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# WATER REUSE AND ENVIRONMENTAL CONSERVATION PROJECT

CONTRACT NO. EDH–I–00–08–00024–00 ORDER NO. 04

# AS SAMRA BIOSOLIDS USE AND DISPOSAL OPTIONS SELECTION REPORT

30 APRIL 2014

IMPLEMENTED BY AECOM

This document was produced for review by the United States Agency for International Development. It was prepared by AECOM.

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# AS SAMRA BIOSOLIDS USE AND DISPOSAL OPTIONS SELECTION REPORT

**30 APRIL 2014**

Submitted to:
USAID Jordan

Prepared by:
AECOM

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## LIST OF ACRONYMS

| | |
|---|---|
| BFP | Belt Filter Press |
| DS | Dry Solids |
| ET | Evapotranspiration |
| FBI | Fluid Bed Incineration |
| GAM | Greater Amman Municipality |
| GCL | Geosynthetic Clay Liner |
| GHG | Green House Gas |
| GM | Geomembrane |
| HDPE | High Density Polyethylene |
| HHV | Higher Heating Value |
| JS | Jordanian Standards |
| MHI | Multiple Hearth Incinerator |
| MoEnv | Ministry of Environment |
| MSW | Municipal Solid Waste |
| MWI | Ministry of Water and Irrigation |
| ORC | Organic Rankine Cycle |
| PPP | Public-Private Partnership |
| RPA | Restated Project Agreement |
| TCC | Total Capital Cost |
| TIC | Total Installed Cost |
| TOR | Terms of Reference |
| TPE | Total Process Equipment |
| USAID | United States Agency for International Development |
| USEPA | United States Environmental Protection Agency |
| WAJ | Water Authority of Jordan |
| WWTP | Wastewater Treatment Plant |

# 1. INTRODUCTION

The USAID Water Reuse and Environmental Conservation Project (the project) works throughout Jordan in institutional capacity building, pollution prevention for industries, solid waste and wastewater management, and water reuse. The project goal is to protect and conserve scarce resources through regulation, education, and coordination with industry, local communities and the private sector. The project is implemented by the project team and a team of international and Jordanian partners. This five-year project has four primary tasks:

- Task 1 – Institutional and Regulatory Strengthening
- Task 2 – Pollution Prevention and Industrial Water Management
- Task 3 – Disposal Sites Rehabilitation and Feasibility Studies
- Task 4 – Water Reuse for Community Livelihood Enhancement , including a Biosolids Management Initiative

As part of Task 4, the project is undertaking activities described in Part 4, Study Tasks, of the *Terms of Reference for the As-Samra Sludge Management Feasibility Study* (TOR) dated November 2012. As stated therein, “The goal of this study is to analyze the current situation of sludge storage, disposal and reuse, and develop options for recovery/reuse and disposal over the project period in ways that meet the government requirements per the RPA and its annexes, which are compliant with the applicable laws in Jordan and in conformance with international best practices, settling short, medium and long term commitments.” Main components of the study are as follows:

- Phase I – Developing Options
- Phase II – Assessment of the Proposed Option
- Phase III – Landfill Design and Tender Documents

The As-Samra Biosolids Management Feasibility Study “Draft” Inception Findings Report - the first of the Phase I deliverables – was issued in August 2013 and provides the basis for projected biosolids quantities and quality, a discussion of policy objectives, and an overview of the regulatory framework and review for conformance with standards and best practices. This was followed by a Workshop on 11 September 2013, the objective of which was to reach MWI, USAID, and stakeholder consensus on the range of biosolids management options to be evaluated for selection.

This Options Evaluation and Selection Report is the culmination of the combined Phase I efforts and is organized as follows:

- Section 2 – Overview of Biosolids Drying Options: this section discusses the various biosolids drying and processing “pathways” along which the biosolids must proceed to make disposal or beneficial use possible.

- Section 3 – Fatal Flaw Technologies: this section summarizes those biosolids processing technologies that were considered for application at As-Samra but were ultimately discarded from detailed consideration, and the basis for that rejection.

- Section 4 – The Original Six Biosolids Management Alternatives: this section describes the cement kiln, incineration, gasification, land application, landfill and composting options originally identified in the Terms of Reference as worthy of further study. It also describes two technologies (windrow drying and greenhouse drying) that can achieve the 75% DS required for some of these options.

- Section 5 – Options Screening: this section presents the screening level evaluation of the six biosolids management alternatives described in Section 4. Much of this material was presented at the Biosolids Workshops held on 11 September and 29 October, 2013. The section concludes with the results of this screening level evaluation, which reduced the number of options from six to a short-list of four.

- Section 6 – Evaluation of Short-Listed Options: this section evaluates in detail the four short-listed options – landfilling, incineration, gasification, and use of biosolids as a fuel source for cement kiln operation. It also describes the basis of design for the windrow biosolids drying system, the project team's preferred method for achieving 75% DS.

- Section 7 – Criteria for Evaluation and Selection of Alternatives: this section provides an overview of the evaluation criteria and ranking methodology used to identify the preferred alternative.

- Section 8 – Comparison of Options and Recommendations: this section provides a detailed matrix of findings from the technical evaluation presented in Section 6, a numerical ranking and identification of the preferred alternative based on the evaluation criteria presented in Section 7, results of a preliminary financial analysis, and associated recommendations.

The draft of this report provided the basis for subsequent discussions with the MWI and other applicable stakeholders in which the approach forward was developed. This final report includes a preliminary financial analysis and recommendations moving forward. The Phase II work involving conceptual design and more detailed technical and environmental evaluation of the selected alternative will now move forward.

A note on the use of the words "sludge" and "biosolids"

The word "sludge" is used in the TOR. However, to enhance the public image of the sludge produced from the As-Samra WWTP and the Kingdom in general, the word "biosolids" is routinely used in this document. "Biosolids" refers to the sludge produced from wastewater treatment that includes the stabilization process that prepares it for beneficial re-use as opposed to disposal. When referencing documents which contain the word "sludge," and also where this word is appropriate because the sludge has not been stabilized, the project team has the word used "sludge" rather than "biosolids."

## 2. OVERVIEW OF BIOSOLIDS DRYING OPTIONS

The potential methods of disposal or beneficial use of As-Samra biosolids evaluated in this report require different levels of biosolids dryness, described as the Dry Solids (DS) percentage.

The new belt filter press (BFP) mechanical dewatering facility at the As-Samra wastewater treatment plant, expected to be operational by November 2014, is required to produce a minimum of 18% DS cake. Further drying would follow in order to reach the 30%, 50% or 75% DS required for the various options related to disposal or beneficial use of the biosolids.

Figure 2-1 and the following text provide an overview of the pathways along which the As-Samra biosolids must proceed to meet these various percent DS levels. Certain cost assumptions related to various drying processes involved are provided in Section 6, where windrow biosolids drying technology – which can achieve the 75% DS required for certain beneficial uses – is analyzed in some detail.

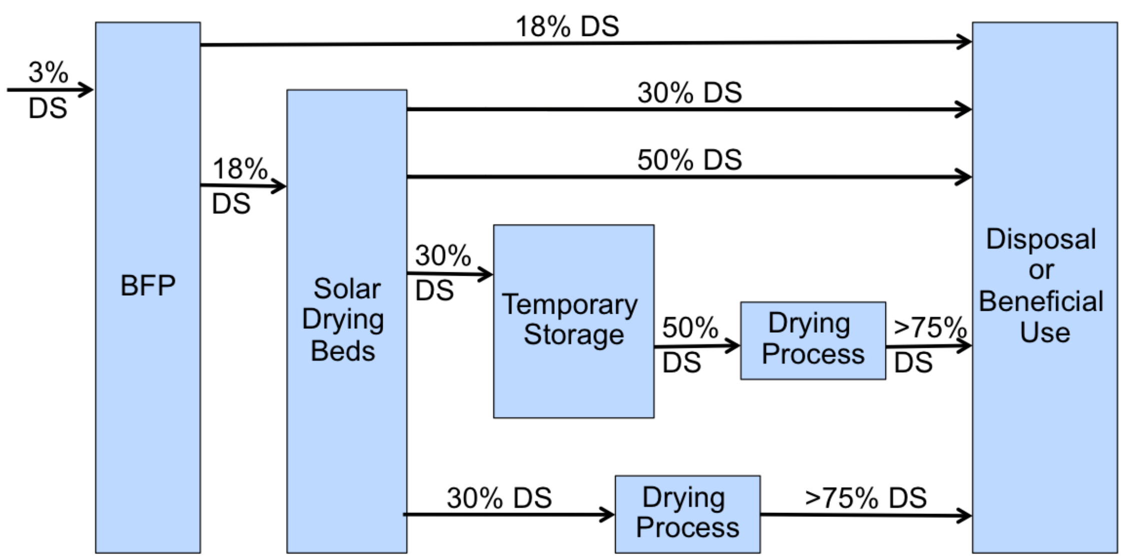



**Figure 2-1. Biosolids processing after BFP for disposal or beneficial use**

- Dewatered 18% cake solids can be transferred directly to a disposal or beneficial use outlet such as landfill, composting, land application or incineration.
- Dewatered 18% cake solids can be transferred directly to a drying process to achieve greater than 75% DS for disposal or to a beneficial use outlet such as land application, incineration, or cement kiln.
- Dewatered 18% cake solids can be transported to the solar drying beds where it is allowed to further dry. Dewatered biosolids should not be allowed to mix with the old biosolids in the solar drying beds.
- Solar drying beds can achieve 30% DS for disposal or a beneficial use outlet such as landfill, composting, land application or incineration.

- Solar drying beds can achieve 50% DS for disposal or a beneficial use outlet such as landfill, land application or incineration.

- Solar drying beds can achieve 30% DS and the biosolids can be transferred to the temporary storage area to further dry to 50% for disposal or a beneficial use outlet such as landfill, land application or incineration.

- Solar drying beds can achieve 30% DS and the biosolids can be transferred to the temporary storage area to further dry to 50% before additional further drying to achieve greater than 75% DS for disposal or a beneficial use outlet such as land application, incineration, or cement kiln.

