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Tetra Tech International Development

# Economic Resilience Initiative - Infrastructure Technical Assistance TA2017141 R0 ERI

## Task 1.8: AAWDC Project Greenhouse Gases Emissions Report

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*A project implemented by the TTID ERI-ITA Consortium*

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# Glossary of Terms and Abbreviations

| | |
|---|---|
| **AAWDC** | Aqaba Amman Water Desalination and Conveyance |
| **AP** | Acidification Potential |
| **BPS** | Booster Pump Station |
| **BOT** | Build-Operate-Transfer |
| **CED** | Cumulative Energy Demand |
| **CIPP** | Cured-In-Place Pipe |
| **$CO_2$** | Carbon Dioxide |
| **$CO_2e$** | Carbon Dioxide Equivalent |
| **DI** | Ductile Iron |
| **EIB** | European Investment Bank |
| **FRP** | Fiber Reinforced Polymer |
| **GGE** | Greenhouse Gases Emission |
| **GHG** | Greenhouse Gas |
| **GRP** | Glassfibre Reinforced Plastic |
| **GWh/year** | Gegawatt Hours per year |
| **GWP** | Global Warming Potential |
| **HDPE** | High Density Polyethylene |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IPS** | Intake Pump Station |
| **Km** | Kilometres |
| **LCA** | Life Cycle Assessment |
| **LEED** | Leadership in Energy and Environmental Design |
| **m** | Meters |
| **MCM** | Million Cubic Meter |
| **masl** | Mean Average Sea Level |
| **MSL** | Mean Sea Level |
| **MW** | Megawatt |
| **MWh** | Megawatt-hour |
| **MWI** | Ministry of Water and Irrigation |
| **PCCP** | Pre-stressed Concrete Cylinder |
| **PS** | Pump Station |
| **PFCs** | Perfluorocarbons |

| | |
|---|---|
| **PO** | Photochemical Oxidation |
| **PS** | Pumping Station |
| **psi** | Pound per square inch |
| **PVC** | Polyvinyl Chloride |
| **RGT** | Regulating Tank |
| **SWRO** | Sea Water Reverse Osmosis |
| **$tCO_2e$** | Tonne of Carbon Dioxide Equivalent |
| **T&D** | Transmission and Distribution |
| **WRI** | World Resources Institute |

# 1. Introduction

The scarcity of freshwater resources and the need for additional water supplies is already critical in many arid regions of the world and will be increasingly important in the future. One option, water desalination, enables the production of water from different water sources that would otherwise not be fit for human consumption or for use in industrial processes. A 2015 survey by the International Desalination Association reported that 18,426 desalination plants already produce more than 86.9 million cubic meters each day for over 300 million people (IWA, 2016) in 150 countries (Bienkowski, 2015). In recent years, more and larger desalination facilities are being built.

Water desalination is typically an energy-intensive largely powered process. As a result, the Carbon Dioxide ($CO_2$) emissions associated with water desalination are considerable. The carbon footprint for seawater reverse osmosis (SWRO) desalination has been estimated between 0.4–6.7 kg $CO_2e/m^3$ (Tal, 2018). This means that desalinating 1,000 cubic meters of seawater could potentially release as much as 6.7 tons of $CO_2$. With heroic global efforts underway to keep global warming below 2°C (UNFCCC, 2015), the cumulative carbon footprint of seawater desalination facilities can no longer be ignored.

A middle-income country located in the heart of the Middle East; Jordan is one of the driest countries in the world. Water scarcity impacts every aspect of Jordanian life and is its greatest challenge to economic growth and development. The demand for water and energy by the large number of Syrian refugees is an important element in current and future water scarcity and energy concerns. Climate change will act as a threat multiplier aggravating already existing water problems by decreasing water availability and putting further pressure on groundwater aquifers where recharge rates have already been exceeded (MWI, 2016). The combined effects of climate change and population growth (including migration) is anticipated to put more pressure on limited land and water resources and to increase the challenge of sustainable development in Jordan (Ministry of Foreign Affairs of the Netherlands, 2018).

Jordan's first desalination plant has been inaugurated in the southern port city of Aqaba on March 21st, 2017. The new desalination plant is designed to meet Aqaba's water needs until 2035 by providing 5 MCM of water annually. The plant will relieve some pressure on the Disi-Amman Water Conveyance system, which conveys 100 MCM of water annually to cater to domestic needs of northern Jordan (The Economist, 2017).

Later, the Ministry of Water and Irrigation (MWI) on 26th February 2020 announced the launch of the Aqaba-Amman Water Desalination and Conveyance National (AAWDC) Project, describing it as “the largest water generation scheme to be implemented in the history of the Kingdom”. In accordance with the relevant water strategy and projections, the Project will generate 300 MCM/year of drinking water after commissioning. The Project will be implemented through a build-operate-transfer (BOT) scheme.

The objective of this report (Task 1-8) is to estimate the carbon footprint of the AAWDC Project by quantifying the greenhouse gases (GHGs) emissions (GGE) during the construction and operation phases of the Project and assuming an operation period of 30 years.

The execution of this current task is guided through the European Investment Bank (EIB) ‘Project Carbon Footprint Methodologies - Methodologies for the Assessment of Project GHG Emissions and Emission Variations, version 11.1’, dated July 2020.

# 2. GHGs Footprint Calculation Methodology

## 2.1. Introduction

The primary GHGs included in the footprint include the carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane ($CH_4$), sulphur hexafluoride ($SF_6$), and two classes of compounds called hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) (EIB, 2020). Carbon dioxide is the most abundant of these GHGs and has had the largest effect on our climate. Other GHGs are emitted in smaller amounts, but can trap heat more effectively than carbon dioxide, and some stay in our atmosphere for a very long time.

Global warming potential (GWP) is a relative measure of how much heat a GHG traps in the atmosphere (**Error! Reference source not found.**) (EIB, 2020). In order to compare different emissions and pollutants, we use the effect of carbon dioxide on our climate as a common reference. In this report, emissions are reported as carbon dioxide equivalent ($CO_2e$), meaning emissions are stated in terms that reflect their GWP.

***Table 1: IPCC Global Warming Potential (GWP) Factors (Source: EIB, 2020)***

| Greenhouse Gas (GHGs) | Global Warming Potential (GWP) |
|---|---|
| **Carbon Dioxide ($CO_2$)** | 1 |
| **Methane ($CH_4$),** | 28 |
| **Nitrous Oxide ($N_2O$)** | 265 |
| **Sulphur Hexafluoride ($SF_6$)** | 23,500 |
| **Hydrofluorocarbons (HFCs)** | Up to 12,400 |
| **Perfluorocarbons (PFCs)** | Up to 11,100 |

A reverse osmosis desalination plant is an energy intensive process. Calculations of the carbon footprint of AAWDC Project will be made based on $CO_2e$ resulting from the GGEs resulting from construction and operation of the various Project components.

## 2.2. Project Boundaries

The project boundary defines what is to be included in the calculation of the absolute and relative emissions. The EIB methodologies use the concept of “scope” based on definitions from the World Resources Institute (WRI) GHGs Protocol ‘Corporate Accounting and Reporting Standard’, when defining the boundary to be included in the emissions calculation (EIB, 2020).

1. **Scope 1: Direct GHGs emissions**. Direct GHGs emissions physically occur from sources that are operated by the project. For example, emissions produced by the combustion of fossil fuels.
2. **Scope 2: Indirect GHG emissions**. Scope 2 accounts for indirect GHG emissions associated with energy consumption (electricity, heating, cooling and steam) consumed but not produced by the project. These are included because the project has direct control over energy consumption, for example by improving it with energy efficiency measures or switching to consume electricity from renewable sources.
3. **Scope 3: Other indirect GHG emissions**. Scope 3 emissions are all other indirect emissions that can be considered a consequence of the activities of the project (e.g. emissions from the production or extraction of raw material and vehicle emissions from the use of road infrastructure).

The GHG assessment for the AAWDC Project includes all emissions from all scopes 1, 2 and 3 with the exception of the following:

- Emissions associated with future maintenance activities have not been included in the assessment because the exact nature of these maintenance activities is not currently known, and the emissions associated with these activities are expected to be negligible.
- Emissions associated with the establishment of temporary accommodation facilities close to the AAWDC Project site during construction for the workforce have not been included because it is not

certain that any such temporary accommodation facilities will be established or what the nature of any such facilities would be.

- Emissions associated with outsourced activities, such as construction catering, have not been included as the GHG emissions associated with those activities are expected to be negligible.
- Emissions associated with the transportation of any contaminated soil that is encountered during the construction works to landfill and the decomposition of any such contaminated soil have not been included as there is currently no indication that significant quantities of contaminated soil will be encountered.
- Emissions associated with the private transportation of clerical and administrative workers to project location have not been included on grounds of immateriality.

## 2.3. Quantification Process and Methodologies

The first step in the quantification process will be to set boundaries for absolute and relative emission calculations (EIB, 2020):

- Absolute emissions are based on a project boundary that includes all significant Scope 1, Scope 2 and Scope 3 emissions (as applicable) that occur within the project.
- Relative emissions are based on a project boundary that adequately covers the “with” and “without” project scenarios. It includes all significant Scope 1, Scope 2 and Scope 3 emissions (as applicable), but it may also require a boundary outside the physical limits of the project to adequately represent the baseline.

Figure 1 illustrates a calculation flow in order to quantify the carbon footprint as well as the associated relative emissions compared to the baseline.

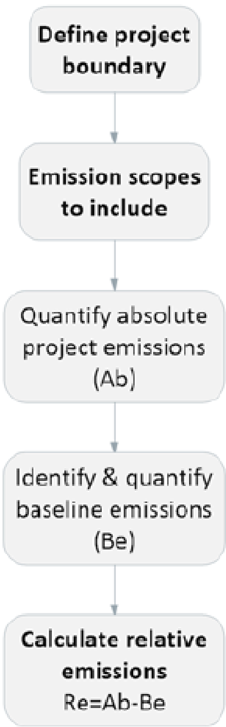



***Figure 1: Project Carbon Footprint Calculation Flow (Source: EIB, 2020)***

The absolute emissions are calculated as such (EIB, 2020):

| | | | | |
|---|---|---|---|---|
| **Absolute Emissions ($tCO_2e$)** | **=** | **Activity Data (e.g. quantity of fuel, electricity or product)** | **x** | **Emissions Factor (e.g. $tCO_2e$/unit of fuel or product)** |

A project's absolute emissions (gross emissions) will be quantified and included in the footprint if the emissions are greater than positive or negative 20,000 tonnes $CO_2e$/year (EIB, 2020). The absolute emissions should be calculated based on project-specific data. Where project-specific data is not available, it is good practice to use default factors based on sector specific activity data and through the application of documented emission factors (EIB, 2020).

The EIB Carbon Footprint Methodology provides a series of emissions factors from which GHGs emissions can be calculated. These have been derived from internationally recognised sources, e.g. WRI/WBCSD's GHG Protocol (WBCSD, 2004) and IPCC Guidelines for National GHG Inventories (Eggleston et al., 2006). These default factors can be used where no other relevant factor is available or where factors that have been provided appear to be unsubstantiated. Where possible, project specific factors will be used in place of the defaults provided the source of the factors used is consistent with the guiding principles described in EIB (2020) methodology.

For Jordan, the grid emission factor for purchased electricity is 0.4585 kg$CO_2$/KWh (MoEnv/UNDP/GEF, 2020). Projects that purchase electricity from the grid must consider the losses from the transmission and distribution (T&D) of the electricity. The size of the losses will depend on the project's capacity, i.e. whether it is connected to the high, medium or low voltage grid. For simplicity T&D losses for this project are assumed to be 2% of the T&D losses since the project consumption is greater than 10MW which is generally connected to the high voltage grid (EIB, 2020).

