161,126	25,617
14-APR-2021	166,464	26,466
15-APR-2021	163,963	26,068
16-APR-2021	143,955	22,887
17-APR-2021	143,118	22,754
18-APR-2021	141,273	22,461
19-APR-2021	150,397	23,911
20-APR-2021	155,066	24,654
21-APR-2021	110,734	17,605
22-APR-2021	147,463	23,445
23-APR-2021	148,920	23,676
24-APR-2021	154,409	24,549
25-APR-2021	144,225	22,930
26-APR-2021	143,797	22,862
27-APR-2021	148,905	23,674
28-APR-2021	142,270	22,619
29-APR-2021	138,720	22,055
30-APR-2021	150,016	23,851
01-MAY-2021	151,281	24,052
02-MAY-2021	148,710	23,643
03-MAY-2021	151,415	24,073
04-MAY-2021	144,068	22,905
05-MAY-2021	144,068	22,905
06-MAY-2021	158,943	25,270
07-MAY-2021	147,804	23,499
08-MAY-2021	164,759	26,195

09-MAY-2021	166,806	26,520
10-MAY-2021	161,971	25,751
11-MAY-2021	166,806	26,520
12-MAY-2021	147,301	23,419
13-MAY-2021	148,060	23,540
14-MAY-2021	160,681	25,546
15-MAY-2021	160,681	25,546
16-MAY-2021	160,661	25,543
17-MAY-2021	159,724	25,394
18-MAY-2021	161,000	25,597
19-MAY-2021	162,975	25,911
20-MAY-2021	156,937	24,951
21-MAY-2021	166,574	26,483
22-MAY-2021	159,642	25,381
23-MAY-2021	164,208	26,107
24-MAY-2021	174,978	27,819
25-MAY-2021	169,021	26,872
26-MAY-2021	168,001	26,710
27-MAY-2021	165,189	26,263
28-MAY-2021	147,427	23,439
29-MAY-2021	149,710	23,802
30-MAY-2021	143,759	22,856
31-MAY-2021	139,552	22,187
Total	**9,439,817**	**1,500,812**
Average	**154,751**	**24,603**
Minimum	**110,734**	**17,605**
Maximum	**177,137**	**28,163**

(Source: KOC report)

Table 18. The cost associated with the transportation and the operational processes.

Type of cost	Element description	Value (KWD)	Reference
Transportaion	a. Carbon steel pipeline: from gc1 and gc 2 with distance 4km and 9 km b. Plastic pipeline: from *wp* to reinjection and disposal wells with distance 5km and 9 km c. Truck: from *wp* to reuse location with 15 km distance	a. 122,000/km b. 80,000/km c. 150/km	(KOC, 2018)
Operational	a. Water treatment b. Facility maintenance c. Facility operations d. Electricity e. Disposal operations f. Reinjection operations	a. 0.183/m^3 b. 0.02/m^3 c. 0.313/m^3 d. 0.010/m^3 e. 1.750/m^3 f. 0.075/m^3	a. (Elaila *et al.*, 2017) b. (KOC, 2018) c. (Elaila *et al.*, 2017) d. (Al-Abdullah *et al.*, 2019) e. (Karapataki, 2012) f. (Elaila *et al.*, 2017)

Table 18. The values of the MILP model parameters

Parameters	Values	Descriptions	Reference
oc	80,000,000	The capacity of treated water at treatment facility WP.	(KOC,2018)
ou	5,000,000	The demand of treated water at treatment facility WP.	(KOC,2018)
oi	2,500,000	The capacity of treated water at filter locations.	(KOC,2018)
oe	1,500,000	The demand of treated water at filter locations.	(KOC,2018)
ok	40,236	The capacity of treated water at tank locations.	(KOC,2018)
ow	20,000	The demand of treated water at tank locations.	(KOC,2018)
cwd(j)	j1: 17,500,000; j2: 15,750,000; j3: 1,750,000	The capacity of treated at j location.	(Bartholomew and Mauter, 2016)
dwd(j)	j1: 3,500,000 ; j2: 3,150,000; j3: 15,600	The demand of treated water at j location.	(Bartholomew and Mauter, 2016)
fcpg(g)	g1: 19,900,000; g2: 19,900,000	The capacity of pipeline from gathering centre gc1 and gc2 to treatment plant.	(KOC,2018)
fcpt(j)	j1: 19,900,000; j2: 19,900,000	The capacity of truck per unit m3 from treatment facility wp to j3 location.	(KOC,2018)
fcpw(j)	j3: 150,000	The capacity of pipeline per unit m3 from treatment facility to j1 and j2 locations.	(KOC,2018)
ec	22,542,455	The amount of electricity produced in kwh/m3.	(KOC,2018)
dg(g)	g1: 4; g2: 9	Distance from g to wp location in km.	(KOC,2018)