- Solar drying beds can achieve 30% DS and the biosolids can be dried further to achieve greater than 75% DS for disposal or a beneficial use outlet such land application, incineration, or cement kiln.

# 3. FATAL FLAW TECHNOLOGIES

This section briefly discusses technologies that were ultimately not selected for further analysis.

## 3.1 Upgrade to the Planned Mechanical Dewatering Facility

Mechanical dewatering is a physical separation process aimed at reducing the moisture content of biosolids after some form of chemical conditioning (e.g., with polymers). It involves a high level of moisture removal and achieves typical solids concentrations of 12-30% depending on biosolids characteristics, the specific dewatering device, and polymer dosage. Mechanical dewatering can be the final stage of biosolids processing before hauling and disposal or it can be followed by another process such as drying or incineration. The process is generally accomplished by technologies such as centrifuges, belt filter presses, rotary fan presses, and screw presses.

Construction of a new belt filter press facility is underway that is expected to be in operation by November 2014 and produce a minimum of 18% DS. Drying lagoons should be able to achieve 30-50% DS from the BFP dewatered biosolids. Accordingly, using additional mechanical dewatering devices should not be considered.

## 3.2 Thermal Drying

Thermal drying is a physical separation process aimed at significantly reducing the moisture content of dewatered biosolids. Thermal drying is normally the last step in biosolids processing before final disposal or beneficial use, or it can be an intermediate process prior to incineration, gasification, or pyrolysis.

Biosolids dryers come in several types, all of which operate with the goal of decreasing water content in the biosolids and reducing pathogens. Dryers are typically fed dewatered biosolids at solids concentrations of approximately 15-35% DS, and dried solids concentrations are approximately 90-95% DS. Accordingly, thermal drying can be practiced after BFP dewatering or solar drying achieving 30% DS. The thermal drying process greatly reduces storage, transportation, and disposal cost since it significantly lowers the water content and reduces the weight and volume to be hauled. Thermal drying, however, is very energy intensive and consumes large amounts of fuel.

Biosolids thermal dryers are classified into three categories:

- Direct dryers use a drying medium such as hot air, which comes in direct contact with the biosolids to increase the biosolids temperature through convective heat transfer, evaporating the water in the biosolids.
- Indirect dryers use a medium such as hot oil or steam that heats the biosolids through a conducting surface, so that the heating medium does not come in direct contact with the biosolids.
- Combination dryers use two media, one which comes in direct contact with the biosolids and one which heats them through a conducting surface.

Because of the high capital and operating costs associated with thermal drying, this process is not considered favorable for As-Samra. Furthermore, with the local climate and sufficient land area available, drying lagoons and/or further drying in the temporary storage area can achieve 50% DS – the required dryness for many outlets considered. If further drying beyond

75% DS is required, mechanical windrow drying or greenhouse drying should be more cost effective when compared to energy intensive thermal drying.

## 3.3 Lime Stabilization

Lime stabilization involves addition of lime to biosolids in order to raise the pH to levels unfavorable for pathogen growth. The heat produced by the reaction of the lime with the water in the biosolids raises the pH and temperature of the biosolids sufficiently to comply with Jordan's Class 2 requirements. Class 2 requirements (excluding dry solids requirement) that can be achieved by lime stabilization are already achieved by the existing anaerobic digestion process.

Quicklime (calcium oxide) is commonly used because it has a high heat of hydrolysis (1,142 kJ/kg lime) and can significantly enhance pathogen destruction. Other materials such as hydrated lime can also be used. In general, lime stabilization is a non-proprietary process, although several patented processes are available.

One of the major disadvantages of the lime stabilization process is that it increases the total mass and volume of the material that needs to be hauled and disposed of. Moreover, the process is usually used in conjunction with acidic solids, which is not the case in Jordan for land application. Lastly, offensive strong odor (H2S, ammonia, trimethyl amine, etc.) is usually generated from lime addtion requiring odor control and hindering public acceptance of lime stablized biosolids for land application. Accordingly, lime stabilization was not considered further.

## 3.4 Co-incineration with MSW

Co-incineration of As-Samra biosolids with municipal solid waste (MSW) was discussed in the Inception Findings Report. The main driver for implementing co-incineration is reduction in the combined cost of incinerating biosolids and solid wastes. The process produces the heat energy necessary to evaporate water from biosolids, supporting combustion of solid wastes and biosolids, and provides excess heat for steam generation, if desired, without the use of auxiliary fossil fuels.

Co-incineration with MSW is economically feasible if a MSW or Refuse Derived Fuel (RDF) facility already exists. Currently, however, there is no known MSW incineration or RDF facility near As-Samra or in the Kingdom of Jordan. Given the capital investment of a full scale MSW collection, separation and incineration facility, it is not feasible to consider this option at this time.

## 3.5 Reed Beds

Reed beds consist of channels or trenches filled with sand or rock to support emergent vegetation. Liquid biosolids are applied to the surface of the beds and the filtrate flows through the gravel to underdrains. Reed beds are similar in appearance to subsurface flow constructed wetlands, but they use surface application as opposed to subsurface application.

Typically, reed beds consist of a 250-mm-deep drainage layer composed of 20 mm washed gravel, 250-mm-deep layer of 4 to 6 mm washed gravel, covered by a 100 to 150 mm layer of sand. One meter of freeboard above the sand layer is typically provided for a 10-year accumulation of biosolids, and reeds (or other wet land plants) are planted in the gravel layer just below the sand. The plants create pathways in the underdrain and also uptake water directly. The process is a form of passive composting and biological stabilization.

Biosolids are not applied until after the reeds are well established. The reeds are typically harvested in the winter by cutting the tops back to a level above the biosolids whenever the plant growth becomes too thick and restricts the even distribution of biosolids. The reeds can then be composted or burned if desired.

The process is best suited for small plants with available land area. However, to practice reed bed technology for As-Samra an area of about 100 hectares would be required. Furthermore, a significant amount of water is required, up to 3 million cubic meters in 2014 and 5 million cubic meters by 2034. Accordingly, reed beds are not considered further in this evaluation.

# 4. THE ORIGINAL SIX BIOSOLIDS MANAGEMENT ALTERNATIVES

This section discusses the six biosolids disposal or beneficial use options identified in the TOR:

- Landfill, either separately or with MSW
- Composting
- Land application
- Incineration for energy recovery
- Gasification
- Cement kiln

The evaluation of each option includes required regulatory reform measures, marketing efforts, required public awareness and educational programs, physical investment, required piloting, public private partnership (PPP) potential, and cost of construction.

## 4.1 Landfill

Sludge and biosolids landfilling is widely practiced where land is available. Landfilling biosolids can be practiced alone in a mono landfill, referred to here in this study as monofill, or in existing MSW landfills (typically referred to as co-disposal). In MSW landfills, sludge or biosolids are either mixed with MSW or used as a daily cover material. Use of biosolids as a daily landfill cover for MSW is considered a beneficial use since it replaces construction grade material that would otherwise be used for this purpose.

### 4.1.1 Monofill

Figure 4-1 is a schematic process diagram of the monofill option, which can be practiced after achieving 30% DS from the solar drying beds or after achieving 50% DS from either the solar drying beds or after transferring to the temporary storage area. Monofill can be a standalone option for biosolids disposal or a backup to other options. The direct disposal of dewatered cake solids between 18-30% DS is not commonly practiced; instead the biosolids are usually mixed with soil for improved handling landfill stability. The applicability of a monofill is therefore typically more suitable for biosolids with a dryness greater than 50% DS. Based on the design biosolids loading, the required size of a monofill for biosolids at 30% DS is about 4 million cubic meters of biosolids and 2.4 million cubic meters for 50% DS. Accordingly the costs associated with landfilling 50% DS biosolids should be significantly less expensive than landfilling 30% DS biosolids considering the substantial additional volume required for the wetter biosolids. Table 4-1 lists the component evaluation of the monofill option.

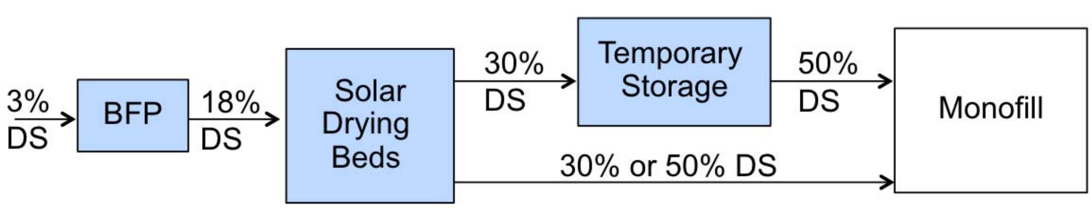



**Figure 4-1. Schematic diagram of monofill option**

**Table 4-1. Component Evaluation of Monofill**

| Component | Monofill |
|---|---|
| Regulatory Reform | Use USEPA Subpart D |
| Marketing Efforts | None |
| Awareness and Educational Programs | Landfills considered beneficial use because recovered biomethane is used for energy generation |
| Physical Investment | • Loading station at As-Samra with scale<br>• Transportation trucks from As-Samra<br>• Receiving station at landfill<br>• Landfill construction and closure<br>• Energy recovery system at landfill |
| Piloting | • None required<br>• Design requires running shear strength testing on biosolids at different moisture content |
| PPP Potential | Low |
| Cost of Construction | Low |

### 4.1.2 Landfill with MSW

Figure 4-2 is a schematic process diagram for the landfill with MSW option, which can be practiced after achieving 30% DS from the solar drying beds or after achieving 50% DS from either the solar drying beds or after transferring to the temporary storage area. Landfill with MSW can be a standalone option for the produced biosolids or a backup to other options. Ghabawi MSW landfill, operated by Greater Amman Municipality (GAM), is about 40 km south of As-Samra and is considered a suitable option for landfilling the produced biosolids.