As for using renewable sources of energy in Jordan, a study conducted by Hussein (2016) concluded that, on average, solar and wind energy emit an equivalent of 61 and 26 g $CO_2e$/KWh. For the AAWDC Project, the weighted average of 38 g $CO_2e$/KWh will be used.

The project's emissions are calculated from year 2050 (i.e. not including commissioning/unplanned shutdowns).

Measuring baseline emissions is a useful complement to absolute emissions. It provides a credible alternative scenario "without" the project, against which the "with" project scenario can be compared – giving an indication of how, measured in GHGs metrics, the proposed project performs. However, the" without" project scenario, or baseline, is clearly theoretical and hence incorporates an additional level of uncertainty beyond those involved in estimating absolute emissions (EIB, 2020).

The relative emissions can then be calculated as (EIB, 2020):

**Relative Emissions = Absolute Emissions – Baseline Emissions, or**

***Relative Emissions = "With" Project Emissions (Wp) – "Without" Project Emissions, or Baseline Emissions (Be)***

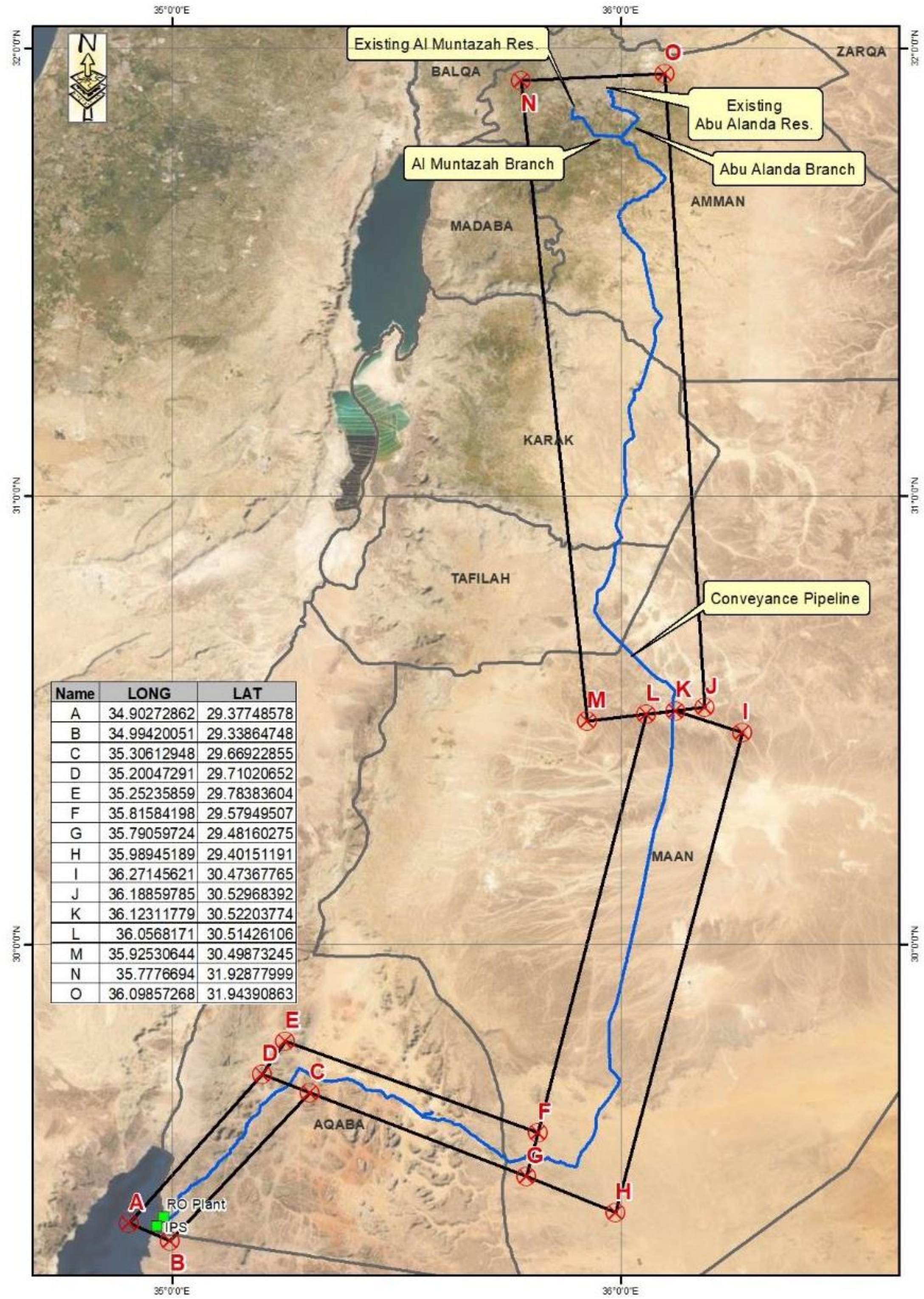
***(Re = Wp – Be)***

Relative emissions may be positive or negative: where negative, the project is expected to result in a savings in GHGs emissions relative to the baseline and vice versa. Expressing a project's relative carbon footprint is one way of evaluating the impact of a project in emissions terms since it provides a context to the absolute emissions of the project, i.e. whether the project reduces or increases GHGs emissions overall. This can then be used as an indicator, along with others, of the environmental performance of the project (EIB, 2020).

# 3. AAWDC Project Boundaries

The Project has been designed to generate 300 MCM/year of drinking water. A general layout of AAWDC Project boundaries along with its key technical components is presented in Figure 2. The figure illustrates the general alignment of the water conveyance system along with the location of the Intake Pumping Station (IPS) and Desalination Plant Sea Water Reverse Osmosis (SWRO), existing Abu Alanda reservoir and Al Muntazah Pumping Station (PS). A summary of the project scope of facilities is described below:

1. Seawater Intake Towers and Conveyance Pipeline to the Intake Pump Station (IPS).
2. Seawater IPS.
3. Seawater Pipeline from IPS to Desalination Plant.
4. Desalination Plant.
5. Brine Line.
6. Conveyance Pipeline from Desalination Plant to Amman PS ADC.
7. Pump Stations along Conveyance Pipeline from Desalination Plant to Amman (BPS 1 to 4, Mudawarra PS, and PS ADC).
8. Conveyance Pipeline from PS ADC to Abu Alanda Reservoir.
9. Conveyance Pipeline from PS ADC to Al Muntazah Reservoir.
10. Regulating Tanks on Conveyance Pipeline.




| Name | LONG | LAT |
|---|---|---|
| A | 34.90272862 | 29.37748578 |
| B | 34.99420051 | 29.33864748 |
| C | 35.30612948 | 29.66922855 |
| D | 35.20047291 | 29.71020652 |
| E | 35.25235859 | 29.78383604 |
| F | 35.81584198 | 29.57949507 |
| G | 35.79059724 | 29.48160275 |
| H | 35.98945189 | 29.40151191 |
| I | 36.27145621 | 30.47367765 |
| J | 36.18859785 | 30.52968392 |
| K | 36.12311779 | 30.52203774 |
| L | 36.0568171 | 30.51426106 |
| M | 35.92530644 | 30.49873245 |
| N | 35.7776694 | 31.92877999 |
| O | 36.09857268 | 31.94390863 |

***Figure 2: Overall Boundary of AAWDC Project***

# 4. GGE Calculations for Marine Works

## 4.1. Description

The Marine works consist of the following components (Dar/HR Wallingford, 2021):

- Submerged offshore intake tower/intake head structures;
- Intake pipelines (marine pipelines) required to convey the intake water to the onshore facilities;
- Onshore intake pumping station (IPS) structure required to deliver the intake water to the desalination plant process facilities via onshore seawater pipeline(s);
- A brine reservoir at the desalination plant to collect reject brine;
- Onshore brine pipeline(s) to convey the brine from the brine reservoir to outfall headwork including brine discharge chamber, emergency overflow reservoir and a hydropower generation system;
- Brine outfall pipeline(s) (marine pipeline(s)) terminating in submerged multi-port type diffuser arrangements discharging the brine into the Gulf of Aqaba.

Seawater will enter the intake system via 4 submerged offshore Intake Towers / Intake Head structures located at the seabed. The intake towers shall be constructed from reinforced concrete in the general form of a typical “velocity cap” type structure (Dar/HR Wallingford, 2021). The depth of water at the intake towers will be typically at -12m. The intake tower will have a rectangular structure of the order of typically 13m long by 5.5m wide incorporating 6 No. 4.5m wide by 2.8m high intake opening screens (Figure 3, Figure 4 and Figure 5).

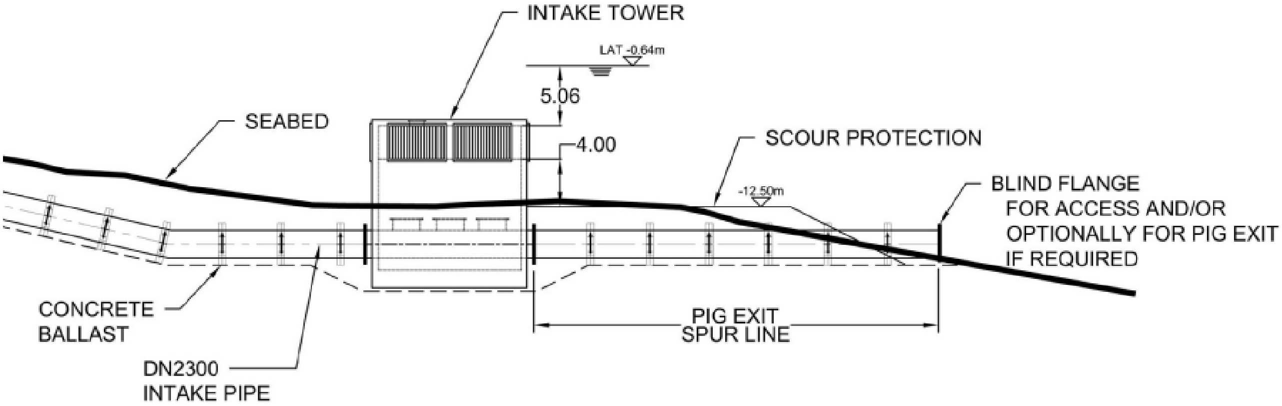



*Figure 3: View of Intake Pipeline and Intake Tower (Source: Dar/HR Wallingford, 2021)*