dp(j)	j1: 5; j2: 10	Distance for pipeline from wp to j locations in km.	(KOC,2018)
dt(j)	j3: 20	Distance for trucks from wp to j location in km.	(KOC,2018)
dr	0.015	Discount rate per time period.	(Central Bank of Kuwait, 2020)
icy(g)	g1: 150,000; g2: 150,000	The pipe capital cost coefficient per unit km between g and wp facility.	(KOC,2018)
icg(g)	g1: .0038; g2: .0038	Unit variable transportation cost for pipeline transporting pumped treated PW	(Elaila et al., 2017)
icp(j)	j1: 150,000; j2:150,000	The pipe capital cost coefficient per unit km between wp and j locations.	(KOC,2018)
icd(j)	j1: .0038; j2: .0038	Unit variable transportation cost for pipeline transporting pumped treated PW	(Elaila et al., 2017)
ict(j)	j3 50	The truck capital cost coefficient per unit km between wp and j location.	(KOC,2018)
icc(j)	j3 .063	Unit variable transportation cost for truck transporting treated PW.	(Elaila et al., 2017)
f(h)	1: .0027; 2: .0027; 3: .0027; 4: .0027	The unit price chemical treatment per m3 for treatment type h.	(Elaila et al., 2017)
c(i)	1: 2.4; 2:2.4; 3: 2.4	Central treatment cost coefficient per m3.	(Elaila et al., 2017)
er	0.3	Central maintenance cost coefficient per m3.	(Al-Abdullah et al., 2019)

d	0.04	The unit price of electricity produced in wp per Kwh.	(Karapataki, 2012)
id(j)	j2: 1.75	Disposal cost coefficient per m3.	(Karapataki, 2012)
ij(j)	j1: .075	Injection cost coefficient per m3.	(Elaila et al., 2017)
ea(h)	1: 2.9; 2: 10.46; 3: 4.36 ; 4: 11.72	The air emissions coefficients associated with treatment by chemicals.	LCA
ee(i)	1: 1; 2: 3.88; 3: 1	The air emissions coefficients associated with electricity. consumption inside wp.	LCA

Appendix Three – model's general output

Table 19. The cost associated with the transportation and the operational processes.

ET	5,922,739	5,922,739	5,922,739	5,922,739	5,922,739	4,313,572	3,678,567
EU	54,190,326	54,190,326	54,190,326	54,190,326	54,190,326	54,739,936	54,975,483
TOE	323,574	323,574	323,574	323,574	323,574	323,574	323,574
TWS	26,759,795	26,759,795	26,759,795	26,759,795	26,759,795	26,759,795	26,759,795
TWN	1,274,276	1,274,276	1,274,276	1,274,276	1,274,276	1,274,276	1,274,276
TWD	1,294,295	1,294,295	1,294,295	1,294,295	1,294,295	1,294,295	1,294,295
TWF	2,109	2,109	2,109	2,109	2,109	1,741	1,579
TWC	37,259,801	37,259,801	37,259,801	37,259,801	37,259,801	37,421,049	37,491,631
TCJ	95,418	95,418	95,418	95,418	95,418	95,418	95,418
TCP	903,886	903,886	903,886	903,886	903,886	903,886	903,886
TCG	1,468,354	2,760,436	3,421,049	4,772,151	4,772,151	4,772,151	4,772,151
Total Env.	6.01E+07	6.01E+07	6.01E+07	6.01E+07	6.01E+07	5.91E+07	5.87E+07
Total cost	6.94E+07	7.07E+07	7.13E+07	7.27E+07	7.27E+07	7.28E+07	7.29E+07
TEE	0.2038	0.2038	0.2038	0.2038	0.2038	0.2002	0.1988
TCE	0.2168	0.2209	0.2229	0.2271	0.2271	0.2276	0.2278
5 yrs	1	0.97	0.95	0.92	0.89	0.862	0.5

3,237,422	3,237,422	3,237,422	**ET**	11,845,478	11,845,478	11,845,478	11,845,478	11,371,147
55,368,062	55,368,062	55,368,062	**EU**	122,713,610	108,380,650	108,380,650	108,380,650	108,537,680
323,574	323,574	323,574	**TOE**	623,935	623,935	623,935	623,935	623,935
26,759,795	26,759,795	26,759,795	**TWS**	51,599,852	51,599,852	51,599,852	51,599,852	51,599,852
1,274,276	1,274,276	1,274,276	**TWN**	2,457,136	2,457,136	2,457,136	2,457,136	2,457,136
1,294,295	1,294,295	1,294,295	**TWD**	2,495,739	2,495,739	2,495,739	2,495,739	2,495,739
1,314	1,314	1,314	**TWF**	4,068	4,068	4,068	4,068	3,971
37,607,547	37,607,547	37,607,547	**TWC**	71,846,595	71,846,595	71,846,595	71,846,595	71,888,676
95,418	95,418	100,418	**TCJ**	183,990	183,990	183,990	183,990	183,990
903,886	903,886	12,153,886	**TCP**	1,742,928	1,742,928	1,742,928	1,742,928	1,742,928
4,772,151	4,772,151	14,522,151	**TCG**	5,898,153	9,201,950	7,850,848	9,201,950	9,201,950
5.86E+07	5.86E+07	58,605,484	**Total Env.**	134,559,080	15	120,226,130	120,226,130	119,908,830
7.30E+07	7.30E+07	94,037,257	**Total cost**	136,852,400	14	138,805,090	140,156,190	140,198,180
0.1987	0.1987	0.1987	**TEE**	0.4561	0.4075	0.4075	0.4075	0.4065
0.2282	0.2282	0.2939	**TCE**	0.4277	0.4317	0.4338	0.438	0.4381
0.3	0.2	0	**10 yrs**	1	0.97	0.95	0.92	0.89