The produced biosolids from As-Samra constitute only 9-10% of the Ghabawi landfill capacity according to the July 2011 report "Study on Sludge Management at Samra Wastewater Treatment Plant" prepared by Sogreah. However, the report indicated that GAM objects to using the Ghabawi landfill for biosolids from As-Samra due to capacity limitations and operational challenges connected to mixing the biosolids with MSW. For use of biosolids as daily landfill cover, GAM indicated that that the design of the landfill is based on using excavated material and not biosolids. Further discussions with GAM regarding using Ghabawi as a contingency landfill is recommended and it is further recommended that landfill at Ghabawi should be limited to 50% DS or greater. This should reduce the volume needed for a biosolids landfill at Ghabawi and reduce hauling costs. Table 4-2 lists the component evaluation of landfilling with MSW option, if feasible.

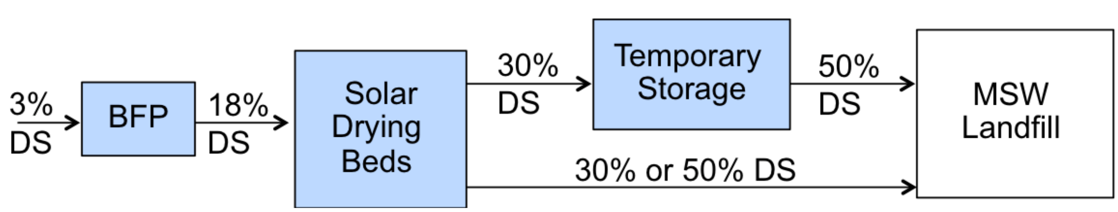



**Figure 4-2. Schematic diagram for landfilling with MSW option**

**Table 4-2. Component Evaluation of Landfilling with MSW**

| Component | Landfill with MSW |
|---|---|
| Regulatory Reform | Use USEPA Subpart D |
| Marketing Efforts | • Education regarding the high rate of biogas produced from biological degradation of the biosolids leading to more methane gas production |
| Awareness and Educational Programs | • Require educating existing MSW landfill staff regarding physical characteristics and appearance of 50% DS biosolids that behave like soil and the use of biosolids as a daily cover in MSW landfill<br>• Landfills considered beneficial use because recovered biomethane is used for energy generation |
| Physical Investment | • Loading station at As-Samra with scale<br>• Transportation trucks from As-Samra<br>• Receiving station at MSW landfill |
| Piloting | None required |
| PPP Potential | Low |
| Cost of Construction | Low |

## 4.2 Composting

Composting is a process in which biodegradable material is decomposed by aerobic microorganisms in a controlled environment. The heat generated in composting pasteurizes the product, significantly reducing pathogens. The heat generated also drives off water vapor, further dewatering the product and reducing reuse volume. Composting that is performed according to regulatory guidelines produces Category 1 Biosolids, if recommended modifications to the existing JS 1145/2006 as discussed in the Inception Findings Report are accepted. Composting that is performed properly produces a nuisance-free, humus-like material. The three different methods of composting typically used for wastewater biosolids are aerated static pile, windrow and in-vessel composting.

All composting processes generally include common basic steps. First, the dewatered biosolids are mixed with an amendment and/or bulking agent to increase porosity of the mixture and provide a carbon source to improve the degradability of the compost. A rule of thumb for composting is to have a ratio of between 25:1 and 35:1 of carbon to nitrogen (mass basis). The resulting mixture is piled or placed in a vessel where microbial activity causes the temperature to rise, starting the “active composting” period. The desired temperature required for optimal operation and end quality varies based on the method of composting and desired use of the end product. After the “active composting” period is complete, the material is cured and distributed.

Figure 4-3 shows a schematic diagram of the composting option. Because water is needed for the composting process to proceed, it is recommended to compost biosolids at 30% DS. The required bulking agent for practicing composting is estimated to be about 640 dry tonnes (2025-2034). Bulking agents are not readily available in the Kingdom of Jordan and this availability is likely to limit biosolids composting to about 10% of the produced biosolids from As-Samra. Composting therefore cannot be a standalone option, but it could be a component of other options for processing the biosolids; if practiced, the composting site should be adjacent to As-Samra. Additionally, bulking agents are typically received from municipalities and landscaping contractors for a tipping fee, thereby supporting the operations cost of the composting facility.  In Jordan, bulking agents would need to be purchased, making the process less economically feasible. Table 4-3 lists the component evaluation of composting a portion of As-Samra biosolids.

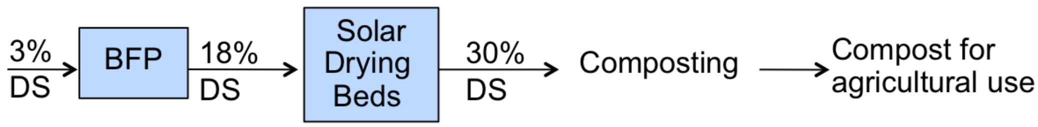



**Figure 4-3. Schematic diagram for composting option**

**Table 4-3. Component Evaluation of Biosolids Composting**

| Component | Composting |
|---|---|
| Regulatory Reform | Yes, modify JS to allow compost product (usually 60% DS range) to be categorized as Category 1 |
| Marketing Efforts | Yes, extensive marketing effort of compost product; however, the product is expected to generate revenue |
| Awareness and Educational Programs | Compost material recognized for agriculture use, but biosolids-based compost requires education of farmers and end users |
| Physical Investment | • Loading station at As-Samra with scale<br>• Trucks to compost facility or conveyors<br>• Facility construction with odor control, bagging if needed<br>• Trucks to end users |
| Piloting | Required |
| PPP Potential | Medium |
| Cost of Construction | Medium |

## 4.3 Land Application

Land application of biosolids is defined as the spreading of biosolids on or just below the soil surface. Biosolids may be applied to agricultural land, forest land, disturbed land, and dedicated land disposal sites. To qualify for application to agricultural and non-agricultural land, biosolids or material derived from biosolids must meet defined pathogen and vector attraction requirements and the requirements of JS 1145/2006.

The application of biosolids to land for agricultural purposes is beneficial because it provides essential macro-nutrients such as nitrogen, phosphorous and magnesium and micro-nutrients such as iron, manganese, copper, chromium, selenium, and zinc which can be used to reduce or eliminate the need for purchasing chemical fertilizers. The organic matter improves soil structure, tilth, water-holding capacity, water infiltration, and soil aeration. Organic matter also contributes to the cation-exchange capacity of the soil which allows the soil to retain potassium, calcium, and magnesium. Land application of biosolids can also be used for site reclamation to improve damaged soils.

Figure 4-4 is a schematic diagram of the biosolids land application option. If the biosolids are to be used as Category 2 per the JS 1145/2006, then they must be dried to greater than 50% by either the solar drying beds or temporary storage area. It is estimated that the agriculture and rangeland/Badia within a reasonable distance from As-Samra will use about 35% of the produced biosolids, with another option required for processing the remaining half of the produced biosolids. It is recommended that the biosolids be stored on a concrete pad prior to land application to avoid compromising the quality of the biosolids during turning and loading. Note that if a portion of the biosolids is required to meet Category I, a portion of the storage area can be transformed to greenhouse or windrow drying to produce greater than 90% DS. Table 4-4 lists the component evaluation of land application a portion (~ 50%) of As-Samra biosolids.

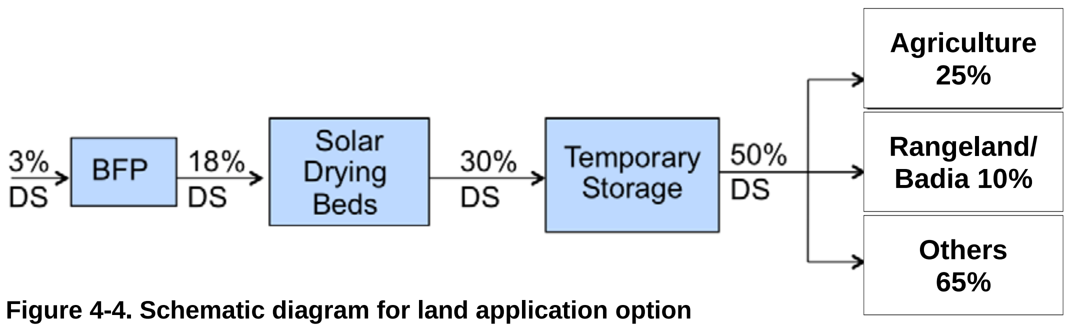



**Figure 4-4. Schematic diagram for land application option**

**Table 4-4. Component Evaluation of Biosolids Land Application Option**

| Component | Land Application |
|---|---|
| Regulatory Reform | JS962 should be aligned with JS1145 |
| Marketing Efforts | Yes, significant marketing effort |
| Awareness and Educational Programs | Vibrant program required |
| Physical Investment | Minimum capital investment<br>• Loading station with scale<br>• Trucks to end users |
| Piloting | Demonstration is required to prove viability, safety, and advantage over chemical fertilizer |
| PPP Potential | Low |
| Cost of Construction | No significant capital investment from MWI for practicing land application |

## 4.4 Mono Incineration for Energy Recovery

### 4.4.1 Incineration and Energy Recovery Overview

Incineration or advanced thermal oxidation is a combustion reaction that occurs in the presence of excess oxygen. Fluidized Bed Incineration (FBI) and Multiple Hearth Incineration (MHI) are established technologies and are the most common types of incineration used for dewatered biosolids. MHI is now considered an outdated technology and very few if any new systems are being constructed, so it is not discussed further in this report.

FBIs consist of a vertically oriented outer shell constructed of steel and lined with refractory material. Partially dewatered biosolids are fed into the lower portion of the furnace on top of a bed of sand. Air at 20 – 35 kPa is injected through nozzles, known as tuyeres, simultaneously fluidizing the bed of hot sand and the incoming biosolids. The fluidizing action creates turbulence and mixing to allow for optimal combustion conditions. Combustion temperatures of 760-950°C are maintained in the bed with residence times of approximately 2-5 seconds. The combustion reaction is separated into two zones, one within the bed and one in the freeboard area above the bed. The residual ash particles remaining after combustion along with some sand are carried out the top of the furnace thus requiring downstream removal. The resulting flue gas must be treated in accordance with air permitting requirements.

The fluidizing combustion air is typically preheated utilizing a large air to air heat exchanger (or air preheater) before being injected into the furnace. This is known as a “hot windbox” design. If ambient air is used, it is known as a “cold windbox” design. A cold windbox design does not require an air preheater but tends to require more auxiliary fuel (natural gas or oil) to operate unless the biosolids are very dry (>35 or 40%) or have a very high heat value. With solar drying a cold windbox type design would be suitable.