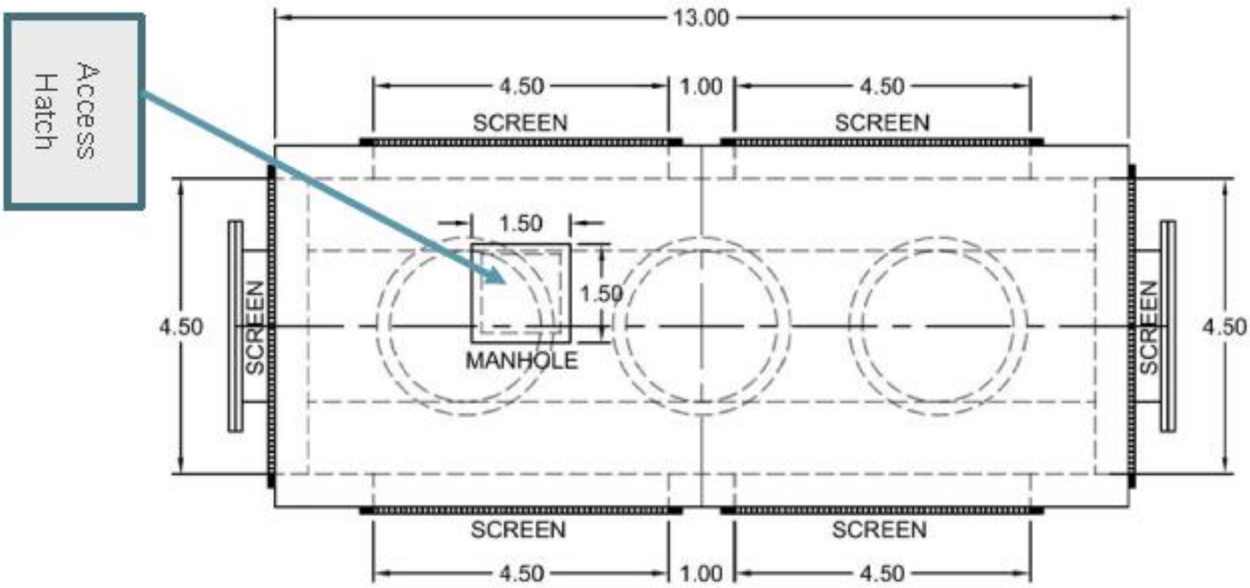



*Figure 4: Intake Tower – Top View (Source: Dar/HR Wallingford, 2021)*

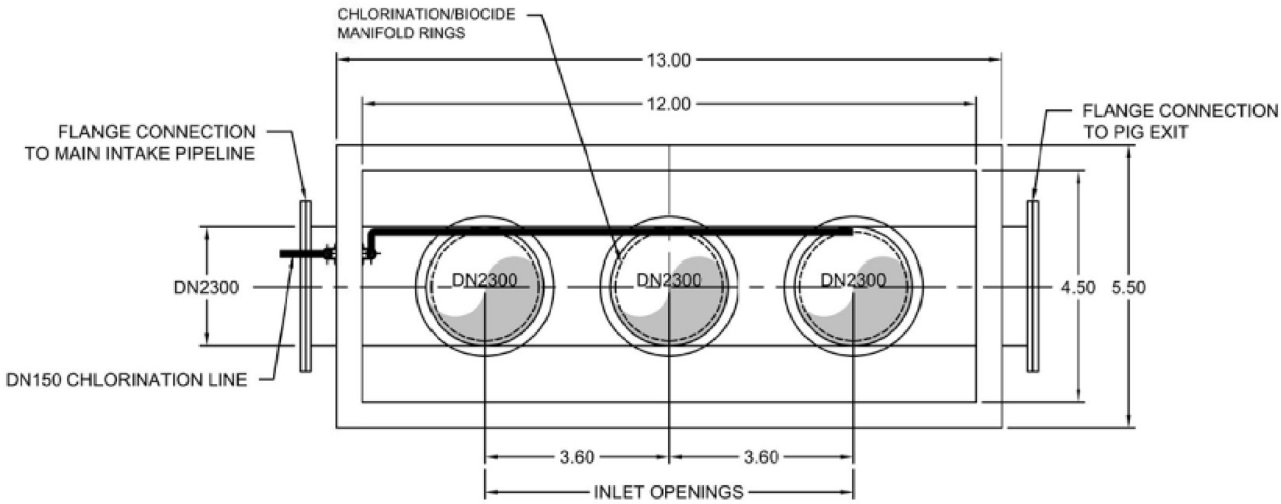



*Figure 5: Intake Tower -Internal Plan View (Source: Dar/HR Wallingford, 2021)*

For the intake and outfall pipes, the material that is considered feasible is High Density Polyethylene (HDPE) PE 100 SDR26 PN6. (Dar/HR Wallingford, 2021). Dar/HR Wallingford (2021) undertook a comparison between Glassfibre Reinforced Plastic (GRP) and HDPE pipes with respect to structural, hydraulic, construction and cost considerations. Whilst the pipe materials are very similar in terms of achieving the hydraulic and main structural criteria required for this project, the study considered that HDPE may be considered as the primary choice for the offshore pipelines based on the following considerations:

- HDPE can be assessed to be relatively more suited to the seismic location;
- Sub-sea construction activities can be relatively less labor intensive which, considering the relatively deep-water activity (35m+ depth) requirements, can be considered important in this case;
- Environmental impacts associated with dredging/excavation works can (where feasible) be minimized by installing (largely or at least partially) on the seabed.

The suitability of SDR26 pipe shall be subject to further confirmation during detailed design stages of the project considering the geotechnical characteristics of the site and installation conditions of the pipe.

Dar/HR Wallingford (2021) proposed to use 4 intake pipelines of ND2300 (each of length = 175m) and 2 outfall pipelines of DN2300 (length of outfall 1 = 282m and length of outfall 2 = 380m) based on maintaining a pipe size common with that of the intake and to have available a potentially wider choice of possible suppliers. The length of the diffusers section at the end of each outfall pipe is 86m. The two 86m long diffuser sections are arranged staggered – one further offshore than the other – such that the total combined diffuser length with both pipelines in operation will be just under 200m (Dar/HR Wallingford, 2021).

Figure 6 below presents the proposed routing for the intake and outfall pipelines. Under this arrangement, the intake and outfall pipelines would be laid and buried in a common trench and protected with rock in the near shore shallow reef areas extending offshore to the location of the intake towers (approximately -12.5mMSL) (Dar/HR Wallingford, 2021).

For the outfall pipelines alignment, Dar/HR Wallingford (2021) proposed to lay much of the pipelines and the diffusers directly onto the bed in the offshore area and avoid almost all excavation/dredging work for the deep offshore areas. The pipelines/diffusers can be stabilized “on the bed” with ballast blocks and suitable collars/anchors where needed.

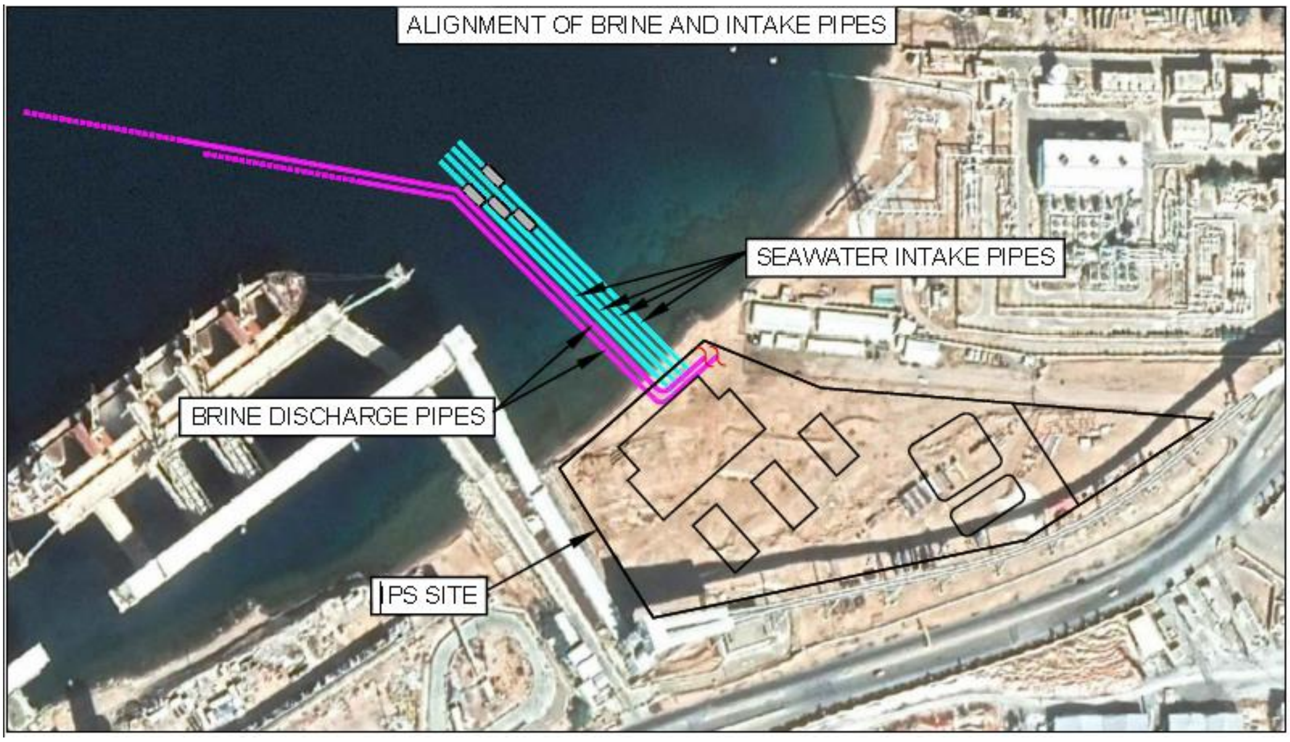



*Figure 6: Intake and Outfall Pipelines Routing (Source: Dar/HR Wallingford, 2021)*

In order to protect the intake and outfall pipelines, they will be placed in a pipeline corridor arranged within a common trench with backfill and rock cover protection (Figure 7). For the deeper area of the corridor, the pipelines are considered to be placed directly on the seabed (Figure 8).

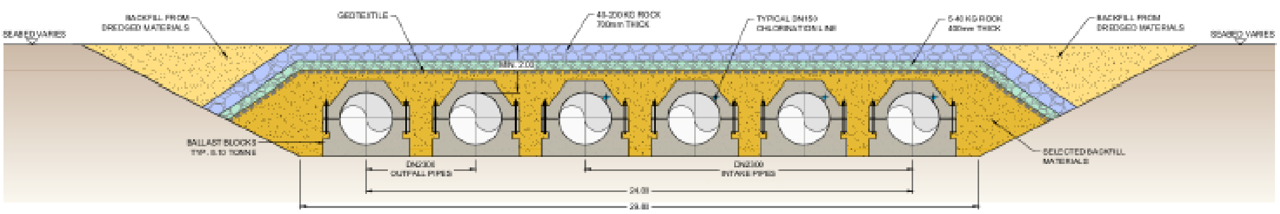



*Figure 7: Shallow Area of the Pipeline Corridor - Typical Example Cross-Section with Intake/Outfall Pipelines Having Common Invert Elevation Laid in A Common Trench (Source: Dar/HR Wallingford, 2021)*

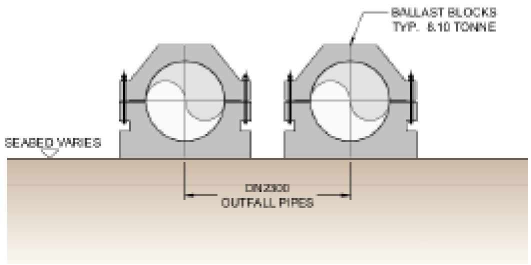



***Figure 8: Deep Area of the Pipeline Corridor – Typical Example Cross-Sections with Outfall Pipeline on Seabed (Source: Dar/HR Wallingford, 2021)***

The SWRO plant is fed from a sea water intake pumping station (IPS) located at the southern coast of Aqaba about 1.5 km from the international Jordanian – Saudi borders. This IPS extracts water from the Red Sea to a nearby site at an elevation of about 100m where the SWRO plant will be constructed as shown in Figure 9 (CDM/USAID, 2020b). The IPS will consist of 8 pumps pumping a total demand load of 27.32 MW.


***Figure 9: Intake Pumping Station Location with respect to SWRO Plant***

## 4.2. GGEs during Construction Phase

### 4.2.1. Sea Water Submerged Intake Towers

Construction of the new intake towers will result in temporary GHGs emissions caused by combustion pollutants from offshore marine vessels, onshore equipment for material transfer, construction worker vehicles, and off-site haul trucks. Construction emissions can vary substantially from day to day, depending on the level of activity and the specific type of operation.

The fuel and electricity consumed by each construction machinery give rise to carbon emissions. The total carbon emission from energy consumption can be calculated by multiplying the number of mechanical shifts by the construction energy consumption and then multiplying it by the corresponding energy carbon emission factor in the construction stage. In practical engineering, the labor and time required for construction are relatively small (Kong et al., 2020). Therefore, carbon emissions of these two parts are not considered.