7,992,139	7,357,134	6,474,844	6,474,844	6,474,844	**ET**	23,690,957	23,690,957	23,690,957
109,715,420	109,950,970	110,736,120	110,736,120	110,736,120	**EU**	259,760,170	216,761,310	216,761,310
623,935	623,935	623,935	623,935	623,935	**TOE**	1,161,559	1,161,559	1,161,559
51,599,852	51,599,852	51,599,852	51,599,852	51,599,852	**TWS**	96,061,753	96,061,753	96,061,753
2,457,136	2,457,136	2,457,136	2,457,136	2,457,136	**TWN**	4,574,369	4,574,369	4,574,369
2,495,739	2,495,739	2,495,739	2,495,739	2,495,739	**TWD**	4,646,235	4,646,235	4,646,235
3,206	3,045	2,533	2,533	2,533	**TWF**	7,573	7,573	7,573
72,223,043	72,293,625	72,293,625	72,293,625	72,517,140	**TWC**	133,754,450	133,754,450	133,754,450
183,990	183,990	183,990	183,990	193,990	**TCJ**	342,529	342,529	342,529
1,742,928	1,742,928	1,742,928	1,742,928	24,242,928	**TCP**	3,244,753	3,244,753	3,244,753
9,201,950	9,201,950	9,201,950	9,201,950	28,701,950	**TCG**	13,827,172	17,130,969	15,779,867
117,707,560	117,308,100	117,210,970	117,210,970	117,210,970	**Total Env.**	2.83E+08	29.78	2.40E+08
140,531,780	140,602,200	140,825,200	140,825,200	182,835,200	**Total cost**	257,620,390	26.09	2.60E+08
0.399	0.3977	0.3973	0.3973	0.3973	**TEE**	0.9609	0.8151	0.8151
0.4392	0.4394	0.4401	0.4401	0.57	**TCE**	0.8051	0.8091	0.8112
0.862	0.5	0.3	0.2	0	**20 yrs**	1	0.97	0.95

23,690,957	20,844,966	15,349,273	14,714,267	12,949,688	12,949,688	12,949,688
216,761,310	217,703,490	217,703,490	219,901,930	221,472,250	221,472,250	221,472,250
1,161,559	1,161,559	1,161,559	1,161,559	1,161,559	1,161,559	1,161,559
96,061,753	96,061,753	96,061,753	96,061,753	96,061,753	96,061,753	96,061,753
4,574,369	4,574,369	4,574,369	4,574,369	4,574,369	4,574,369	4,574,369
4,646,235	4,646,235	4,646,235	4,646,235	4,646,235	4,646,235	4,646,235
7,573	7,036	5,830	5,668	4,716	4,716	4,716
133,754,450	133,989,130	134,516,090	134,586,670	135,002,780	135,002,780	135,002,780
342,529	342,529	342,529	342,529	342,529	342,529	362,529
3,244,753	3,244,753	3,244,753	3,244,753	3,244,753	3,244,753	3,244,753
17,130,969	17,130,969	17,130,969	17,130,969	17,130,969	17,130,969	56,130,969
2.40E+08	2.39E+08	2.35E+08	234,616,200	234,421,930	234,421,930	234,421,930
2.61E+08	2.61E+08	261,684,090	261,754,510	262,169,670	262,169,670	301,189,670
0.8151	0.8086	0.7967	0.7953	0.7947	0.7947	0.7947
0.8154	0.8161	0.8178	0.818	0.8193	0.8193	0.9412
0.92	0.89	0.862	0.5	0.3	0.2	0

Appendix Four – Global sensitivity analysis statistical data

Results are shown in table 18. The values seem to be of different units; accordingly, the values have normalized them according to the range of 0 to 1 so that they can be dimensionless as shown in table 19.

Then the values are fitted the input and output parameters using the normalized range of 0 to 1. See "Regression Coefficients" tables 20, 21 and 22.

Then the values are used their absolute value to reveal their influence on the output parameters. The higher the value the more relevant the parameter (variable) is. See "Relevance" Table 28.

Finally, Table 23 represents the R^2for different years period.

Table 20. model's results of the environmental impact and the cost associated with the transportation and the operational processes.