Partially dried biosolids can also be combusted in a reciprocating grate furnace. In these types of systems the bottom of the furnace is tilted and the moving grates agitate the solids while also slowly transferring them through the furnace. Major differences between this type of furnace and FBIs are that reciprocating grate furnaces do not require pressurized air and the majority of the ash is extracted directly out the furnace by a screw or belt conveyor. These systems are also much less common than FBIs for this application, with only a handful of installations worldwide burning biosolids.

There are several methods to recover heat or energy from a combustion process. For example, the heat in the hot flue gases can be recovered in a boiler and used to generate electricity via a steam turbine. A similar system setup can be used with a hot oil heater and an Organic Rankin Cycle (ORC) turbine. Both of these electricity generation approaches require a substantial amount of ancillary equipment and a skill set different from that possessed by standard WWTP operators.

### 4.4.2 Mono Incineration at As-Samra

Specific incineration and energy recovery from As-Samra produced biosolids were previously discussed in the Inception Findings Report. Based on the calorific value of the biosolids, 3,600 Cal/g, the energy that can be recovered from the biosolids depends on the dryness of the biosolids. At 30% DS there is not enough energy in the biosolids to sustain autogenous combustion requiring additional fuel; autogenous burning is sustained at ~ 35% DS. It is possible to recover about 8,000 MJ/tonne of biosolids and 13,000 MJ/tonne of biosolids at

50% and 75% DS, respectively. Drying the biosolids beyond 75% to greater than 90% DS, results in smaller amount of energy recovery. Accordingly, to generate energy from the biosolids, incineration should be practiced at 50% or 75% DS.

Figure 4-5 is a schematic diagram of the incineration option at 50% DS that can be achieved directly from the solar drying beds or from the temporary storage area. Figure 4-6 is a schematic diagram of the incineration option at 75% DS. Additional drying beyond the solar drying beds and temporary storage area is required to achieve 75% DS, which can be achieved by either greenhouse drying or windrow drying. The additional drying process can also receive 30% DS from the solar drying beds or 50% from the solar drying beds or 50% from the temporary storage area.

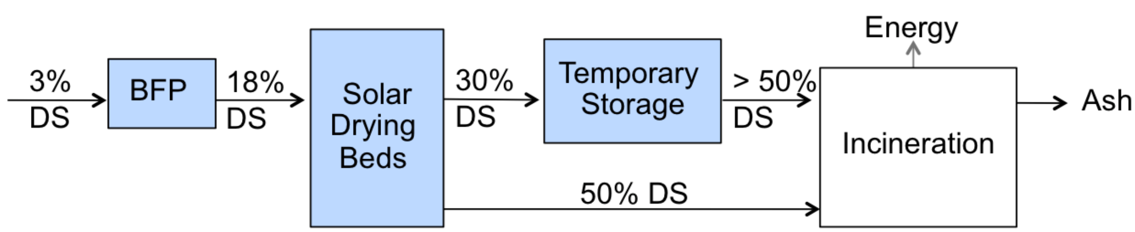



**Figure 4-5. Schematic diagram - Incineration at 50% DS**

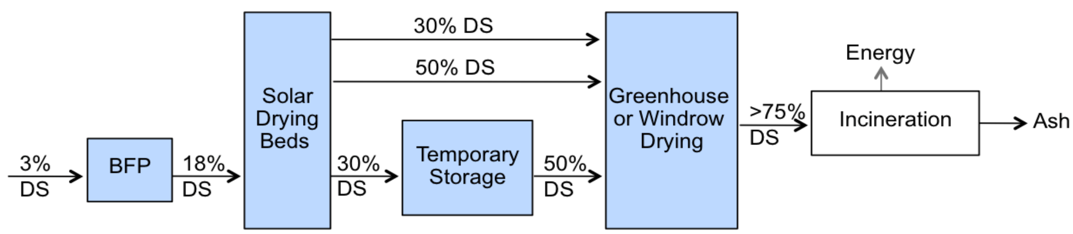



**Figure 4-6. Schematic diagram - Incineration at 75% DS**

With drying to either 50% or 75% DS, incineration processes all the produced biosolids from As-Samra at the design year of 2034. Furthermore, incineration can be used to process scum, grease and screenings generated from various wastewater treatment processes. Construction of a concrete pad for biosolids drying is recommended to maintain integrity during turning and loading to prevent mixing with dirt and gravel. Table 4-5 lists the component evaluation of incinerating As-Samra biosolids at either 50% or 75% DS.

**Table 4-5. Component Evaluation of Biosolids Incineration at 50% or 75% DS**

| Component | Incineration |
|---|---|
| Regulatory Reform | Jordanian Standards do not include incineration standards specific to biosolids |
| Marketing Efforts | None (Incineration facility should be located adjacent to As-Samra) |
| Awareness and Educational Programs | None |
| Physical Investment | • Additional drying facilities (only for 75% drying)<br>• Loading station or conveyance system to incineration facility<br>• Incineration facility with emission control |

**Table 4-5. Component Evaluation of Biosolids Incineration at 50% or 75% DS**

| Component | Incineration |
|---|---|
| | • Energy recovery system<br>• Trucks transporting ash to final location |
| Piloting | None |
| PPP Potential | High |
| Cost of Construction | High |

## 4.5 Gasification

Gasification is an established process for converting organic waste to a fuel gas called syngas, and has been practiced since the 1800s to generate fuel gas from coal and other biomass. Syngas is composed mainly of CO, $CO_2$, $H_2$ and $CH_4$ and has a low heating value of 4,470-5,600 kJ/$m^3$, which is approximately 25% of the heat value of biogas generated from anaerobic digestion. Although gasification is common in many industries, gasification of biosolids is still a relatively new process. Currently, there are only a few biosolids gasification systems worldwide.

Pyrolysis is also an established technology used in the chemical industry to produce charcoal, activated carbon and methanol. Similar to gasification, pyrolysis at high temperatures generates a combustible gas, pyrolysis gas, with a low heating value. Pyrolysis can also be used to generate char and oil. Pyrolysis is the first step in both gasification and combustion reactions. Pyrolysis of biosolids, however, is still considered embryonic technology, and will not be considered in this evaluation.

Gasification and pyrolysis differ from incineration based on the amount of oxygen that is supplied to the process. Table 4-6 shows the operating difference between incineration, gasification and pyrolysis and the main byproducts from each process.

**Table 4-6. Comparison of Incineration, Gasification, and Pyrolysis**

| Parameter | Incineration | Gasification | Pyrolysis |
|---|---|---|---|
| Temperature (°C) | 750-1,100 | 600-1000 | 200-600 |
| $O_2$ Supplied | > Stoichiometric rate (Excess Air) | < Stoichiometric rate (Limited Air) | None |
| By-Products | Flue Gas ($CO_2$, $H_2O$) and Ash | Syngas (CO, $H_2$) and Ash | Pyrolysis Gas, Oils, Tars and Char |

To effectively gasify biosolids, most commercially available systems require the biosolids be dried to greater than 75% solids content and be in granular form. Pelletization is not required for gasification; however, a certain degree of uniformity in the dried granular material along with low dust content is required. The required dryness depends on the gasification technology. There are two energy recovery methods from gasification and pyrolysis: close-couple gasification and two-stage gasification.

Syngas oxidation generates a high temperature flue gas, approximately 980°C, which can be used for close coupled heat recovery. The energy recovered from the flue gas can be used as the energy source to dry the biosolids and minimize or eliminate the need for fossil fuels (e.g., natural gas or fuel oil). The hot flue gas can also be used as an energy source for generating electricity through the use of steam turbines or an ORC. The close coupled method of electrical production is commonly practiced with other types of biomass gasification, but is uncommon for biosolids since it is generally more economical to use flue gas heat for thermal drying the biosolids prior to gasification.

In two-stage gasification systems, the syngas produced from gasifying the dried biosolids is cleaned and the cleaned syngas can be used as a fuel source for multiple purposes such as process heat and electrical production mainly via internal combustion engines. The cleaned syngas can be further refined to a marketable fuel product such as biodiesel, methane, hydrogen or methanol. Syngas cleaning is required to remove sulfur, siloxanes, and other contaminants that could damage downstream processing equipment or contribute to air pollution. The level of cleaning required is dependent on the downstream process and air permitting regulations. Syngas cleaning is not fully developed for biosolids applications and is currently considered to be in the demonstration phase, so it is not considered further in this analysis.

Figure 4-7 shows a schematic diagram of the gasification option at greater than 75% DS. Additional drying beyond the solar drying beds and temporary storage area is required to achieve 75% DS, which can be achieved by either greenhouse drying or windrow drying. The additional drying process can also receive 30% DS from the solar drying beds or 50% from the solar drying beds or from the temporary storage area.

With the gasification process, all the produced biosolids from As-Samra at the design year of 2034 can be processed. Similar to incineration, gasification can be used to process scum, grease and screenings generated from various wastewater treatment processes. Construction of a concrete pad for biosolids drying is recommended to maintain integrity during turning and loading to prevent mixing with dirt and gravel. Table 4-7 lists the component evaluation of gasification of As-Samra biosolids.