For the calculation of the GGEs resulting from the construction of the intake towers, it was assumed that the towers will be fully constructed onshore, then lifted by cranes and placed in their final location following the excavation of the seabed. The excavated material will serve in backfilling the pipeline trench.

As stated in the previous section, 4 rectangular shape intake towers (length = 13m, width = 5.5m and depth = 15m) are needed for seawater abstraction. The constructed reinforced concrete volume for the four intake towers is 4 * 588 $m^3$ = 2,352 $m^3$. According to Circular Ecology (2019), the emission factor for reinforced concrete production is assumed to be 373 kg $CO_2e/m^3$. The GGE from the excavation of one square meter of sand of slope 1:6 is 224.5 kg of carbon dioxide (Forsythe and Ding, 2014). The total GGEs from the construction of the 4 intake towers are 82 $tCO_2e$ and 877 $tCO_2e$ from excavation and concrete production respectively, totalling emissions of **959 $tCO_2e$** excluding the emissions from offshore marine vessels and material transfer since data on these activities is not available at this stage of the design.

### 4.2.2. Sea Water Submerged Intake and Outfall Pipelines

As discussed in Section 4.1, HDPE PE 100 SDR26 PN6 will be considered feasible for the intake and outfall pipes. The total length of the 4 intake pipes is 700m while the total length of the 2 outfall pipes is 662m including the diffusers section. A study conducted by Du et al. (2013) calculated the GHGs emissions factors of the production, installation and transportation of one Kilometre of HDPE pipe (Table 2). Since these pipes are not produced in Jordan, the emissions related to their transportation from their production factory to Aqaba port are excluded from the calculations. Hence the total emissions from the construction of intake and outfall pipelines are shown in Table 2 below.

*Table 2: GGEs from Construction of Intake and Outfall Pipelines*

| Phase | Emission Factor ($tCO_2/km$) | Total GGEs ($tCO_2e$) |
|---|---|---|
| **Production** | 215 | 298 |
| **Installation** | 2.81 | 4 |
| **Transportation** | 0.17 | 0.2 |
| | **Total Emissions** | **302** |

### 4.2.3. Intake Onshore Intake Pumping Station

According to Doorn et at. (2006), the emission factor used for emission estimation for land clearing for the IPS sites is 10.5 $tCO_2e/ha$. In practical engineering, the labor and time required for construction are relatively small (Kong et al., 2020). Therefore, carbon emissions of these two parts are not considered. Then, the carbon emissions generated by energy consumption are approximately equal to the total carbon emissions in the construction stage is approximately 11.136 kg $CO_2e/m^3$ (Kong et al., 2020). In order to arrive to this factor, tower cranes were used for hoisting the IPS in the correct location. An electric secondary structure pouring pump is used for concrete pouring. Since the detailed design of the IPS facility is not final yet, the building is assumed to be composed of 3 floors and 1 basement (assuming floor and basement height is 3.8m). Assuming that the IPS building area to site area ratio is 0.8, therefore the calculation of carbon emissions in the construction stage is presented in Table 3 below.

*Table 3: GGEs from Construction of IPS*

| Pump ID | Required Land size (ha) | Required Land Size ($m^2$) | Emissions of $CO_2e$ for land Clearing ($tCO_2e$) | Building Area ($m^2$) | Building Volume ($m^3$) | Emissions of $CO_2e$ from Construction ($tCO_2e$) | Emissions of $CO_2e$ ($tCO_2e$) |
|---|---|---|---|---|---|---|---|
| **IPS** | 2.77 | 27,700 | 29.1 | 22,160 | 110,803 | 1,234 | **1,263** |
| | | | | | | **Total Emissions** | **1,263** |

### 4.2.4. Seawater Pipeline and Brine Pipeline

According to drawing "J19092-0100D-PD-ENV-WW-401", 2 twin ND2700 GRP pipelines will convey the seawater from the IPS to the SWRO site. The length of each pipe is 3.452 km. The GRP brine discharge pipe (ND2700) from the SWRO plant to the outfall pipes location is 3.254 km long (J19092-0100D-PD-ENV-WW-402). The average trench depth is 5m and the trench width is equal to pipe diameter + 600mm which sums up to 3.3m.

According to Herbert et al. (2021), the emission factor for producing 1 km of GRP pipe is 104 $tCO_2$ e. The GHGs emissions from the excavation of one cubic meter of pavement is 4.2 kg of $CO_2e$ (World Bank, 2011). Vahidi et al. (2015) performed a Life Cycle Analysis for GRP pipes in "energy consumption" at different life cycle stages. The results showed that the production stage has the maximum impact on GGEs. Accordingly, the emissions from installation of GRP pipes are temporary and minimal hence it will be excluded from the calculations. The GGEs from the construction of seawater and brine pipelines are shown in Table 4 below.

*Table 4: GGEs from the Construction of Seawater and Brine discharge pipelines*

| Pipe | Length (m) | Emissions from Production ($tCO_2$) | Emissions from Excavation ($tCO_2$) | Total Emissions ($tCO_2$) |
|---|---|---|---|---|
| **Seawater Pipeline** | 3,452 | 718 | 478 | 1,196 |
| **Brine Discharge Pipeline** | 3,254 | 338 | 226 | 564 |
| | | | **Total** | **1,760** |

## 4.3. GGEs during Operation Phase

The emissions of operation of the intake structure system are expected to cause little to no impact on the surrounding environment and community except for the operation of the IPS. The pump is expected to be in operation 24 hours a day with an estimated energy consumption of 238 GWh/year.

The energy requirements for the operation of the IPS are translated into GHGs emissions using a conversion factor based on the specific country's electricity mix ($kgCO_2$/KWh). For Jordan, the grid emission factor is 0.4585 $kgCO_2$/KWh (MoEnv/UNDP/GEF, 2020), the emission factor from renewable energy is 38 $gCO_2$/KWh (Hussein, 2016). The T&D losses from purchased energy are considered 2%. Accordingly, the GHGs emitted from the operation of the IPS are presented in Table 5 below.

*Table 5: GGEs from the Operation of the IPS using Different Sources of Energy*

| Source of Electricity | Emission Factor (kg $CO_2$/KWh) | Emissions ($tCO_2e$)/year |
|---|---|---|
| **Electricity Grid with 2% T&D loss** | 0.4679 | 111,360 |
| **Dedicated Electricity Source** | 0.4585 | 109,123 |
| **Renewable Energy Source** | 0.038 | 9,044 |

# 5. GGE Calculations for Desalination Plant

## 5.1. Description

The Water Desalination Component consists of several facilities to produce desalinated water (freshwater) through a SWRO desalination process with a freshwater recovery efficiency ranging between 42% and 45%. The resulting brine from the SWRO process will be conveyed to the Gulf of Aqaba through 2 sea outfalls.

The SWRO desalination plant includes:

- Pre-treatment system
- RO membranes in a building, including energy recovery system
- Post-treatment system
- Solids treatment system
- Bulk chemical storage area/systems
- Instrumentation and control systems
- Electrical facilities within the SWRO desalination plant site
- Piping within the plant site
- Civil works, including paving and grading within the SWRO desalination plant site
- Administration and maintenance buildings
- Seawater, treated water, and brine reservoirs
- High service pumps (freshwater booster pump station BPS1)

Figure 10 represents a simplified process flow diagram of water desalination component starting from the intake system (at the Gulf of Aqaba), continuing to the SWRO desalination plant, reaching the freshwater booster pump station (BPS1), and ending at the brine discharge outfall.

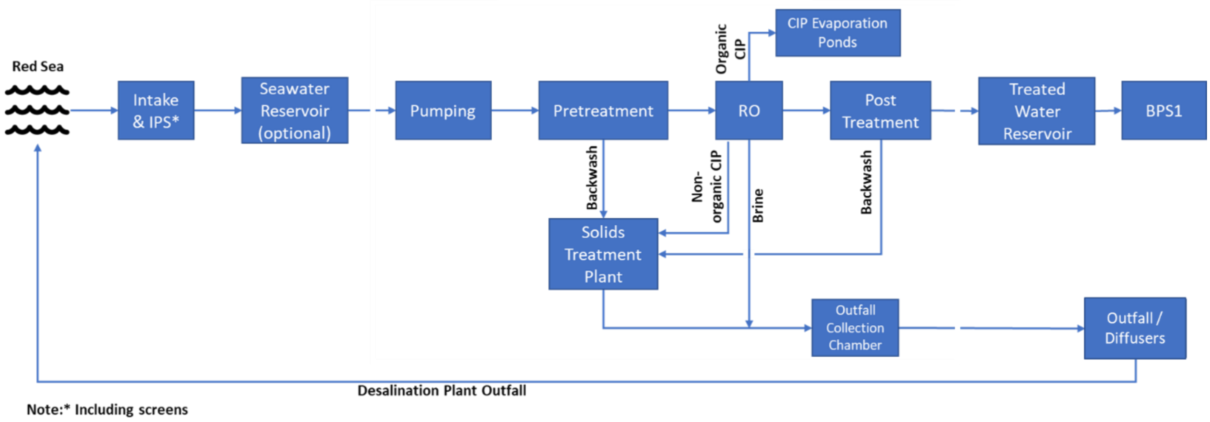



*Figure 10: Process Flow of the Entire Desalination Plant (Source: CDM Smith*

## 5.2. GGEs during Construction Phase

### 5.2.1. Desalination Plant

The carbon footprints of the desalination plant construction stage are mainly the result of the energy and raw material consumption during the equipment manufacturing process. These activities include site clearing, pipeline excavation, building construction, drainage installation, power connection, equipment installation, landscaping, manufacturing of centrifugal pumps, and other special pumps and reverse osmosis membranes (UNEP, 2001). According to the data for a desalination plant (Liu et al., 2015), the carbon footprint for the construction period was estimated to be 10% of the operation stage (Ameen et al., 2018; Raluy et al., 2004). Biswas (2009) completely omitted the GGEs by an RO desalination plant construction since it is minimal especially with the long life of the plant.

Hence, if such factor is applied to the SWRO plant of the AAWDC Project using the GGEs calculated in the subsequent Section 5.2, the GHGs emissions from the construction of the SWRO will be **46,801 $tCO_2e$**.

### 5.2.2. Seawater, Brine and Freshwater Reservoirs

Since the design of the seawater, brine and freshwater reservoirs are not available, information about the estimated capacity of these reservoirs were retrieved from the study conducted by Dar (2018), keeping in mind that the Project capacity has increased since.

Since the SWRO plant site is cleared, emissions from land clearing is considered negligible. The GHG emitted from the excavation of one cubic meter of pavement is considered to be 4.2 kg of $CO_2e$ (World Bank, 2011) and the emission factor for reinforced concrete production is assumed to be 373 kg $CO_2e/m^3$ (Circular Ecology, 2019).

The following data was assumed for the calculation of GGEs:

- Reservoirs are circular.
- Reservoir depth is 8 m.
- Depth of excavation is 2 m.
- Wall thickness is 0.5 m.
- Depth of reservoir bottom slab is 1 m.

The calculation of GHG emissions in the construction stage is presented in Table 6 below

*Table 6: GGEs from Seawater, Brine and Freshwater Reservoirs during Construction*

| Facility | Capacity ($m^3$) | Area of Reservoir ($m^2$) | Diameter of Reservoir (m) | Emissions from Excavation ($tCO_2$) | Emissions from Concrete Production ($tCO_2$) | Total Emissions ($tCO_2$) |
|---|---|---|---|---|---|---|
| **Seawater Reservoir** | 50,000 | 6,250 | 89 | 53 | 1,842 | 1,895 |
| **Treated Water Reservoir** | 42,000 | 5,250 | 82 | 44 | 1,554 | 1,598 |
| **Brine Reservoir** | 15,000 | 1,875 | 49 | 16 | 573 | 589 |
| | | | | | **Total** | **4,082** |

## 5.3. GGEs during Operation Phase

The impacts of desalination plant energy consumption on the environment are highest during the operational stage compared to the construction and other stages (Ameen et al., 2018). The total plant carbon footprint is dependent on two key factors: (1) how much electricity is used by the desalination plant; and (2) what sources (fossil fuels, wind, sunlight, etc.) are used to generate the electricity supplied to the plant. The reverse osmosis process does not require thermal energy and all processes can be done using electricity (Antonyan, 2019).