5 yrs	Discount Rate	Electricity cost	Treatment cost	Water capacity	Discount Rate x Electricity	Discount Rate x Treatment	Discount Rate x Water	Electricity cost x	Electricity cost x Water	Treatment cost x Water	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
1	0	0	0	7,500,000	0	0	112,500	0	7,500	750,000	36,299,301	58,654,050	2,760,436	903,886	95,418	3,177,257	1,579	1,294,295	1,274,276	26,759,795	32,357	54,975,483	3,678,567
2	0	0	0	80,000,000	0	0	1,200,000	0	80,000	8,000,000	36,299,301	58,654,050	2,760,436	903,886	95,418	3,177,257	1,579	1,294,295	1,274,276	26,759,795	32,357	54,975,483	3,678,567
3	0	0	2	7,500,000	0	0	112,500	0	7,500	18,000,000	108,905,22	60,113,066	2,760,436	903,886	95,418	75,782,645	2,109	1,294,295	1,274,276	26,759,795	32,357	54,190,326	5,922,739
4	0	0	2	80,000,000	0	0	1,200,000	0	80,000	192,000,00	108,905,22	60,113,066	2,760,436	903,886	95,418	75,782,645	2,109	1,294,295	1,274,276	26,759,795	32,357	54,190,326	5,922,739

3,678,567	3,678,567	5,922,739	5,922,739	3,678,567	3,678,567	5,922,739	5,922,739	3,678,567	3,678,567
54,975,483	54,975,483	54,190,326	54,190,326	54,975,483	54,975,483	54,190,326	54,190,326	54,975,483	54,975,483
9,707,216	9,707,216	9,707,216	9,707,216	28,991	28,991	28,991	28,991	8,697,261	8,697,261
26,759,795	26,759,795	26,759,795	26,759,795	23,975,661	23,975,661	23,975,661	23,975,661	23,975,661	23,975,661
1,274,276	1,274,276	1,274,276	1,274,276	1,141,698	1,141,698	1,141,698	1,141,698	1,141,698	1,141,698
1,294,295	1,294,295	1,294,295	1,294,295	1,159,635	1,159,635	1,159,635	1,159,635	1,159,635	1,159,635
1,579	1,579	2,109	2,109	1,415	1,415	1,890	1,890	1,415	1,415
3,177,257	3,177,257	75,782,645	75,782,645	2,846,690	2,846,690	67,898,091	67,898,091	2,846,690	2,846,690
95,418	95,418	95,418	95,418	85,490	85,490	85,490	85,490	85,490	85,490
903,886	903,886	903,886	903,886	809,845	809,845	809,845	809,845	809,845	809,845
2,760,436	2,760,436	2,760,436	2,760,436	3,595,069	3,595,069	3,595,069	3,595,069	3,595,069	3,595,069
58,654,050	58,654,050	60,113,066	60,113,066	58,654,050	58,654,050	60,113,066	60,113,066	58,654,050	58,654,050
45,974,159	45,974,159	118,580,08	118,580,08	33,644,493	33,644,493	98,696,369	98,696,369	42,312,763	42,312,763
750,000	8,000,000	18,000,000	192,000,00	750,000	8,000,000	18,000,000	192,000,00	750,000	8,000,000
2,250,000	24,000,000	2,250,000	24,000,000	7,500	80,000	7,500	80,000	2,250,000	24,000,000
0	0	1	1	0	0	0	0	0	0
112,500	1,200,000	112,500	1,200,000	562,500	6,000,000	562,500	6,000,000	562,500	6,000,000
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000
0	0	2	2	0	0	2	2	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
5	6	7	8	9	10	11	12	13	14

5,922,739	5,922,739	ET	7,357,134	7,357,134	11,845,478	11,845,478	7,357,134	7,357,134
54,190,326	54,190,326	EU	109,950,97	109,950,97	108,380,65	108,380,65	109,950,97	109,950,97
8,697,261	8,697,261	TOE	62,393	62,393	62,393	62,393	18,718,039	18,718,039
23,975,661	23,975,661	TWS	51,599,852	51,599,852	51,599,852	51,599,852	51,599,852	51,599,852
1,141,698	1,141,698	TWN	2,457,136	2,457,136	2,457,136	2,457,136	2,457,136	2,457,136
1,159,635	1,159,635	TWD	2,495,739	2,495,739	2,495,739	2,495,739	2,495,739	2,495,739
1,890	1,890	TWF	3,045	3,045	4,068	4,068	3,045	3,045
67,898,091	67,898,091	TWC	6,126,578	6,126,578	146,128,67	146,128,67	6,126,578	6,126,578
85,490	85,490	TCJ	183,990	183,990	183,990	183,990	183,990	183,990
809,845	809,845	TCP	1,742,928	1,742,928	1,742,928	1,742,928	1,742,928	1,742,928
3,595,069	3,595,069	TCG	7,190,235	7,190,235	7,190,235	7,190,235	7,190,235	7,190,235
60,113,066	60,113,066	Total Env.	117,308,10	117,308,10	120,226,13	120,226,13	117,308,10	117,308,10
107,364,64	107,364,64	Total cost	71,861,896	71,861,896	211,865,01	211,865,01	90,517,542	90,517,542
18,000,000	192,000,00	Treatment cost x Water	750,000	8,000,000	18,000,000	192,000,00	750,000	8,000,000
2,250,000	24,000,000	Electricity cost x Water	7,500	80,000	7,500	80,000	2,250,000	24,000,000
1	1	Electricity cost x	0	0	0	0	0	0
562,500	6,000,000	Discount Rate x Water	112,500	1,200,000	112,500	1,200,000	112,500	1,200,000
0	0	Discount Rate x Treatment	0	0	0	0	0	0
0	0	Discount Rate x Electricity	0	0	0	0	0	0
7,500,000	80,000,000	Water capacity	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000
2	2	Treatment cost	0	0	2	2	0	0
0	0	Electricity cost	0	0	0	0	0	0
0	0	Discount Rate	0	0	0	0	0	0
15	16	10 yrs	1	2	3	4	5	6