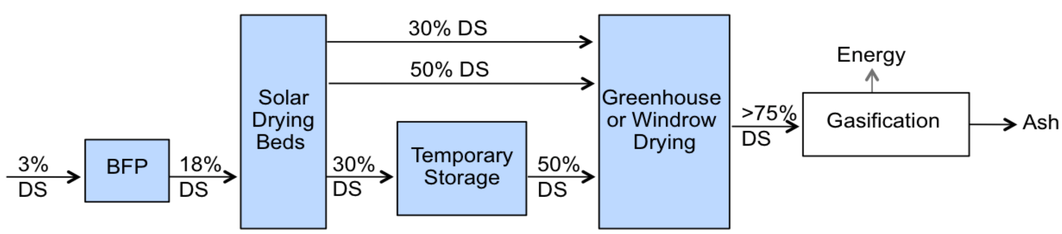



**Figure 4-7. Schematic diagram gasification at 75% DS**

**Table 4-7. Component Evaluation of Biosolids Gasification**

| Component | Gasification |
|---|---|
| Regulatory Reform | As with incineration, JS do not include gasification standards specific to biosolids |
| Marketing Efforts | None (gasification facility should be located adjacent to As-Samra) |

**Table 4-7. Component Evaluation of Biosolids Gasification**

| Component | Gasification |
|---|---|
| Awareness and Educational Programs | None |
| Physical Investment | • Additional drying facilities<br>• Loading station or conveyance system to incineration facility<br>• Incineration facility with emission control<br>• Energy recovery system<br>• Trucks transporting ash to final location |
| Piloting | None |
| PPP Potential | High |
| Cost of Construction | High |

## 4.6 Cement Kiln

Once dried, the biosolids can be used in lieu of coal in cement kilns for cement production. The Inception Findings Report discusses in detail using the dried biosolids in a cement kiln. A discussion regarding use at the nearby Al Rajhi cement kiln, Lafarage Cement Factory, and Manaseer Cement Company was reported in the Inception Report Findings, which indicated willingness to use the dried biosolids if uniform and greater than 75% DS. Figure 4-8 is a schematic diagram of achieving >75% DS for the cement kiln option.

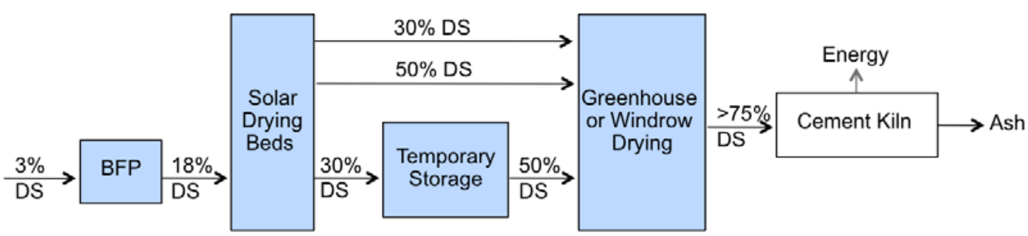



**Figure 4-8. Schematic diagram cement kiln option**

For the cement kiln option, MWI should be able to generate revenue from the dried biosolids. This revenue should be based on the calorific value of the dried biosolids and the value of energy source being replaced by the dried biosolids. The energy recovery value and carbon credit go to cement companies, however, and not MWI. Taking the cement kiln option requires minimum capital investment. Based on the inception report findings, when the biosolids are dried to 75% DS, at the design year As-Samra generates 25% more biosolids than Al Rajhi capacity. However, at 90% DS, Al Rajhi can process all biosolids until 2034, so the cement kiln can be a standalone option at this level of dry solids. Manaseer Cement Company can take only one third of the produced biosolids at the design year. Table 4-8 lists the component evaluation of the cement kiln option for As-Samra biosolids.

**Table 4-8. Component Evaluation of Cement Kiln Option.**

| Component | Cement Kiln |
|---|---|
| Regulatory Reform | None |
| Marketing Efforts | None |
| Awareness and Educational Programs | None |
| Physical Investment | • Additional drying facilities<br>• Loading station with scale<br>• Trucks to cement kiln facility |
| Piloting | None |
| PPP Potential | High |
| Cost of Construction | Very low |

## 4.7 Drying Options

To achieve biosolids concentrations greater than 75% DS, passive solar drying methods were considered in lieu of thermal dryers which were determined cost prohibitive from a capital and operating cost standpoint. Conventional drying beds are very popular worldwide where land is abundant and neighbors are unlikely to be impacted by odors. In conventional drying beds, liquid sludge is pumped into a drying bed where sufficient time is allowed for drainage and evaporation of the liquid providing both dewatering and drying. The drying bed process, however, can also follow mechanical dewatering and both open air windrow drying and greenhouse drying have been successfully used worldwide.

### 4.7.1 Mechanical Windrow Drying

Windrow drying is a simple and low tech process in which dewatered biosolids are formed into windrows typically on a concrete, asphalt or even dirt or clay surface. The drying efficiency, however, is improved when applied to a hard surface and the city of Phoenix noted an efficiency gain of six times when drying on hard surface versus packed clay (Brown Bear website). The biosolids are periodically turned and aerated with mechanical turners (typically once or twice a day) such as the one shown in Figure 4-9 below. The turning process breaks the surface crust, aerates the biosolids and exposes the moist solids to air and the sun to enhance the drying process.

**Figure 4-9: Pictures of Windrow Drying Turners**
(Source: Left Picture: http://www.brownbearcorp.com/environmental_sludge%20drying.html, Right Picture: http://www.brownbearcorp.com/testimonials/Pinery%20WWTP.pdf)

There are several windrow drying reference facilities in the US, with some used in large cities including:

- Phoenix, Arizona
- Miami, Florida
- Chicago, Illinois
- Parker, Colorado

These cities all use Brown Bear™ turners for the windrow drying process to produce a product used for land application and many claim to meet Class A requirements with the process. Cities in temperate areas with cold snowy winters, like Chicago and Parker operate the system only in the spring, summer and early fall months when the weather is suitable; during the wintertime period they store biosolids onsite.

In order to gauge the sizing and operation requirement, the project team attempted to contact the facilities to discuss their sizing and operation but was only able to speak with Dan Collins at the Chicago Metro Water Reclamation District regarding their drying operation. Points learned from the call include:

- They have approximately 200 acres (81 hectares) total for drying 45,000-65,000 dry tonnes of material per year and they only operate the drying during spring, summer and fall.
- They operate 6-10 Brown Bears at a time. They also use a rototiller to turn their biosolids. The rototiller is faster than the brown bear.
- Some biosolids are thickened in lagoons to 8-10% then spread onto the drying beds approximately 230 mm (9 inches) thick until they are ~30% dry, then the piles are windrowed up to 460-610 mm (18-24 inches) tall. The windrow spacing is kept to a minimum, typically less than 300 mm.
- During the spring and fall it takes ~12 weeks and during the summer it takes ~ 8 weeks to get to 60-70% dry solids.
- The drying beds average 5,800 tonnes/ha (2,600 tons per acre[1]) water evaporation rate.

The observations from Chicago and feedback from Brown Bear Corporation's experience were used as the basis to align the windrow drying sizing criteria with Amman's climatic conditions.

### 4.7.2 Greenhouse Drying

Greenhouse drying is essentially an improved drying bed enclosed inside a greenhouse that maximizes the readily available solar energy while protecting the biosolids from potential precipitation. In most greenhouse drying systems, dewatered biosolids are distributed in a greenhouse either manually or automatically. It is also possible to add liquid sludge directly to the greenhouse; however, the additional greenhouse area required typically outweighs the benefit from eliminating the dewatering step. Greenhouse drying is best suited for tropical or arid environments, such as in Jordan, but installations exist in more temperate climates as well.

During the drying cycle, greenhouse conditions such as temperature, humidity and solar radiation are monitored to control the greenhouse. The greenhouse contains circulation fans

[1] http://www.brownbearcorp.com/testimonials/Chicago%20Speed%20Dries%20Its%20Sludge.pdf

and exhaust fans to provide convective drying and control of internal climatic conditions. A schematic of a typical greenhouse drying system is shown in Figure 4-10. The biosolids are periodically turned and aerated with varying devices depending on the manufacturer as illustrated in Figure 4-11. In addition, low temperature waste heat can be used to enhance greenhouse drying and reduce area requirements for the greenhouse.

There are numerous installations worldwide for greenhouse drying, including more than 16 in the United States, but most installations are at small to medium-sized plants. Although the process is reported to work well, there can be issues with odor in the greenhouse, especially for unstabilized sludge. Most odors are reported when the sludge or biosolids are still moist enough to allow fermentation and biological activity to occur. Greenhouse drying also requires a fairly large footprint so this technology is typically only feasible where sufficient land area is available. The application at As-Samra would likely be one of the larger greenhouse drying systems in the world, if not the largest.