At the current design stage, the electrical demand of the SWRO amounts to a total of 980.3 GWh/year (Communication with CDM, 2021).

The energy requirements for operation of the SWRO are translated into GHG emissions using a conversion factor based on the specific country's electricity mix ($kgCO_2/kWh$). For Jordan, the grid emission factor is 0.4585 $kgCO_2/KWh$ (MoEnv/UNDP/GEF, 2020), the emission factor from renewable energy is 38 $gCO_2/KWh$ (Hussein, 2016). The T&D losses from purchased energy are considered 2%. Accordingly, the GHGs emissions from the operation of the SWRO are presented in Table 7 below.

*Table 7: GGEs from Operation of the SWRO Plant*

| Source of Electricity | Emission Factor (kg $CO_2$/KWh) | Emissions ($tCO_2e$)/year |
|---|---|---|
| **Electricity Grid with 2% T&D loss** | 0.4679 | 449,468 |
| **Dedicated Electricity Source** | 0.4585 | 458,640 |

| | | |
|---|---|---|
| **Renewable Energy Source** | 0.038 | 37,251 |

# 6. GGE Calculations for Water Conveyance System

## 6.1. Description

The conveyance pipeline from the SWRO desalination plant to the existing Abu Alanda and Al Muntazah Reservoirs consists of all works associated with approximately 420 km of pipeline downstream of the freshwater reservoirs at the desalination plant, passing by Regulating Tanks (RGT) and up to the delivery points at the existing Abu Alanda and Al Muntazah Reservoirs. The pipeline diameter will range from 84 to 90 inches along the pipeline route and a series of pump stations (PS) will pump the desalinated water from an elevation of about 100 meters (m) to an elevation of 985m as shown in Figure 11. The diameters and lengths of the pipeline are detailed in Table 8.

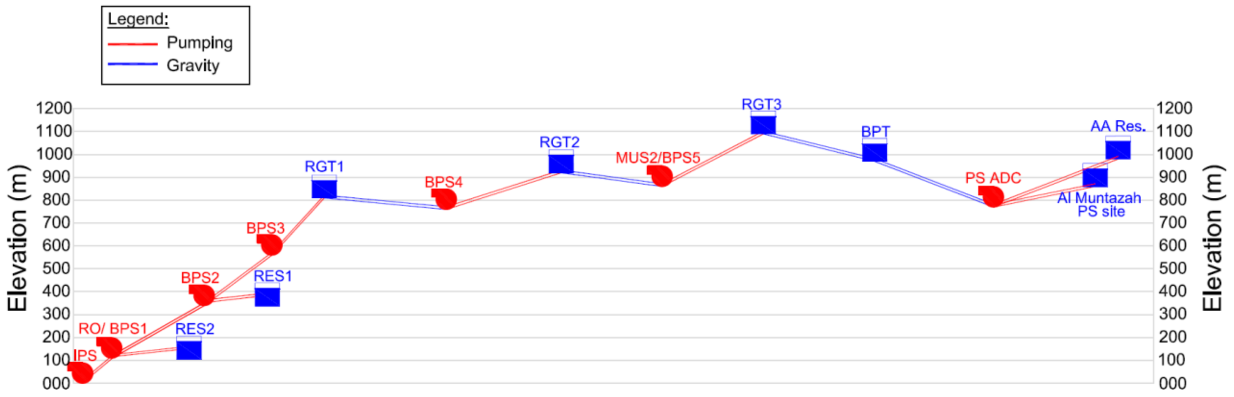



*Figure 11: Schematic Profile of AAWDC Project*

*Table 8: AAWDC Project Pipelines Diameters and Lengths (Source: Communication with CDM, 2021)*

| Reach | Diameter (in) | Length (km) |
|---|---|---|
| **RO to IPS** | 96" | 3.46 |
| **IPS to RO** | 96" | 7.37 |
| **BPS1 to BPS2** | 90" | 7.81 |
| **BPS2 to BPS3** | 90" | 5.81 |
| **BPS3 to RGT1** | 90" | 4.31 |
| **RGT1 to BPS4** | 84" | 29.52 |
| **BPS4 to RGT2** | 90" | 37.38 |
| **RGT2 to BPS5** | 90" | 48.63 |
| **BPS5 to RGT3** | 90" | 21.31 |
| **RGT3 to BPT** | 90" | 94.43 |
| **BPT to PS ADC** | 90" | 63.10 |
| | 87" | 100.74 |
| **PS ADC to AL MUNTAZAH** | 51" | 15.85 |
| **PS ADC to ABU ALANDA** | 81" | 17.28 |

The pump stations and reservoirs along the conveyance system pipeline include the freshwater reservoir and the initial high-pressure BPS1 after the RO desalination plant, five subsequent pressure re-boosting stations (BPS2, BPS3, BPS4, Mudawarra PS [MUS2/BPS], Abu Alanda PS [PS AA]), and five intermediate reservoirs (RGT1, RGT2, RGT3, BPT), including all associated civil works, support facilities, mechanical equipment, piping and valves, Instrumentation and Control, and low-voltage electrical systems (Table 9).

***Table 9: Water Conveyance System Various Component Site Locations and Areas***

| Facility | Coordinates | Area (ha) | Elevation (masl) |
|---|---|---|---|
| **Booster Pump Station 1 - BPS1** | 29°23'26.97"N, 34°59'6.17"E | 0.57 | 118 |
| **Booster Pump Station 2 - BPS2** | 29°26'26.00"N, 35°1'6.01"E | 3.48 | 339 |
| **Booster Pump Station 3 - BPS3** | 29°28'26.82"N, 35°3'46.90"E | 3.03 | 557 |
| **Regulating Tank 1 - RGT1** | 29°30'4.03"N, 35° 5'42.17"E | 2.52 | 806 |
| **Booster Pump Station 4 - BPS4** | 29°42'9.65"N, 35°16'7.43"E | 4.68 | 754 |
| **Regulating Tank 2 - RGT2** | 29°37'37.02"N, 35°34'38.20"E | 2.22 | 921 |
| **Mudawwara Site 2/ Booster Pump Station 5 - MUS2/BPS5** | 29°33'24.51"N, 35°55'34.85"E | 4.69 | 862 |
| **Regulating Tank 3 - RGT3** | 29°43'23.93"N, 35°58'30.14"E | 2.4 | 1089 |
| **Break Pressure Tank - BPT** | 30°33'43.13"N, 36° 7'14.38"E | 2.41 | 974 |
| **Pump Station Abu Alanda - PS ADC** | 31°48'6.29"N, 36° 0'4.85"E | 6.42 | 762 |
| **Existing Abu Alanda Reservoir** | 31°54'13.59"N, 35°58'14.57"E | - | 985 |
| **Existing Al Muntazah Reservoir** | 31°51'52.33"N, 35°53'40.35"E | - | 860 |
| **Aqaba Reservoir 1 at the BPS2 site** | 29°26'25.37"N, 35° 1'0.74"E | 0.12 | 336 |
| **Aqaba Reservoir 2 at the SWRO Desalination Plant site** | 29°23'19.97"N, 34°59'5.65"E | 0.18 | 110 |

As included in Appendix 1, the four life cycle phases for the different materials for pipelines were considered in this study. These phases are as follows:

1. Material production and pipeline fabrication.
2. Pipe transportation to the job site.
3. Pipe installation in the trench.
4. Operation of the pipeline

## 6.2. GGEs during Construction Phase

### 6.2.1. Water Transmission Pipelines

The term pipeline refers to a long line of connected segments of pipe, with pumps, valves, control devices, and other equipment or facilities needed for operating the system. Water transmission pipelines are generally large diameter (more than 12 in.) pipes which transport the water from one place to another. Installation of these pipes is a complex process due to variability of ground conditions over long distance installations. Sometimes, it is difficult to relate pipelines to the environment because of their out of sight nature. But it follows a close relationship with our environment due to various energy consuming activities involved in pipeline installation such as, pipe manufacturing, transporting the pipe to the job site and installation of the pipe in the trench. Since, every construction activity impacts the environment, it becomes utmost important for the design engineer to evaluate this impact and take necessary steps to minimize it.

The construction of water pipelines can be detrimental to environment and land use. Construction activities can disturb ecosystems, devastate scenery, and disturb surface and subsurface. Underground transmission pipelines require huge trenches leading to disruption of the ground.

Construction operations can consume substantial amounts of energy. As the transmission pipeline would run underground, construction activities would primarily consist of clearing, earthworks, trenching, laying and connecting pipes, stockpiling, excavation, truck movements, use of machinery and some chemical storage and hazardous materials handling.

According to a study conducted by Du et al. (2013), the GHG emission factors of the production, installation and transportation of one kilometre of HDPE pipe were calculated. Since these pipes are not produced in Jordan and thus their country of origin is not yet known, the emissions related to their transportation from their production factory to Aqaba port are excluded from the calculations. The total emissions from the construction of conveyance pipelines are shown in Table 10 below.

***Table 10: GGEs from Construction of Freshwater Pipelines***

| Phase | Emission Factor ($tCO_2/km$) | Total GGEs ($tCO_2e$) |
|---|---|---|
| **Production** | 215 | 98,256 |
| **Installation** | 2.81 | 1,284 |
| **Transportation** | 0.17 | 78 |
| | **Total Emissions** | **99,618** |

### 6.2.2. Pumping Stations

According to Doorn et at. (2006), the emission factor used for emission estimation for land clearing for the PS sites is 10.5 $tCO_2e/ha$. The fuel and electricity consumed by each construction machinery give rise to carbon emissions. The total carbon emission from energy consumption can be calculated by multiplying the number of mechanical shifts by the construction energy consumption and then multiplying it by the corresponding energy carbon emission factor in the construction stage. In practical engineering, the labor and time required for construction are relatively small (Kong et al., 2020). Therefore, artificial carbon emissions of these two parts are not considered. Then, the carbon emissions generated by energy consumption are approximately equal to the total carbon emissions in the construction stage is approximately 11.136 kg $CO_2e/m^3$ (Kong et al., 2020). In order to arrive to this factor, tower cranes were used for hoisting the PS in the correct location. An electric secondary structure pouring pump is used for concrete pouring. Since the detailed design of the PS facility is not final yet, all the buildings are assumed to be composed of 3 floors and 1 basement (assuming floor and basement height is 3.8 m). Assuming that the PS building area to site area ratio is 0.8, therefore the calculation of carbon emissions in the construction stage is presented in Table 11 below.

***Table 11: GGEs from Pumping Stations during Construction***

| Pump ID | Required Land size (ha) | Required Land Size ($m^2$) | Emissions of $CO_2e$ for land Clearing ($tCO_2e$) | Building Area ($m^2$) | Building Volume ($m^3$) | Emissions of $CO_2e$ from Buildings ($tCO_2e$) | Emissions of $CO_2e$ ($tCO_2e$) |
|---|---|---|---|---|---|---|---|
| **BPS1** | 0.57 | 5,700 | 6.0 | 4,560 | 22,803 | 254 | **260** |
| **BPS2** | 3.48 | 34,800 | 36.5 | 27,840 | 139,203 | 1,550 | **1,587** |
| **BPS3** | 3.03 | 30,300 | 31.8 | 24,240 | 121,203 | 1,350 | **1,382** |
| **BPS4** | 4.68 | 46,800 | 49.1 | 37,440 | 187,203 | 2,085 | **2,134** |
| **BPS5** | 4.69 | 46,900 | 49.2 | 37,520 | 187,603 | 2,089 | **2,138** |
| **PS ADC** | 6.42 | 64,200 | 67.4 | 51,360 | 256,803 | 2,860 | **2,927** |
| | | | | | | **Total Emissions** | **10,428** |

### 6.2.3. Regulating Tanks

Since the design of the regulating tanks and reservoirs are not available at this design stage, information about the capacity of the regulating tanks and break pressure tank were retrieved from the study conducted by Dar (2018). The capacity of Aqaba Reservoir 1 at the BPS2 site and Aqaba Reservoir 2 at the SWRO Desalination Plant site were retrieved from Task 1-2 report.