11,845,478	11,845,478	7,357,134	7,357,134	11,845,478	11,845,478	7,357,134	7,357,134	11,845,478	11,845,478
108,380,65	108,380,65	109,950,97	109,950,97	108,380,65	108,380,65	109,950,97	109,950,97	108,380,65	108,380,65
18,718,039	18,718,039	49,185	49,185	49,185	49,185	14,755,413	14,755,413	14,755,413	14,755,413
51,599,852	51,599,852	40,676,115	40,676,115	40,676,115	40,676,115	40,676,115	40,676,115	40,676,115	40,676,115
2,457,136	2,457,136	1,936,958	1,936,958	1,936,958	1,936,958	1,936,958	1,936,958	1,936,958	1,936,958
2,495,739	2,495,739	1,967,388	1,967,388	1,967,388	1,967,388	1,967,388	1,967,388	1,967,388	1,967,388
4,068	4,068	2,400	2,400	3,206	3,206	2,400	2,400	3,206	3,206
146,128,67	146,128,67	4,829,576	4,829,576	115,193,09	115,193,09	4,829,576	4,829,576	115,193,09	115,193,09
183,990	183,990	145,039	145,039	145,039	145,039	145,039	145,039	145,039	145,039
1,742,928	1,742,928	1,373,949	1,373,949	1,373,949	1,373,949	1,373,949	1,373,949	1,373,949	1,373,949
7,190,235	7,190,235	6,573,309	6,573,309	6,573,309	6,573,309	6,573,309	6,573,309	6,573,309	6,573,309
120,226,13	120,226,13	117,308,10	117,308,10	120,226,13	120,226,13	117,308,10	117,308,10	120,226,13	120,226,13
230,520,65	230,520,65	57,553,919	57,553,919	167,918,24	167,918,24	72,260,147	72,260,147	182,624,47	182,624,47
18,000,000	192,000,00	750,000	8,000,000	18,000,000	192,000,00	750,000	8,000,000	18,000,000	192,000,00
2,250,000	24,000,000	7,500	80,000	7,500	80,000	2,250,000	24,000,000	2,250,000	24,000,000
1	1	0	0	0	0	0	0	1	1
112,500	1,200,000	562,500	6,000,000	562,500	6,000,000	562,500	6,000,000	562,500	6,000,000
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000
2	2	0	0	2	2	0	0	2	2
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
7	8	9	10	11	12	13	14	15	16

ET	14,714,267	14,714,267	23,690,957	23,690,957	14,714,267	14,714,267	23,690,957	23,690,957
EU	219,901,93	219,901,93	216,761,31	216,761,31	219,901,93	219,901,93	216,761,31	216,761,31
TOE	116,156	116,156	116,156	116,156	34,846,760	34,846,760	34,846,760	34,846,760
TWS	96,061,753	96,061,753	96,061,753	96,061,753	96,061,753	96,061,753	96,061,753	96,061,753
TWN	4,574,369	4,574,369	4,574,369	4,574,369	4,574,369	4,574,369	4,574,369	4,574,369
TWD	4,646,235	4,646,235	4,646,235	4,646,235	4,646,235	4,646,235	4,646,235	4,646,235
TWF	5,668	5,668	7,573	7,573	5,668	5,668	7,573	7,573
TWC	11,405,650	11,405,650	272,042,95	272,042,95	11,405,650	11,405,650	272,042,95	272,042,95
TCJ	342,529	342,529	342,529	342,529	342,529	342,529	342,529	342,529
TCP	3,244,753	3,244,753	3,244,753	3,244,753	3,244,753	3,244,753	3,244,753	3,244,753
TCG	15,119,254	15,119,254	15,119,254	15,119,254	15,119,254	15,119,254	15,119,254	15,119,254
Total Env.	234,616,20	234,616,20	240,452,26	240,452,26	234,616,20	234,616,20	240,452,26	240,452,26
Total cost	135,516,37	135,516,37	396,155,57	396,155,57	170,246,97	170,246,97	430,886,18	430,886,18
Treatment cost x Water	750,000	8,000,000	18,000,000	192,000,00	750,000	8,000,000	18,000,000	192,000,00
Electricity cost x Water	7,500	80,000	7,500	80,000	2,250,000	24,000,000	2,250,000	24,000,000
Electricity cost x	0	0	0	0	0	0	1	1
Discount Rate x Water	112,500	1,200,000	112,500	1,200,000	112,500	1,200,000	112,500	1,200,000
Discount Rate x Treatment	0	0	0	0	0	0	0	0
Discount Rate x Electricity	0	0	0	0	0	0	0	0
Water capacity	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000
Treatment cost	0	0	2	2	0	0	2	2
Electricity cost	0	0	0	0	0	0	0	0
Discount Rate	0	0	0	0	0	0	0	0
20 yrs	1	2	3	4	5	6	7	8