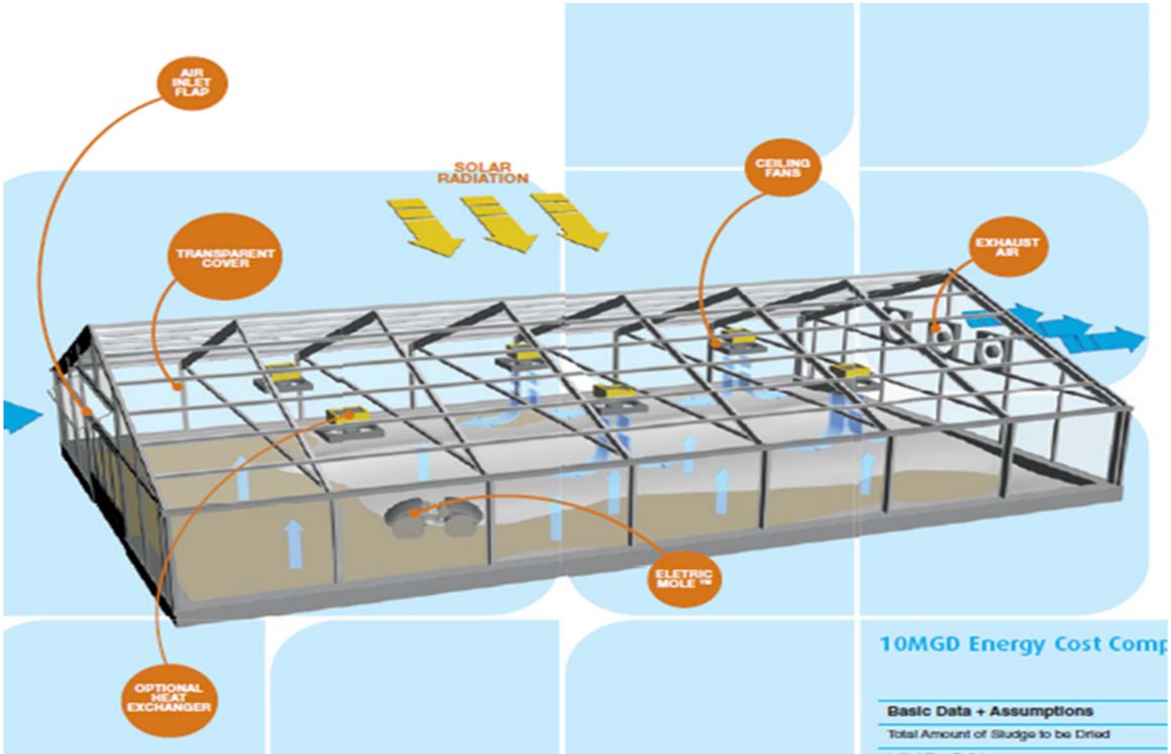



**Figure 4-10. Greenhouse drying Schematic (Courtesy of Parkson)**

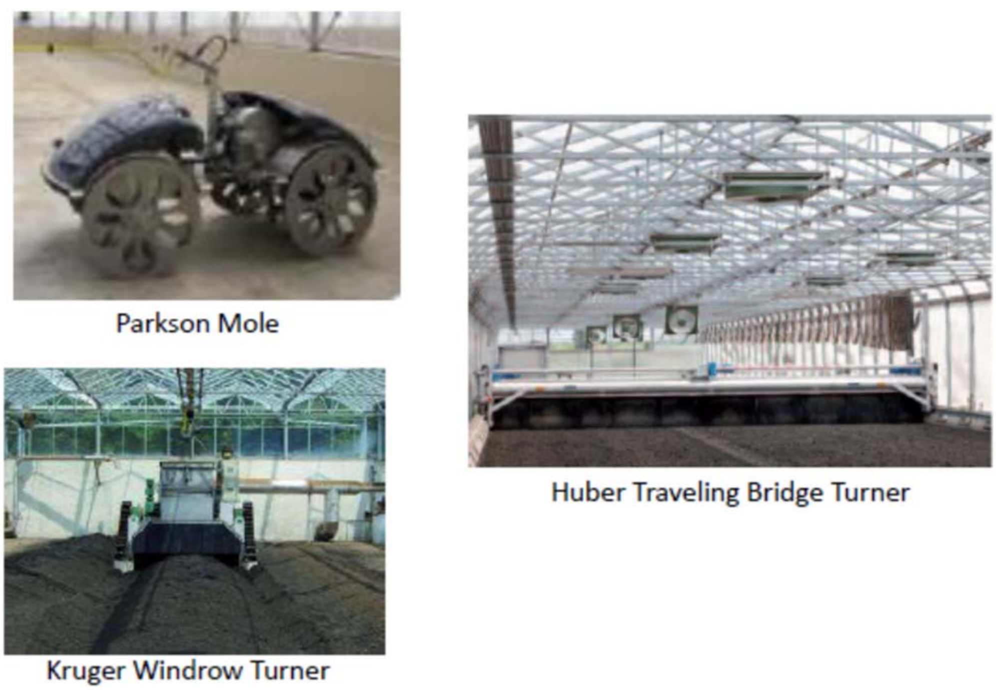



**Figure 4-11. Various greenhouse drying sludge turners (Courtesy of Parkson, Kruger, and Huber)**

## 4.8 Options for Beneficial Use of the Existing Stored Biosolids

As presented in the Inception Findings Report dated September 2013, the volatile contents and calorific values are much lower for the stored/dried biosolids than for the digested biosolids coming out of the digester. With the low volatile content and higher heat values (HHV), the stored biosolids are not suited for incineration or gasification. Additionally, the potential for energy recovery for the stored biosolids when landfilled is also significantly reduced making landfilling of stored biosolids less viable than landfilling of future dewatered and dried biosolids.

Remaining potential beneficial uses of the existing stored biosolids are land application and cover material for landfills. These two options are discussed in the paragraphs that follow.

### 4.8.1 Use in Land Application

Biosolids have been accumulating at As-Samra WWTP since the commencement of the plant's operation in 2008. The quantity of dry biosolids produced from 2008 through the end of 2013 is estimated at 223,015 Tonnes Dry Solids (SPC, 2013). The stored biosolids meet Category 1 of Jordanian Standards JS 1145/2006 after a storage period of two years. Moreover, the stored biosolids fall within the requirements of JS 962/2011 for Organic Fertilizers and Soil Conditioners in terms to the pathogen content, nutrient content, and heavy metal limits. Hence, the biosolids could be used for land application as organic fertilizer and/or soil conditioner. It should be noted that JS 962/2011 currently prohibits the use of fertilizers originating from human waste to be used as soil conditioners and organic fertilizers. This contradicts the intent of JS1145/2006 which provides parameters in which biosolids can be used in land application. The WRECP team is continuing its attempts to work with the Ministries to align these to Jordanian standards.

Based on the sampling results, the stored biosolids produced from As-Samra WWTP have considerable agronomic value. The stored biosolids have significant nutrients content (N, P, K, Ca, Mg, and Na) for plant growth, similar to most common organic fertilizers used in agriculture in Jordan (animal manure). Also, they have favorable pH value to stimulate microbiological growth and nutrient mobilization in the alkaline soils of Jordan.

Additionally, the stored biosolids produced from As-Samra WWTP have a good carbon-nitrogen ratio of less than 20:1 (high nitrogen content), which allows microorganisms in the soil to obtain adequate nitrogen for their needs and convert the excess nitrogen to ammonium, the form of nitrogen that plants can absorb and utilize. Moreover, they consist of more than 25% organic matter, which helps to coat the soil particles (sand, silt, clay) to facilitate aggregation, and provides pores and channels in the soil that allow rainfall or irrigation water to pass through. This reduces the runoff of water and nutrients while also preventing soil erosion.

Forage production needs intensive agriculture, leading to high nutrient requirements. Also, soil in semi-arid regions is poor in terms of nutrients and organic matter. Based on these facts, the annual application rate of biosolids is assumed at 6 tonnes of DS per hectare per year (maximum allowable per JS 1145/2006). Thus, the total agricultural land required to accommodate all the stored biosolids produced from As-Samra WWTP until the end of 2013 is estimated at 37,170 ha. However, this large area of agricultural land is not available within a reasonable distance from As-Samra WWTP as shown in Table 4-9 below, which quantifies the agricultural land uses and potential associated areas of use around the facility.

**Table 4-9. Available Agricultural Land around As-Samra WWTP**

| | Agricultural Land Use | | |
|---|---|---|---|
| | **Irrigated Farms** | **Rangelands** | **Badia Rangelands** |
| Area (ha) | 2,400 | 4,500 | 1,350 (micro-harvesting) |
| Total Area (ha) | 8,250 | | |

Source: MoA, 2013; BRP, CAP, 2013; WAJ, 2013

The total land area around As-Samra WWTP that offers a potential for biosolids application is estimated at 8,250 ha. It includes both agricultural farms and rangelands. These consist of:

(i) The irrigated farms that use the treated effluent from As-Samra WWTP extending over a distance of 42 km between the WWTP and the King Talal Dam. These farms cover an overall area of more than 2,400 ha and are mainly planted with forage crops and fruit trees.
(ii) Three rangeland reserves that are located within 30 to 50 km distance from As-Samra WWTP. These rangelands reserves have an estimated area of 4,500 ha (MoA, 2013).
(iii) One Badia rangeland within the middle Badia region located 50 km from As-Samra WWTP with an estimated area of 1,350 ha based on the water harvesting micro-catchments within the site.

The available land area as stated above with its given land use, along with the amount of biosolids currently stored at As-Samra WWTP, offers an opportunity for land application of an estimated 49,500 tonnes DS per year of the stored biosolids as organic fertilizer and/or soil conditioner. This is equivalent to 22% of the total amount of stored biosolids at As-Samra WWTP at the end of 2013. Based on this, it is estimated that the total amount of biosolids currently stored at As-Samra WWTP will be sufficient for land application for a period of approximately 5 years.

However, depending on the land use, cropping patterns and social acceptance, the period of time to distribute existing stored biosolids could be considerably greater. Biosolids can only be applied once for rangeland rehabilitation prior to and during the physical interventions, and once every growing season for fodder farms; and as was the case in the early stages of wastewater reuse in agriculture in Jordan, acceptance and implementation of reuse of biosolids for land application in Jordan may take considerable time. Therefore, the available stored biosolids may be sufficient for use in land application in the As-Samra area for a period of 15 years or more.

### 4.8.2 Use as Cover Material for Landfill Closure

Another potential beneficial use of the existing As-Samra stored biosolids is in construction of a Municipal Solid Waste (MSW) landfill cover. As an alternative to the commonly used synthetic plastic liners, evapotranspiration (ET) cover systems have been recently used as MSW landfill covers as reported and approved by the USEPA. ET covers rely on storing moisture within the cover system itself until it is drawn out by evaporation, transpiration or both. Typical ET cover designs are either monolithic (single fine-grained soil layer) or include a capillary break. The capillary break allows the ET cover to retain more moisture especially under unsaturated conditions. The design of an ET cover depends on climate conditions of the landfill area, ET soil properties, and type of vegetation to be used in the cover.

The Russeifah landfill, where all the waste from Amman and Zarqa was disposed of prior to the new landfill at Ghabawe, could significantly benefit from an ET cover system to prevent water and resulting leachate from filtering through the landfill into groundwater aquifers.

Mixing dried biosolids from the As-Samra plant with local soil available at Russeifah (Figure 4-12 below) will enhance its capacity to be used as ET cover in two ways. First, permeability of the biosolids material is low, approximately $10^{-7}$ cm/sec (O'Kelly, 2005) which will enhance the capacity of the ET cover to retain water. Second, dried biosolids from Samra have some nutrient value for vegetation which can enhance the transpiration capacity of the ET cover if parts of the cover are to be vegetated.

The approximate area of the landfill is approximately 800,000 $m^2$, and assuming the ET cover would be 1 meter thick, the total cover volume would be around 800,000 $m^3$. Biosolids would likely be mixed at a rate of 15% to 25%. The total volume of biosolids that can be used at the site would therefore be 120,000 $m^3$ to 200,000$m^3$.