According to Doorn et at. (2006), the emission factor used for emission estimation for land clearing for the tank sites is 10.5 $tCO_2e/ha$. The GHGs emissions from the excavation of one cubic meter of pavement is 4.2 kg of $CO_2e$ (World Bank, 2011) and the emission factor for reinforced concrete production is assumed to be 373 kg $CO_2e/m^3$ (Circular Ecology, 2019).

The following data was assumed for the calculations of GGEs:

- Tanks and reservoirs are circular.
- Tanks and reservoirs depth is 8m.
- Depth of excavation is 2m.
- Wall thickness is 0.5m.
- Depth of tank/reservoir bottom slab is 1m.

The calculation of carbon emissions in the construction stage is presented in Table 12 below

*Table 12: GGEs from Tanks and Reservoirs during Construction*

| Facility | Area (ha) | Capacity ($m^3$) | Area of Reservoir ($m^2$) | Diameter of Reservoir (m) | Emission of CO2e from Land Clearing ($tCO_2$) | Emissions from Excavation ($tCO_2$) | Emissions from Concrete Production ($tCO_2$) | Total Emissions ($tCO_2$) |
|---|---|---|---|---|---|---|---|---|
| **Regulating Tank 1 - RGT1** | 2.5 | 42,000 | 5,250 | 82 | 26 | 44 | 1,554 | 1,624 |
| **Regulating Tank 1 - RGT2** | 2.2 | 42,000 | 5,250 | 82 | 23 | 44 | 1,554 | 1,621 |
| **Regulating Tank 1 - RGT3** | 2.4 | 38,000 | 4,750 | 78 | 25 | 40 | 1,409 | 1,474 |
| **Break Pressure Tank - BPT** | 2.4 | 42,000 | 5,250 | 82 | 25 | 44 | 1,554 | 1,623 |
| **Aqaba Reservoir 1 at the BPS2 site** | 0.1 | 6,000 | 750 | 31 | 1 | 6 | 240 | 247 |
| **Aqaba Reservoir 2 at the SWRO Desalination Plant site** | 0.2 | 9,000 | 1,125 | 38 | 2 | 9 | 352 | 363 |
| | | | | | | | **Total Emissions** | **6,954** |

## 6.3. GGEs during Operation Phase

The emissions from operation of the transmission pipeline are expected to cause little to no impact on the surrounding environment and community except for the operation of the pumping stations (Table 13). The pumps are expected to be in operation 24 hours a day.

The energy requirements for the operation of the PS are translated into GHG emissions using a conversion factor based on the specific country's electricity mix ($kgCO_2/KWh$). For Jordan, the grid emission factor is 0.4585 $kgCO_2/KWh$ (MoEnv/UNDP/GEF, 2020), the emission factor from renewable energy is 38 $gCO_2/KWh$

(Hussein, 2016). The T&D losses from purchased energy are considered 2%. Accordingly, the GHGs emissions from the operation of the PS are presented in Table 13 and Table 14 below.

*Table 13: GGEs from Operation of the Pumping Stations Using Jordan's Electricity Grid Factor*

| Pump Station No. | Estimated Energy Comsumption (GWh/year) | Annual Emissions ($tCO_2$/year) |
|---|---|---|
| **BPS1** | 282 | 131,948 |
| **BPS2** | 230 | 107,617 |
| **BPS3** | 259 | 121,186 |
| **BPS4** | 217 | 101,534 |
| **BPS5** | 258 | 120,718 |
| **PS ADC** | 215 | 100,599 |
| | **Total** | **683,602** |

*Table 14: GGEs from the Operation of the Conveyance System using Different Sources of Energy*

| Source of Electricity | Emission Factor (kg $CO_2$/KWh) | Emissions ($tCO_2e$)/year |
|---|---|---|
| **Electricity Grid with 2% T&D loss** | 0.4679 | 683,602 |
| **Dedicated Electricity Source** | 0.4585 | 669,869 |
| **Renewable Energy Source** | 0.038 | 55,518 |

# 7. Conclusion

The GGEs from the construction of the AAWDC Project are presented in Table 15 below.

*Table 15: GGEs from AAWDC Project during Construction*

| Component | Scope 1 | Scope 2* | Scope 3 | Emissions ($tCO_2e$) |
|---|---|---|---|---|
| Intake Towers | 82 | 0* | 877 | 959 |
| Sea Water Submerged Intake and Outfall Pipelines | 4 | 0* | 298.2 | 302 |
| Onshore Intake Pumping Station | 29. | 0* | 1,234 | 1,263 |
| Seawater Pipeline and Brine Pipeline | 704 | 0* | 1,056 | 1,760 |
| Desalination Plant | 46,801 | 0* | 0* | 46,801 |
| Seawater, Brine and Freshwater Reservoirs | 113 | 0* | 3,969 | 4,082 |
| Water Transmission Pipelines | 1284 | 0* | 98,334 | 99,618 |
| Pumping Stations | 10,428 | 0* | 0* | 10,428 |
| Regulating Tanks | 289 | 0* | 6,663 | 6,954 |
| **Total** | | **0*** | | **172,167** |

* No information regarding the data needed to calculate this component.

The GGEs from the operation of the AAWDC Project using Jordanian electricity grid are presented in Table 17 below, while Table 17 presents the GGEs emissions from the different energy sources.

*Table 16: Annual GGEs from AAWDC Project during Operation (Electricity Grid)*

| Component | Scope 1 | Scope 2 | Scope 3 | Emissions ($tCO_2e/yr$) |
|---|---|---|---|---|
| Onshore Intake Pumping Station | 0* | 111,360 | 0* | 111,360 |
| Desalination Plant | 0* | 449,468 | 0* | 449,468 |
| Pumping Stations | 0* | 683,602 | 0* | 683,602 |
| **Total** | **0*** | **1,244,430** | **0*** | **1,244,430** |

* No information regarding the data needed to calculate this component.

*Table 17: Annual GGEs from AAWDC Project during Operation (Different Energy Sources)*

| Component | Emissions Electricity Grid with 2% T&D loss ($tCO_2e/yr$) | Emissions Dedicated Electricity Source ($tCO_2e/yr$) | Emissions Renewable Energy Source ($tCO_2e/yr$) |
|---|---|---|---|
| Onshore Intake Pumping Station | 111,360 | 109,123 | 9,044 |
| Desalination Plant | 449,468 | 458,640 | 37,251 |
| Pumping Stations | 683,602 | 669,869 | 55,518 |
| **Total** | **1,244,430** | **1,237,632** | **101,813** |

In the case of AAWDC Project, the baseline scenario is the “no project” option, which saves on all the emissions from the construction and operation of the project. The best option for this project is to use renewable energy sources that could directly power the Desalination Plant and associated infrastructure. The AAWDC Project is crucial infrastructure to secure Jordan’s water supply against the effects of rainfall dependency. The need for such security is compelling given decade-long drought, unprecedented population growth and the risks associated with climate change.

# 8. Energy Efficiency Measures

In the climate change literature, mitigation refers to efforts to reduce GHG emissions, while adaptation refers to strategies to deal with climate change impacts. Adaptation and mitigation initiatives push for sustainable desalination alternatives able to produce minimal or negligible quantities of $CO_2$ to prevent climate change conditions. However, desalination is an example of conflict between mitigation and adaptation measures, as it is still the most energy intensive water treatment method and as most countries still power their desalination plants with fossil fuel.

Since most of the GHGs emissions associated with AAWDC Project occur during the operation phase of the project, they are almost entirely from the production of purchased electricity to operate the IPS, SWRO Plant and the Pumping Stations. It is expected that during the 30-year life of the Project, a number of significant factors will lead to reducing the emission factor for purchased electricity. These factors include:

- Future generation fuel costs.
- Future electricity load growth.
- Obligations/targets for renewable energy.
- Timeframe for viable new generation technologies.

The concept of energy efficiency for optimum energy monitoring and power control will be considered in the desalination plant detailed design. Use of high-efficiency motors and pumps are project requirements. Additional means of achieving efficiency in the design includes automatic control of outdoor lighting, HVAC systems and power losses (light, heat, and cold), a solar system to power the auxiliary systems, use of LED technology for illumination, and power factor management among others. Additionally, all process elements will be designed so that the elements in service operate within their optimum efficiency ranges at the desalination plant capacity.

The detailed design of AAWDC Project desalination plant facilities should be configured as series of structures sharing common walls, roofs and equipment, which allows significant reduction of its physical footprint.

Since this project will be of BOT type, the final detailed design of the SWRO facilities should follow the principles of the Leadership in Energy and Environmental Design (LEED) program. This will reduce the overall impact of building construction and functions on the environment by: (1) sustainable site development; (2) energy efficiency; (3) materials selection; (4) indoor environmental quality, and (5) water savings.

Consistent with the principles of the LEED program, the desalination plant buildings should include features and materials that allow minimizing energy use for lighting, air conditioning and ventilation. For example, portions of the walls of the desalination plant will be equipped with translucent panels to maximize daylight use and views to the outside. Non-emergency interior lighting will be automatically controlled to turn-off in unoccupied rooms and facilities. A monitoring system will ensure that the ventilation in the individual working areas in the building is maintained at its design minimum requirements. In addition, building design will incorporate water-conserving fixtures (lavatory faucets, showers, water closets, urinals, etc.) for plant staff service facilities and for landscape irrigation.

A range of energy efficiency measures were identified in order to reduce the GHG emissions associated with the Project. These measures cover both the operational and construction phases of the Project.

During construction these potential measures include:

- As far as reasonably possible, construction materials will be sourced from within or close to the Project area to reduce fuel use from transport of materials.
- Maximum re-use of cleared material.
- Construction equipment will be maintained in good working to maximize fuel efficiency of equipment.
- Appropriately sized equipment will be used for construction activities.
- Use of concrete formwork that is reusable.
- Waste from construction will be minimized.
- Greenhouse reduction initiatives will be undertaken at construction camps and construction sites.

During operation, these potential measures include:

- Minimizing energy consumption through the management of key parameters in the seawater inlet system.
- Adopting efficient processes and mechanical equipment specifications in the pre-treatment plant and the desalination plant, freshwater conveyance pipelines and pumping stations.
- Designing energy efficient offices (administration, visitors' center and control building).
- Considering options for construction crew transport to site.
- Focusing on the re-use of construction spoil either on-site or in other major projects located in the regional area.
- Coordination of transportation: materials, spoil and waste.
- Improve desalination process to become fully automated reducing plant staff requirements and associated GHG emissions for staff transportation and services.

Other supporting measures to save energy, reduce GHG emissions and add more value:

- Desalination plants can be subjected to the true cost of energy supply. Charging pre-determined cost of energy for desalination plants limits the development of more energy efficient plants to achieve a lower lifecycle cost.
- Energy supply for desalination is preferably sourced from renewable energy plants via a grid connection.
- $CO_2$ accounting can be introduced to benchmark and optimize the desalination plants.
- Desalination plants can offer demand response capabilities to be able to reduce electricity peak demand when needed and to create value outside of the water sector.

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# 10. Appendix 1

## 10.1. Introduction

Pipelines used in water supply systems are made of different materials having different performance characteristics, as well as operation and maintenance requirements. In addition to these characteristics, environmental aspects should be taken into consideration when selecting the optimum pipe material for a water supply network.