14,714,267	14,714,267	23,690,957	23,690,957	14,714,267	14,714,267	23,690,957	23,690,957
219,901,93	219,901,93	216,761,31	216,761,31	219,901,93	219,901,93	216,761,31	216,761,31
73,049	73,049	73,049	73,049	21,914,650	21,914,650	21,914,650	21,914,650
60,411,919	60,411,919	60,411,919	60,411,919	60,411,919	60,411,919	60,411,919	60,411,919
2,876,758	2,876,758	2,876,758	2,876,758	2,876,758	2,876,758	2,876,758	2,876,758
2,921,953	2,921,953	2,921,953	2,921,953	2,921,953	2,921,953	2,921,953	2,921,953
3,565	3,565	4,762	4,762	3,565	3,565	4,762	4,762
7,172,857	7,172,857	171,084,08	171,084,08	7,172,857	7,172,857	171,084,08	171,084,08
215,412	215,412	215,412	215,412	215,412	215,412	215,412	215,412
2,040,580	2,040,580	2,040,580	2,040,580	2,040,580	2,040,580	2,040,580	2,040,580
10,092,851	10,092,851	10,092,851	10,092,851	10,092,851	10,092,851	10,092,851	10,092,851
234,616,20	234,616,20	240,452,26	240,452,26	234,616,20	234,616,20	240,452,26	240,452,26
85,808,944	85,808,944	249,721,37	249,721,37	107,650,54	107,650,54	271,562,97	271,562,97
750,000	8,000,000	18,000,000	192,000,00	750,000	8,000,000	18,000,000	192,000,00
7,500	80,000	7,500	80,000	2,250,000	24,000,000	2,250,000	24,000,000
0	0	0	0	0	0	1	1
562,500	6,000,000	562,500	6,000,000	562,500	6,000,000	562,500	6,000,000
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000	7,500,000	80,000,000
0	0	2	2	0	0	2	2
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
9	10	11	12	13	14	15	16

Table 21. The input and output parameters are fitted using a normalized range of 0 to 1.

ET	-	-	1	1	-	-	1	1
EU	1	1	-	-	1	1	-	-
TOE	0	0	0	0	1	1	1	1
TWS	1	1	1	1	1	1	1	1
TWN	1	1	1	1	1	1	1	1
TWD	1	1	1	1	1	1	1	1
TWF	0	0	1	1	0	0	1	1
TWC	0	0	1	1	0	0	1	1
TCJ	1	1	1	1	1	1	1	1
TCP	1	1	1	1	1	1	1	1
TCG	-	-	-	-	-	-	-	-
Total Env.	-	-	1	1	-	-	1	1
Total cost	0	0	1	1	0	0	1	1
Treatment cost x Water	-	0	0	1	-	0	0	1
Electricity cost x Water	-	0	-	0	0	1	0	1
Electricity cost x	-	-	0	0	0	0	1	1
Discount Rate x Water	-	0	-	0	-	0	-	0
Discount Rate x Treatment	-	-	0	0	-	-	0	0
Discount Rate x Electricity	-	-	-	-	0	0	0	0
Water capacity	-	1	-	1	-	1	-	1
Treatment cost	-	-	1	1	-	-	1	1
Electricity cost	-	-	-	-	1	1	1	1
Discount Rate	-	-	-	-	-	-	-	-

-	-	1	1	-	-	1	1	ET
1	1	-	-	1	1	-	-	EU
-	-	-	-	1	1	1	1	TOE
-	-	-	-	-	-	-	-	TWS
-	-	-	-	-	-	-	-	TWN
-	-	-	-	-	-	-	-	TWD
-	-	1	1	-	-	1	1	TWF
-	-	1	1	-	-	1	1	TWC
-	-	-	-	-	-	-	-	TCJ
-	-	-	-	-	-	-	-	TCP
1	1	1	1	1	1	1	1	TCG
-	-	1	1	-	-	1	1	Total Env.
-	-	1	1	0	0	1	1	Total cost
-	0	0	1	-	0	0	1	Treatment cost x Water
-	0	-	0	0	1	0	1	Electricity cost x Water
-	-	0	0	0	0	1	1	Electricity cost x
0	1	0	1	0	1	0	1	Discount Rate x Water
0	0	1	1	0	0	1	1	Discount Rate x Treatment
0	0	0	0	1	1	1	1	Discount Rate x Electricity
-	1	-	1	-	1	-	1	Water capacity
-	-	1	1	-	-	1	1	Treatment cost
-	-	-	-	1	1	1	1	Electricity cost
1	1	1	1	1	1	1	1	Discount Rate