**Figure 4-12. View of Russeifah Landfill Site**

According to USEPA 40 CFR Part 258.60, the regulation dealing with final covers for municipal solid waste landfills should be as follows:

"Owners and/or operators of all municipal solid waste landfill units must have a final cover system that is designed to minimize infiltration and erosion. The final cover system is to be designed and constructed to: (1) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoil's present or permeability no greater than $1x10^{-5}$ cm/sec, whichever is less, and (2) Minimize infiltration through the closed MSWLF by the use of an infiltration layer that contains a minimum 18 inches [460 mm] of earthen material, and (3) Minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6 inches [150 mm] of earthen material that is capable of sustaining native plant growth."

Since the Russeifah landfill has no liner, the cover soil cap should have a permeability of less than $1x10^{-5}$ cm/sec. The permeability of locally available soil in Russeifah, mixed with biosolids, is expected to have relatively low permeability, low enough to be used as landfill cover for Russeifah consistent with EPA regulation 40 CFR Part 258.60 (a).

Additional investigation including Russeifah area soils testing and an associated feasibility study would need to be undertaken as part of the evaluation to confirm the potential to use As-Samra stored biosolids in construction of a landfill cover.

# 5. OPTIONS SCREENING

Section 4 discussed six options for processing the generated biosolids: monofill, composting, land application, incineration, gasification, and cement kiln. The six options require screening to shortlist a minimum of three options for detailed evaluation per the TOR. The material below describes the evaluation criteria, the evaluation methodology and the screening process to shortlist the options that will be carried forward for more detailed evaluation in the sections that follow.

## 5.1 Evaluation Criteria

The TOR specified five evaluation criteria to evaluate the various options:

- Suitability to local situation
- Reliability of technologies applied
- Environmental aspects
- Economic considerations
- Public perception

## 5.2 Evaluation Methodology

The options were evaluated as follows. First, since each of five evaluation criteria carries a different level of importance for MWI and the various stakeholders, the weight of each criterion was determined in an interactive workshop attended by the different parties. Second, each biosolids processing option was given a score based on the five evaluation criteria noted above. Finally, the weight of each evaluation criterion was multiplied by the score of the biosolids processing option to obtain a final scoring number for each option. Options with high final total scores are considered more favorable.

### 5.2.1 Assigning Weights for the Evaluation Criteria

The pairwise method was used to assign weights for each of evaluation criteria. In this method, the importance of the second criterion is weighed against the importance of the first (white cells in Figure 5-1), then the third criterion is weighed against that of the first and second, then the fourth criterion is weighed against that of the first, second and third, then the fifth criterion is weighed against that of the first, second, third and fourth. In this method, the importance of each criterion relative to that of the others is established. Table 5-1 shows the scale used when making these assignments of relative importance:

**Table 5-1. Scale used to assign relative importance in pairwise method**

| Importance | Score |
|---|---|
| Much greater than | 5 |
| Greater than | 4 |
| Equal to | 3 |

**Table 5-1. Scale used to assign relative importance in pairwise method**

| Importance | Score |
|---|---|
| Less than | 2 |
| Much less than | 1 |

During the September 2013 workshop, 15 participants assigned the weighting factors shown in Table 5-1 to the evaluation criteria. Average scores are shown in Figure 5-1. The bottom row of the Figure shows the raw scores reconfigured into percentage terms to facilitate comparison. As the figure shows, economic considerations carry the most weight, followed by public perception, environmental aspects, reliability of the technology applied and finally the suitability to the local situation.

| | | a | b | c | d | e |
|---|---|---|---|---|---|---|
| | | Suitability to the local situation | Reliability of technologies applied | Environmental aspects | Economic considerations | Public perception |
| a | Suitability to the local situation | | 2.7 | 3.1 | 3.9 | 2.9 |
| b | Reliability of technologies applied | 2.3 | | 3.3 | 3.7 | 2.3 |
| c | Environmental aspects | 1.9 | 1.7 | | 3.5 | 3.2 |
| d | Economic considerations | 1.1 | 1.3 | 1.5 | | 2.1 |
| e | Public perception | 2.1 | 2.7 | 1.8 | 2.9 | |
| | Score (100 possible) | **15** | **17** | **19** | **28** | **21** |

**Figure 5-1. Pairwise method for assigning weights to the five evaluation criteria**

### 5.2.2 Assigning Scores to the Various Biosolids Processing Options

The second step after assigning the weights to the various scoring criteria is to assign scores to the various biosolids screening options per the same evaluation criteria. Table 5-2 presents the methodology used for assigning a score of an option per the various evaluation criteria. Each option is assigned a 1 to 3 score based on the scoring category (evaluation criteria).

**Table 5-2. Biosolids Options Scoring Methodology**

| SCORING CATEGORY | 1 | 2 | 3 |
|---|---|---|---|
| Suitability to local situation | Less suitable | Suitable | Very suitable |
| Reliability of technologies applied | Not as reliable | Reliable | Very reliable |
| Environmental aspects | Negative | Moderate | Energy recovery and reduced carbon footprint |

| | | | |
|---|---|---|---|
| Economic consideration | High cost expected | Moderate cost expected | Lowest cost |
| Public perception | Negative | Moderate | Expected to be well accepted |

## 5.3 Options Screening

Figure 5-2 shows the final score for each biosolids option for each of the five evaluation criteria, and the summation of all scores for each option. Options with highest priority score are more favorable. Accordingly, the ranking of the options are as follows:

1. Cement kiln
2. Incineration
3. Gasification
4. Monofill
5. Land application
6. Composting

| | Evaluation Criteria | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Suitability to the local situation | | | Reliability of technologies applied | | | Environmental aspects | | | Economic considerations | | | Public perception | | | | |
| | Score (1-3) | Weight Factor | Final Score | Score (1-3) | Weight Factor | Final Score | Score (1-3) | Weight Factor | Final Score | Score (1-3) | Weight Factor | Final Score | Score (1-3) | Weight Factor | Final Score | Priority Score | Ranking |
| Mono Landfill | 3 | 15 | 45 | 2 | 17 | 34 | 1 | 19 | 19 | 3 | 28 | 84 | 2 | 21 | 42 | 224 | 4 |
| Composting | 1 | 15 | 15 | 3 | 17 | 51 | 2 | 19 | 38 | 1 | 28 | 28 | 1 | 21 | 21 | 153 | 6 |
| Land Application | 1 | 15 | 15 | 3 | 17 | 51 | 2 | 19 | 38 | 3 | 28 | 84 | 1 | 21 | 21 | 209 | 5 |
| Incineration | 3 | 15 | 45 | 3 | 17 | 51 | 3 | 19 | 57 | 2 | 28 | 56 | 3 | 21 | 63 | 272 | 2 |
| Gasification | 3 | 15 | 45 | 2 | 17 | 34 | 3 | 19 | 57 | 2 | 28 | 56 | 3 | 21 | 63 | 255 | 3 |
| Cement Kiln | 3 | 15 | 45 | 2 | 17 | 34 | 3 | 19 | 57 | 3 | 28 | 84 | 3 | 21 | 63 | 283 | 1 |

**Figure 5-2. Final scoring methodology for the various biosolids disposal options showing ranking of these options**

Based on the above results, a detailed evaluation was carried out for cement kiln, incineration, gasification and monofill and the results of this evaluation are presented in Section 6. Although land application was not evaluated in further detail, it can be component of any of processing option as outlined in Section 4-9. Composting can also be a component of any option should MWI desire to diversify its biosolids processing portfolio.

# 6. SHORT-LISTED OPTIONS EVALUATION

This section begins with a summary of the cost assumptions that were made so as to provide a consistent basis for evaluation (subsection 6.1). It then addresses the drying processes necessary prior to disposal or beneficial use of As-Samra biosolids (subsection 6.2), focusing in particular on windrow drying (subsection 6.3), the technology best suited to achieve the 75% DS required by some of the short-listed options.

Subsections 6.4-6.7 contain the evaluation of the four options whose shortlisting was described in Section 5.

## 6.1 Overall Cost Assumptions

Consistent assumptions were made for arriving at the capital and operation costs of the shortlisted options to ensure the evaluation was conducted on an even footing. The cost numbers presented are in "today's value". The following was assumed for the evaluation:

- Specific contractual cost for biosolids handling was based on RPA:
  - Transporting: JD 1.217/$m^3$
  - Drying biosolids cost estimate uses pre-established formula
    - JD 0.538/$m^3$ to achieve 30% DS
    - JD 0.985/$m^3$ to achieve 50% DS
  - Storage cost is JD 0.0526/$m^3$/month
- Electrical purchased costs assumed to be JD 0.133/kW-h based on the 2017 cost rate, which represents a 75% increase from the JD 0.076/kW-h cost in 2013.
- Electrical generation costs vary depending on renewable material used for electricity generation:
  - Electricity generation from the biogas produced from the monofill is estimated to be JD 0.11/kW-h, which is based on a cost value of JD 0.060/kW-h in 2012 and applying the same 75% increase as the purchased electricity cost.
  - Electricity generation from biomass in the case of incineration or gasification is estimated to be JD 0.16/kW-h, which is based on a cost value of JD 0.090/kW-h in 2012 and applying the same 75% increase as the purchased electricity cost.
- Annual operator salary is JD 5,950 per year.
- Diesel fuel cost is JD 0.71 per liter.
- Fuel oil cost is JD 0.71 per liter.
- Natural gas cost is JD 4.7 per GJ.
- Activated carbon cost is JD 1.60 per kg.
- Lime cost is JD 180 per tonne.
- Indirect Cost Assumption:
  - Overhead: 45% of labor cost
  - Insurance: 0.15% of Equipment Capital
  - Administration expenses and consumables: 1% of equipment capital cost
  - Property tax: not accounted for in the analysis
- Construction cost assumptions (Except Monofill):
  - Installation cost: 25% of equipment capital cost (thermal processing options only)
  - Site work cost: 10% of equipment capital cost
  - Installation and Training costs: 2.5% of equipment capital cost
  - Contingency cost: 25% of installed cost
  - Engineering cost: 15% of installed cost w/ contingency
  - Contractor overhead and profit: 22% of installed cost w/ contingency

- Concrete costs for the greenhouse drying pad: JD 230 per cubic meter (assuming 15 cm thick with light rebar)
- Concrete costs for Incineration / Gasifier Slab: JD 325 per cubic meter
- Concrete costs for the control room slab: JD 370 per cubic meter
- For the thermal processing options, a 140-square-meter building at JD 1525 per square meter cost was assumed for the control room.