For the AAWDC project, several pipe materials were considered by the Design Consultant, CDM Smiths. These are Steel, Ductile Iron (DI), Glassfiber Reinforced Plastic (GRP) and Pre-stressed Concrete Cylinder (PCCP). The materials were analysed based on several considerations including cost, market availability, strength, durability, ease of repair and possibility of partly manufacturing in Jordan. Although High Density Polyethylene (HDPE) pipelines need to be towed by sea from North Europe as they are not available in Jordan and there is no manufacturing facility in the Middle East, the CDM Smiths report proposed to use HDPE or GRP pipes for the sea water intake pipes and the marine outfall.

In this appendix, the abovementioned five pipeline materials are assessed for various environmental categories to the extent possible, such as Global Warming Potential (GWP), ozone layer depletion, ecotoxicity, and energy consumption during production, transportation, and installation phases for each pipe material. It is mainly based on a review of the scientific literature. The following activities are usually considered in each phase:

- Production: raw materials such as steel, polyethylene, iron, limestone, cement, synthetic fibers, etc), pipe manufacturing equipment (extruder for plastic pipes, castings, etc.), protective coatings for pipes (bitumen glue, cement mortar, zinc).
- Transportation: Transportation distance, type of vehicle used, amount of fuel consumed.
- Installation: Use of excavator for trench excavation, roller for compaction, materials required in trenches (sand, gravel, concrete).
- Use: Friction losses during transmission, maintenance and repair.

The following flowchart illustrates the system boundary of the abovementioned phases including a series of activities carried out in each phase (Figure 12).

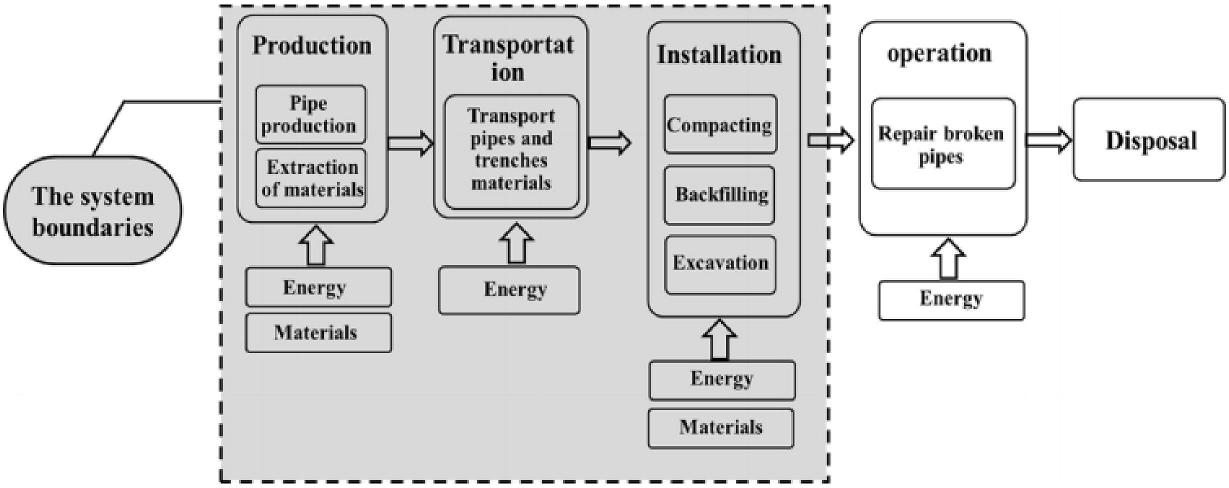


*Figure 12: System Boundary for Environmental Consideration (Source: Hajibabaei et al., 2018)*

## 10.2. Literature Review

To assess the environmental impacts of various pipe materials, several studies used the Life Cycle Assessment (LCA) method. The LCA is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (Finkbeiner et al., 2006). For example, (Vahidi et al., 2015) performed a comparative LCA for four different types of pipe materials namely composite fiber reinforced polymer (FRP) also known as GRP, polyvinyl chloride (PVC), DI, and concrete. The studied environmental impacts were quantified for all pipe materials in terms of “ozone layer depletion”, eco-toxicity”, and “energy consumption” at different life cycle stages. When comparing all stages in terms of environmental impacts, the results showed that the production stage has the maximum impact on different environmental categories for all four studied materials. Moreover, the results presented in Figure 13 (a) demonstrate that the most harmful material to produce pipes is DI. In fact, the production of DI pipes has an impact on almost all categories except for ecotoxicity whereby the production stage of concrete has the highest impact on this category.

Even though the production of DI pipes has a significant negative impact on ozone layer depletion, FRP or GRP production stage is considered as the most impactful stage on ozone layer depletion due to the use of polystyrene and generation of hydrochlorofluorocarbons (HCFC). As an overall conclusion, the production of FRP (or GRP) pipes also has a significant environmental impact but is much lower than that for DI. In addition, the impact of ecotoxicity was found the highest to produce concrete pipelines (Vahidi et al., 2015). In order to assess the effect of the production process of each pipe material in the various environmental categories, the single scores of the production phase of different pipe materials was calculated. This score is calculated as the weighted average of each environmental category over all other categories. The obtained single scores are presented in Figure 13 (b).

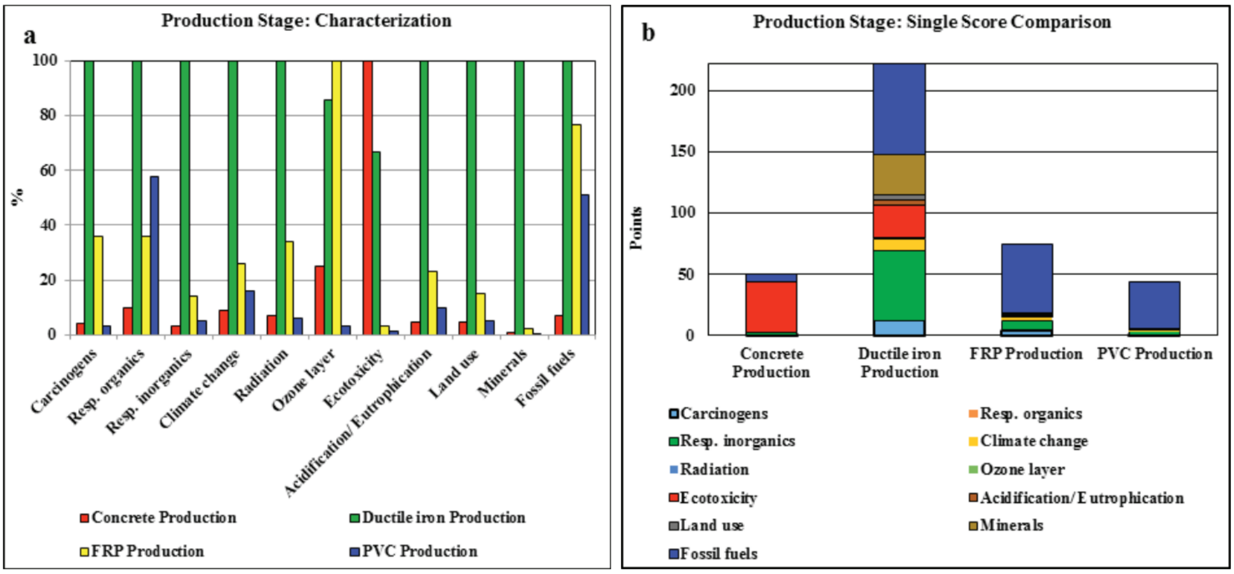


***Figure 13: (a) Characterization Graph for Production Stage Comparison for all Piping Materials, (B) Single Score Graph for Production Stage Comparison for all Piping Materials (Source: Vahidi et al., 2015)***

From the obtained single score results on concrete pipes production stage (Figure 13 (b)), it can be noted that the main environmental impact categories are ecotoxicity and use of fossil fuels with a higher score of ecotoxicity (90%) compared to that of fossil (around 10%) (Vahidi et al., 2015). Ecotoxicity was further confirmed by other studies assessing the potential release of heavy metals and other toxic inorganic compounds found in cement, a primary raw material used for the production of concrete pipes, into the environment (Brunori et al., 2001, Dell’Orso et al., 2012, Napia et al., 2012). As for DI pipe production, the distribution was as follows: 35% impact on fossil fuels, 28% impact on ozone layer and around 13% impact on eco-toxicity. On the other hand, the production of FRP (or GRP) pipes has the single largest impact in terms of use of fossil fuels with a significant percentage of around 75% (Vahidi et al., 2015).

In the same study a comprehensive comparison of the life cycle stages for the four different pipe materials was conducted and the obtained results indicate that the life cycle of the DI has the highest impact within the various environmental categories. The scores of the life cycle of different pipe materials were also calculated and are presented in Figure 14. The study concluded that DI life cycle primarily has around 35% impact on fossil fuel consumption. As for the life cycle of FRP (or GRP) pipes, the results presented in the figure indicate that the single largest impact was on fossil fuels with a considerable percentage of around 75%. In general, it can be noted that the impact on fossil fuel consumption from the life cycle of DI, PVC, and FRP pipes is dominant and that eco-toxicity is the most impactful category in the life cycle of concrete piping materials (Vahidi et al., 2015).

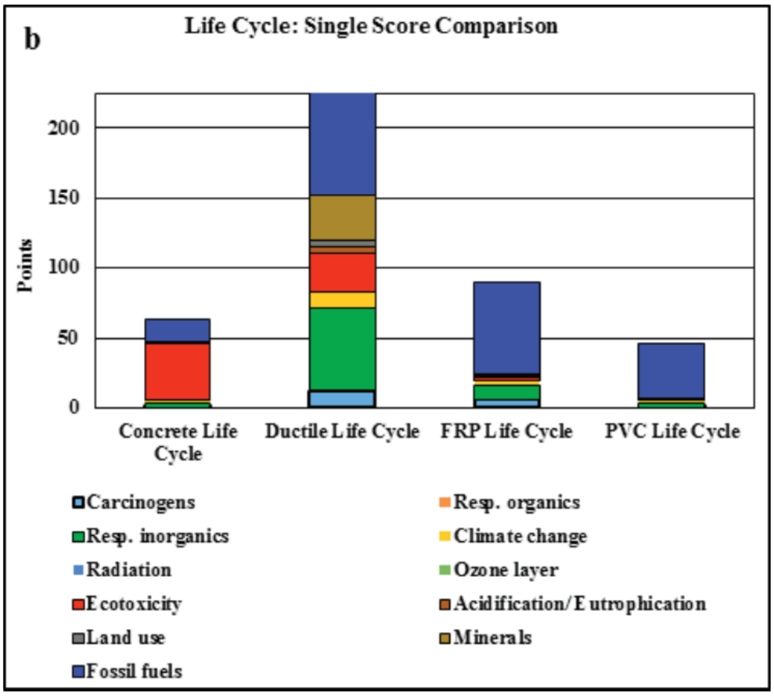


*Figure 14: Concrete Pipe Single Score Graph (Source: Vahidi et al., 2015)*

Another study conducted a LCA on six commonly used types of water and wastewater pipe materials namely PVC, DI, cast iron, HDPE, concrete, and PCCP or reinforced concrete to assess their impacts in terms of GWP during the different phases including pipeline production, transportation, installation, and use. The GWP values in units of equivalent $CO_2$ emissions per km of pipeline were compared for the six pipeline types (Table 18). The results indicated that DI pipes contributed the greatest addition to GWP among the six kinds of pipe materials. Concrete pipes had the lowest GWP, despite the energy demand associated with cement production. The results also indicated that HDPE contribute to GWP more than reinforced concrete (Du et al., 2013).