-	-	1	1	-	-	1	1	-	-
1	1	-	-	1	1	-	-	1	1
0	0	0	0	1	1	1	1	-	-
1	1	1	1	1	1	1	1	-	-
1	1	1	1	1	1	1	1	0	0
1	1	1	1	1	1	1	1	-	-
0	0	1	1	0	0	1	1	-	-
0	0	1	1	0	0	1	1	-	-
1	1	1	1	1	1	1	1	-	-
1	1	1	1	1	1	1	1	-	-
1	1	1	1	1	1	1	1	-	-
-	-	1	1	-	-	1	1	-	-
0	0	1	1	0	0	1	1	-	-
-	0	0	1	-	0	0	1	-	0
-	0	-	0	0	1	0	1	-	0
-	-	0	0	0	0	1	1	-	-
-	0	-	0	-	0	-	0	0	1
-	-	0	0	-	-	0	0	0	0
-	-	-	-	0	0	0	0	0	0
-	1	-	1	-	1	-	1	-	1
-	-	1	1	-	-	1	1	-	-
-	-	-	-	1	1	1	1	-	-
-	-	-	-	-	-	-	-	1	1

1	1	-	-	1	1	ET	-	-
-	-	1	1	-	-	EU	1	1
-	-	1	1	1	1	TOE	0	0
-	-	-	-	-	-	TWS	1	1
0	0	0	0	-	-	TWN	1	1
-	-	-	-	-	-	TWD	1	1
0	0	-	-	0	0	TWF	1	1
1	1	-	-	1	1	TWC	0	0
-	-	-	-	-	-	TCJ	1	1
-	-	-	-	-	-	TCP	1	1
-	-	-	-	-	-	TCG	1	1
1	1	-	-	1	1	Total Env.	-	-
1	1	0	0	1	1	Total cost	0	0
0	1	-	0	0	1	Treatment cost x Water	-	0
-	0	0	1	0	1	Electricity cost x Water	-	0
0	0	0	0	1	1	Electricity cost x	-	-
0	1	0	1	0	1	Discount Rate x Water	-	0
1	1	0	0	1	1	Discount Rate x Treatment	-	-
0	0	1	1	1	1	Discount Rate x Electricity	-	-
-	1	-	1	-	1	Water capacity	-	1
1	1	-	-	1	1	Treatment cost	-	-
-	-	1	1	1	1	Electricity cost	-	-
1	1	1	1	1	1	Discount Rate	-	-

1	1	-	-	1	1	-	-	1	1
-	-	1	1	-	-	1	1	-	-
0	0	1	1	1	1	-	-	-	-
1	1	1	1	1	1	-	-	-	-
1	1	1	1	1	1	-	-	-	-
1	1	1	1	1	1	-	-	-	-
1	1	1	1	1	1	-	-	0	0
1	1	0	0	1	1	-	-	1	1
1	1	1	1	1	1	-	-	-	-
1	1	1	1	1	1	-	-	-	-
1	1	1	1	1	1	-	-	-	-
1	1	-	-	1	1	-	-	1	1
1	1	0	0	1	1	-	-	0	0
0	1	-	0	0	1	-	0	0	1
-	0	0	1	0	1	-	0	-	0
0	0	0	0	1	1	-	-	0	0
-	0	-	0	-	0	0	1	0	1
0	0	-	-	0	0	0	0	1	1
-	-	0	0	0	0	0	0	0	0
-	1	-	1	-	1	-	1	-	1
1	1	-	-	1	1	-	-	1	1
-	-	1	1	1	1	-	-	-	-
-	-	-	-	-	-	1	1	1	1

-	-	1	1
1	1	-	-
1	1	1	1
-	-	-	-
-	-	-	-
-	-	-	-
-	-	0	0
-	-	1	1
-	-	-	-
-	-	-	-
-	-	-	-
-	-	1	1
0	0	1	1
-	0	0	1
0	1	0	1
0	0	1	1
0	1	0	1
0	0	1	1
1	1	1	1
-	1	-	1
-	-	1	1
1	1	1	1
1	1	1	1

Table 22.Regression Coefficients for 5 years period.