*Table 18: Summary of Phase Dependent and Total GWP per km of Different Pipeline Materials (Source: Du et al., 2013)*

| Pipe materials (12-in. pipe) | Total GWP ($10^3$ kg $CO_2$/km) | Production phase ($10^3$ kg $CO_2$/km) | Installation phase ($10^3$ kg $CO_2$/km) | Transportation phase ($10^3$ kg $CO_2$/km) |
|---|---|---|---|---|
| PVC | 318 | 315 | 2.81 | 0.26 |
| Ductile iron | 472 | 468 | 3.28 | 0.88 |
| Concrete | 68.3 | 63.1 | 2.91 | 2.26 |
| HDPE | 218 | 215 | 2.81 | 0.17 |
| Reinforced concrete | 152 | 146 | 2.91 | 2.47 |
| Cast iron | 353 | 349 | 3.28 | 0.84 |

The LCA methodology was also used in a study conducted on five types of pipe materials used in drinking water distribution networks. The materials included are PVC, HDPE, DI, fibrocement, and steel and were evaluated in the following environmental categories: GWP, Ozone Layer Depletion (OLD), photochemical Oxidation (PO), Acidification Potential (AP), Eutrophication (EU) and the Cumulative Energy Demand (CED) (Hajibabaei et al., 2018). The results of this study indicate that during the production phase, PVC pipes produce the least impact in almost all environmental categories. In general, HDPE generates similar impacts to PVC and is therefore comparable but has slightly higher impacts. Moreover, the results show that DI produces more environmental impact in all assessed impact categories except for CED. This is mainly because DI requires more materials for pipe manufacturing. As for steel pipes, the same order of magnitude was observed in the GWP category as DI pipe material. This was also the case with the CED category whereby the energy demand of DI and steel pipe materials are 1,680 MJ and 1,400 MJ, respectively. In addition, the result of the CED shows that the energy demand for DI pipes is approximately 2 to 3 times greater than for HDPE and PVC pipes (Table 19) (Hajibabaei et al., 2018).

*Table 19: Environmental Impact of Each Material in the Production Phase (Source: Hajibabaei et al., 2018)*

| Impact category | Unit | Steel | HDPE | Fibrocement | DI | PVC |
|---|---|---|---|---|---|---|
| GWP | kg CO2 eq | 1/05E+02 | 2/55E+01 | 2/84E+01 | 1/28E+02 | 2/11E+01 |
| OLD | kg CFC-11 eq | 6/25E-06 | 4/36E-07 | 2/41E-06 | 1/20E-05 | 4/69E-07 |
| PO | kg C2H4 eq | 4/22E-02 | 7/82E-03 | 1/60E-02 | 6/50E-02 | 3/77E-03 |
| AP | kg SO2 eq | 5/29E-01 | 9/78E-02 | 3/79E-01 | 9/05E-01 | 7/07E-02 |
| EU | kg PO4— eq | 2/73E-01 | 1/59E-02 | 1/40E-01 | 4/18E-01 | 1/62E-02 |
| CED | MJ | 1/40E+03 | 8/98E+02 | 7/15E+03 | 1/68E+03 | 5/77E+02 |

The study also assessed the environmental impacts during the transportation phase. Table 20 shows that steel and DI pipe materials represent the least environmental impact during the transportation phase. This is since the materials used in DI and steel trenches have the least weight compared to those used in the other trenches. It is worth mentioning that although PVC and HDPE pipes require less materials compared to DI and steel pipes in the production phase, PVC and HDPE have more environmental impact in the transportation phase due to the required use of materials such as crushed gravel and sand for the trench construction (Hajibabaei et al., 2018).

*Table 20: Environmental Impact in the Transportation Phase (Source: Hajibabaei et al., 2018)*

| Impact category | Unit | Steel | PVC | DI | HDPE | Fibrocement II | Fibrocement I |
|---|---|---|---|---|---|---|---|
| GWP | kg CO2 eq | 3/23E+00 | 3/76E+00 | 3/25E+00 | 3/76E+00 | 4/39E+00 | 4/34E+00 |
| OLD | kg CFC-11 eq | 5/99E-07 | 6/96E-07 | 6/03E-07 | 6/96E-07 | 8/14E-07 | 8/04E-07 |
| PO | kg C2H4 eq | 5/44E-04 | 6/33E-04 | 5/48E-04 | 6/33E-04 | 7/40E-04 | 7/31E-04 |
| AP | kg SO2 eq | 1/29E-02 | 1/50E-02 | 1/30E-02 | 1/50E-02 | 1/76E-02 | 1/73E-02 |
| EU | kg PO4— eq | 2/92E-03 | 3/39E-03 | 2/94E-03 | 3/39E-03 | 3/97E-03 | 3/92E-03 |
| CED | MJ | 5/32E+01 | 6/18E+01 | 5/35E+01 | 6/18E+01 | 7/23E+01 | 7/15E+01 |

The observed results during the installation phase presented in Table 21 shows that fibrocement has the highest impact across all environmental categories while PVC and HDPE have similar results as DI and steel pipes (Hajibabaei et al., 2018).

*Table 21: Environmental Impacts in the Installation Phase (Source: Hajibabaei et al., 2018)*

| Impact category | Unit | PVC & HDPE | Fibrocement II | Fibrocement I | DI & Steel |
|---|---|---|---|---|---|
| GWP | kg CO2 eq | 8/83E+00 | 1/07E+01 | 2/80E+01 | 8/73E+00 |
| OLD | kg CFC-11 eq | 1/34E-06 | 1/56E-06 | 2/46E-06 | 1/27E-06 |
| PO | kg C2H4 eq | 2/75E-03 | 3/35E-03 | 4/93E-03 | 2/73E-03 |
| AP | kg SO2 eq | 5/28E-02 | 6/41E-02 | 1/02E-01 | 5/17E-02 |
| EU | kg PO4— eq | 1/29E-02 | 1/60E-02 | 2/74E-02 | 1/30E-02 |
| CED | MJ | 1/37E+02 | 1/65E+02 | 2/76E+02 | 1/35E+02 |

Chilana et al. (2016) analyzed and compared the $CO_2$ footprint of two pipeline materials used for large diameter water transmission pipelines, steel pipe (SP) and PCCP, for 150-miles of a pipeline of different large diameters (66, 72, 84 and 108-inch), and the installation method was open-cut construction method. Three life-cycle phases were considered: fabrication, installation, and operation. The result found that pipe manufacturing consumed a large amount of energy and thus contributed more than 90% of life-cycle carbon emissions for both pipes. SP had 64% larger $CO_2$ emissions from manufacturing compared to PCCP. For the transportation stage, PCCP had larger $CO_2$ emissions due to the heavy weight of the PCCP pipe. In this study, fuel consumption by construction equipment for installation of pipe in the trench was found to be similar for both PCCP and SP. Overall, PCCP was found to have smaller carbon footprint emissions due to the greater energy used during manufacturing of SP (Chilana et al., 2016).

For the installation phase of the pipeline life cycle, Joshi (2012) compared open-cut and pipe-bursting construction methods regarding the environmental aspect. The research was aimed at determining the $CO_2$ emission due to the use of the construction machinery as well as the $CO_2$ emissions due to traffic delay during the construction process. The outcome of the study found that the pipe-bursting installation method had 72.6% less $CO_2$ emissions compared to open-cut installation method. Therefore, it was concluded that this extreme reduction in the $CO_2$ emissions was due to the less excavation, less traffic disruption, and shorter job duration (Joshi, 2012).

Alsadi (2019) studied the $CO_2$ emissions during the fabrication, installation, operation, and disposal phases of the pipeline life cycle. The fabrication phase includes all the energy from the cradle to the factory gate to produce the pipe. The installation phase included transporting the pipeline and construction equipment to the jobsite, pipeline installation, backfilling, and repaving. The operation phase included pumping energy and pipeline cleaning, and the disposal phase includes the energy for disposal of the non-recyclable materials of the pipeline material. His study focused on a large diameter-36-inch, 100-foot section long sewer pressure pipe operating at 100 psi internal pressure, and the life of the pipeline is 100 years. Four pipeline materials were compared: PCCP, PVC, HDPE, and cured-in-place-pipe (CIPP). Three installation methods were used for installing the pipeline: the open-cut method is used to install PCCP, the pipe bursting method is used to install PVC and HDPE, and the CIPP method (Alsadi, 2019). Alsadi (2019) found that PVC pipe using the pipe bursting method has the smallest carbon footprints as compared to PCCP, HDPE, and CIPP (Table 22).

*Table 22: $CO_2$ Emissions during the Pipeline Life-Cycle Phases (Source: Alsadi, 2019)*

| | Stage | PCCP | PVC | HDPE | CIPP | Unit | Remark |
|---|---|---|---|---|---|---|---|
| Phase 1 | Fabrication/ Original | 28,080 | 60,609 | 128,273 | 99591 | lb | From cradle to factory gate |
| | Fabrication/ Optimization | 7,175 | 35,916 | 68,392 | 89,650 | | |
| | Reduction | 75% | 41% | 47% | 10% | | |
| Phase 2 | Installation/ Original | 97,457 | 17,922 | 17,922 | 21,310 | lb | Transportation + Construction+ Backfill+ Repaving |
| | Installation/ Optimization | 30,313 | 7,044 | 7,044 | 4,926 | | |
| | Reduction | 69% | 61% | 61% | 77% | | |
| Phase 3 | Operation/ Original | 788,316 | 680,148 | 693,906 | 738,146 | lb | Pumping + Pipe cleaning |
| | Operation/ Optimization | 732,189 | 680,148 | 693,906 | 738,146 | | |
| | Reduction | 7% | 0 | 0 | 0 | | |
| Phase 4 | Disposal/ Original | 279 | 1,061 | 2,245 | 6,971 | lb | CIPP cannot be recycled |
| | Disposal/ Optimization | 159 | 424 | 898 | 6,971 | | |
| | Reduction | 43% | 60% | 60% | 0 | | |

Another aspect that should be taken into consideration when assessing the environmental impacts of the pipeline materials is the availability of such material in the country where the water supply system will be installed. This is an important aspect since importing material will contribute to GHG emissions from different means transportation. According to CDM Smith's Technical Memorandum-Technical Assessment of Pipe Materials report dated September 3, 2020, all proposed pipeline materials for the AAWDC Project are available in the Middle East except for HDPE pipes. These pipes need to be towed by sea from North Europe, thus shipping of this pipe material will contribute significantly to GHG emissions in comparison to other materials. In addition, the report found that unlike GRP pipe material, steel pipelines can withstand high operating pressure thus reducing the required number of booster pumping stations. This increases the GWP of GRP during operation compared to steel.

## 10.3. Conclusion

The studies show that DI pipes has the highest environmental impact compared to other pipeline materials and that the production of concrete has a significant impact on eco-toxicity. Table 23 presents a summary of environmental performance of the different pipe materials proposed for the AAWDC Project.

*Table 23: Summary of Environmental Performance of the Different Pipe Materials Considered*

| Pipe Material | Summary of Environmental Performance |
|---|---|
| **Steel** | • High impact on ecosystem quality and resources during different life cycle phases<br>• Low energy consumption during operation |
| **Ductile Iron** | • High environmental impact in terms of ozone layer depletion, ecotoxicity, energy consumption, global warming potential, photochemical oxidation, acidification potential, and eutrophication during different stages of its life cycle |
| **GRP** | • Life cycle of GRP has a significant impact on fossil fuel consumption, eco-toxicity and ozone layer depletion<br>• High energy consumption during operation |
| **PCCP** | • Extremely heavy thus transporting this material has a high impact on global warming potential<br>• Relatively medium to low contribution to global warming potential during different life cycle phases |
| **HDPE** | • Relatively medium to low environmental impact in terms of ecosystem quality and resources during different life cycle phases<br>• Not available in the Middle East thus significant GHGs emissions during transportation |