5 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Intercept	0	0	-	1	1	0	0	1	1	1	0	1	0
Discount Rate	0	0	1	-1	-1	0	0	-1	-1	-1	0	0	0
Electricity cost	0	0	-	-	-	0	0	-	-	-	1	0	0
Treatment cost	1	1	-	-	-	1	1	-	-	-	0	-1	1
Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0
Discount Rate x Electricity cost	0	0	-	-	-	0	0	-	-	-	0	0	0
Discount Rate x Treatment cost	0	0	-	-	-	0	0	-	-	-	0	0	0
Discount Rate x Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0
Electricity cost x Treatment cost	0	0	-	-	-	0	0	-	-	-	0	0	0
Electricity cost x Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0

Treatment cost x Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0

Table 23.Regression Coefficients for 10 years period.

10 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Intercept	0	0	1	1	1	0	0	1	1	1	0	1	0
Discount Rate	0	0	-1	-1	-1	0	0	-1	-1	-1	0	0	0
Electricity cost	0	0	-	-	-	0	0	-	0	-	1	0	0
Treatment cost	1	1	-	-	-	1	1	-	0	-	0	-1	1
Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0
Discount Rate x Electricity cost	0	0	-	-	-	0	0	-	0	-	0	0	0
Discount Rate x Treatment cost	0	0	-	-	-	0	0	-	0	-	0	0	0
Discount Rate x Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0
Electricity cost x Treatment cost	0	0	-	-	-	0	0	-	0	-	0	0	0
Electricity cost x Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0
Treatment cost x Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0

Table 24.Regression Coefficients for 20 years period.

20 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Intercept	0	0	1	1	1	0	1	1	1	1	0	1	0
Discount Rate	0	0	-1	-1	-1	0	-1	-1	-1	-1	0	0	0
Electricity cost	0	0	-	-	-	0	0	0	-	-	1	0	0
Treatment cost	1	1	-	-	-	1	1	0	-	-	0	-1	1

Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0
Discount Rate x Electricity cost	0	0	-	-	-	0	0	0	-	-	0	0	0
Discount Rate x Treatment cost	0	0	-	-	-	0	0	0	-	-	0	0	0
Discount Rate x Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0
Electricity cost x Treatment cost	0	0	-	-	-	0	0	0	-	-	0	0	0
Electricity cost x Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0
Treatment cost x Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0

Table 25.Relevance for 5 years.

5 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Intercept	0	0	-	1	1	0	0	1	1	1	0	1	0
Discount Rate	0	0	1	1	1	0	0	1	1	1	0	0	0
Electricity cost	0	0	-	-	-	0	0	-	-	-	1	0	0
Treatment cost	1	1	-	-	-	1	1	-	-	-	0	1	1
Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0
Discount Rate x Electricity cost	0	0	-	-	-	0	0	-	-	-	0	0	0
Discount Rate x Treatment cost	0	0	-	-	-	0	0	-	-	-	0	0	0
Discount Rate x Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0
Electricity cost x Treatment cost	0	0	-	-	-	0	0	-	-	-	0	0	0
Electricity cost x Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0
Treatment cost x Water capacity	0	0	-	-	-	0	0	-	-	-	0	0	0

10 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Intercept	0	0	1	1	1	0	0	1	1	1	0	1	0
Discount Rate	0	0	1	1	1	0	0	1	1	1	0	0	0
Electricity cost	0	0	-	-	-	0	0	-	0	-	1	0	0
Treatment cost	1	1	-	-	-	1	1	-	0	-	0	1	1
Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0
Discount Rate x Electricity cost	0	0	-	-	-	0	0	-	0	-	0	0	0
Discount Rate x Treatment cost	0	0	-	-	-	0	0	-	0	-	0	0	0
Discount Rate x Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0
Electricity cost x Treatment cost	0	0	-	-	-	0	0	-	0	-	0	0	0
Electricity cost x Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0
Treatment cost x Water capacity	0	0	-	-	-	0	0	-	0	-	0	0	0

20 yrs	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
Intercept	0	0	1	1	1	0	1	1	1	1	0	1	0
Discount Rate	0	0	1	1	1	0	1	1	1	1	0	0	0
Electricity cost	0	0	-	-	-	0	0	0	-	-	1	0	0
Treatment cost	1	1	-	-	-	1	1	0	-	-	0	1	1
Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0
Discount Rate x Electricity cost	0	0	-	-	-	0	0	0	-	-	0	0	0
Discount Rate x Treatment cost	0	0	-	-	-	0	0	0	-	-	0	0	0
Discount Rate x Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0
Electricity cost x Treatment cost	0	0	-	-	-	0	0	0	-	-	0	0	0

Electricity cost x Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0
Treatment cost x Water capacity	0	0	-	-	-	0	0	0	-	-	0	0	0

Table 26. R^2for different years period.

	Total cost	Total Env.	TCG	TCP	TCJ	TWC	TWF	TWD	TWN	TWS	TOE	EU	ET
5 yrs	1	1	1	1	1	1	1	1	1	1	1	1	1
10 yrs	1	1	1	1	1	1	1	1	1	1	1	1	1
20 yrs	1	1	1	1	1	1	1	1	1	1	1	1	1