## 6.2 Preliminary Drying Evaluation

As shown in Figure 6-1, under the current operation contract, the existing solar drying beds can be used to dry the biosolids to 30% to 50% DS. It is also possible to transfer the 30% dry solids to a separate storage area where the biosolids continue to dry to 50% DS. Based on the cost calculations, it is more effective to dry to 50% DS in the solar drying beds than dry to 30% DS at the solar drying beds and then transfer to the biosolids storage area to achieve 50%. From the current cost agreements, and at the design throughput of 193.8 dry tonnes per day, using the solar drying beds to dry the biosolids to 50% DS would be JD 15,100 cheaper than transporting the biosolids to the separate storage area for further drying to 50% DS.

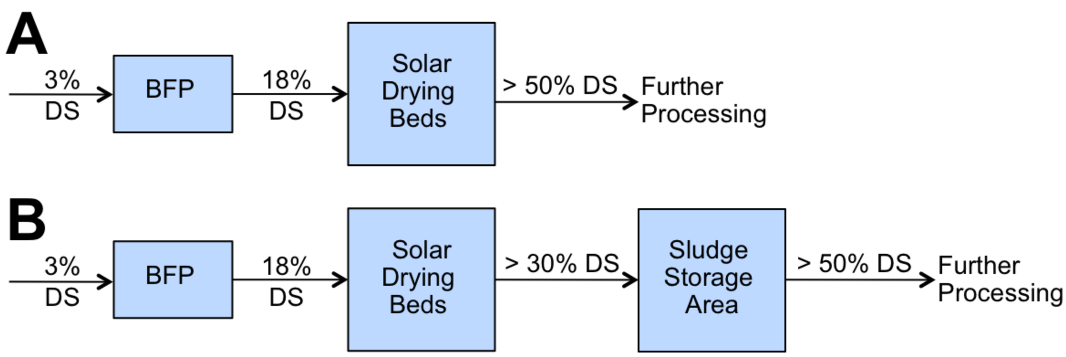



**Figure 6-1. Existing As-Samra options to achieve greater than 50% DS**

It will cost an estimated JD 1,050,000 per year to transport and dry 193.9 dry tonnes per day from 18% DS to 50% DS, which represents a cost of JD 14.8/dry tonne. This operating cost estimate is used as the basis for evaluating options to achieve the 50% dryness.

Per the previous sections, the shortlisted options require processing different dry solids as presented below:

- Both gasification and cement kiln require a drying process to increase the biosolids solid content to greater or equal to 75% DS
- Incineration can process biosolids at greater than 50% DS and accordingly it was initially evaluated at two different solid contents
  - Incineration Option 1: Greater than or equal to 50% DS
  - Incineration Option 2: Greater than or equal to 75% DS
- Biosolids sent to the landfill will be approximately 50% DS from the existing solar drying system

To achieve 75% DS, two different technologies were considered: windrow drying and greenhouse drying. Communications with major vendors for greenhouse drying indicated that it was prohibitively expensive and the costs for equipment and greenhouses alone would range from JD 22,000,000 to over JD 60,000,000, depending on the inlet solids content. Thus using greenhouse drying was not considered further and windrow drying was selected as the technology to achieve the desired 75% DS. Section 6.3 below describes the basis of design for the proposed windrow drying.

## 6.3 Windrow Drying

### 6.3.1 Reference Facilities in the US

There are several windrow drying reference facilities in the US including ones in

- Phoenix, Arizona
- Miami, Florida
- Chicago, Illinois
- Parker, Colorado

### 6.3.2 Windrow drying assumptions

Windrow drying can be practiced with various solid contents to achieve the desired 75% DS as shown in Figure 6-1. In order to size and cost the windrow drying system, several assumptions were made:

- Windrows would have a 1.8 m base and be 0.5 m tall with 0.3 m spacing between each.
- The windrows will be laid out on concrete pads.
- The windrow drying duration and size depend on solid content feed:
  - When starting with 18% DS, the drying duration is 120 days
  - When starting with 30% DS, the drying duration is 90 days
  - When starting with 50% DS, the drying duration is 60 days
- The turner would be a Brown Bear™ or similar turning device that moves 5,600 m/h.

Based on the design throughput, the volume of biosolids at the different starting solid contents was estimated. The total length required for the windrows was estimated based on the assumed windrow dimensions. From the total length, the required surface area for the windrow drying system could be determined assuming that the drying bays would be broken up into several 100 m x 100 m drying bays (1 Ha each).

The size required for drying was also checked by calculating the evapotranspiration rates based on the local climate data. Evapotranspiration is a measurement of the rate of evaporation from open bodies of water, bare soil and grass. In order to calculate the evapotranspiration rate, the Penman Monteith equation was used (Zotarelli et al., 2009). The equation is:

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)}$$

Where:

$ET_0$ = Evapotranspiration rate (mm/d)
$\Delta$ = Slope of saturation vapor curve (kPa/ºC)
$R_n$ = Net solar radiation Flux (MJ/m$^2$·h)
$G$ = Soil heat flux density (MJ/m$^2$·h)
$\gamma$ = Psychometric constant (kPa·ºC)
$T$ = Temperature (ºC)
$u_2$ = Wind speed at 2 m above the ground (m/s)
$e_s$ = mean saturated vapour pressure (kPa)
$e_a$ = mean ambient vapour pressure (kPa)

Using local weather data from the nearby Amman Airport and solar radiation data from the NASA atmospheric science data centre, the average evapotranspiration rates were calculated based on annual average conditions, summertime conditions (June – August) and wintertime conditions (December-February) and these rates were estimated to be 6.0, 10.0 and 2.7 mm/d respectively. To ensure that the windrow drying area was properly sized, the wintertime rate was checked by estimating how much water could be evaporated based on the available surface area in the windrow (area exposed to the sun and air) and calculated evapotranspiration rates. The results showed that there was a 1.4 – 1.6 safety factor in the design for wintertime conditions, so adequate area should be available for drying during the entire year. Less area and or time would be required during the warmer and dryer periods of the year but it is necessary to ensure that the system can still perform during worst case conditions, which are completely dependent on the weather.

Table 6-1 provides a summary of the windrow sizing criteria.

**Table 6-1. Windrow Drying Design**

| Parameter | Drying Option 1 | Drying Option 2 | Drying Option 3 |
|---|---|---|---|
| Mass Throughput, dry tonnes/day | 195 | 195 | 195 |
| Solid Content, %DS | 18% | 30% | 50% |
| Daily Volume, $m^3$/d | 1,083 | 650 | 390 |
| Daily Windrow Length, m | 1,728 | 1,037 | 622 |
| Drying Time, days | 120 | 90 | 60 |
| Total Windrow Length, m | 207,301 | 93,286 | 37,314 |
| Required Drying Area, Ha | 55 | 25 | 10 |
| Number of Turners Required + 1 spare | 7 | 4 | 2 |
| Annual Evaporation Rate, tonnes/yr | 300,520 | 142,350 | 47,450 |
| Specific Evaporation Rate, tonnes per Ha | 5,464 | 5,694 | 4,745 |
| Windrow Surface Area Available for Drying, Ha | 45.8 | 20.6 | 8.2 |
| Wintertime Evaporation Rate, tonnes/yr | 458,000 | 206,000 | 82,000 |
| Safety Factor | 1.5 | 1.5 | 1.7 |

During the drying and storage period it is assumed that 15% of the volatile content will be degraded biologically. A windrow drying pilot is being proposed to determine the true local drying rates and volatile degradation and better size the drying system to the local climatic conditions.

### 6.3.3 Windrow Cost Analysis

The capital and O&M cost estimates for the windrow drying alternatives are presented in Table 6-2. The costs presented include the costs of drying biosolids in the existing solar drying beds and transporting the biosolids between areas where appropriate (drying option 2 and 3). The construction cost includes the cost for the windrow turners and concrete drying bed areas. The cost estimates were based on input provided by Brown Bear as a representative technology.

- Capital cost per Brown Bear turner is JD 355,000.
- Each turner consumes 37.85 L of diesel fuel per operation hour.
- The turner maintenance costs are JD 0.71 per operating hour.
- Oil change and fuel filter costs are JD 0.47 and JD 0.12 per operating hour.
- One operator per turner is required.

**Table 6-2. Windrow Drying Cost Analysis**

| Parameter | Drying Option 1 | Drying Option 2 | Drying Option 3 |
|---|---|---|---|
| Windrow Drying Input | 18% DS from BFP | 30% DS from solar drying beds | 50% DS from solar drying beds |
| Construction Cost, JD | 46,070,000 | 21,570,000 | 8,930,000 |
| Annual O&M Cost, JD | 1,030,000 | 1,310,000 | 1,250,000 |
| Annualized Capital[1], JD | 3,240,000 | 1,520,000 | 630,000 |
| Total Annual, JD | 4,270,000 | 2,830,000 | 1,880,000 |
| Cost, JD per Dry Tonne | JD 60.3 | JD 40.0 | JD 26.6 |
| 1. Assuming 20 year financing at an effective interest rate of 3.5% | | | |

As shown in Table 6-2, drying option 3, where the biosolids are dried to 50% DS in the solar drying beds before being transported to the windrow drying beds, is the most economical method to dry the biosolids to 75% DS and is used as the drying basis for evaluating the incineration, gasification and the cement kiln alternatives.

## 6.4 Landfill

### 6.4.1 Technical Standard and Disposal Reliability

#### *6.4.1.1 Technical Standard*

As per Jordanian Standards, Solid Waste Regulation No. 27 of 2005 pertains to waste disposal. This Regulation was issued by virtue of the Environmental Protection Law No. 1 of 2003, and it states the duties of the Minstry of Enviornment (MoEnv) in relation to waste disposal. Given that the Regulation is generic and does not provide specific details related to the design, operation, closure and post closure of landfills, it is used for guidance purposes only**.** It is generally accepted in Jordan to adhere to the United States Environmental Protection Agency (USEPA) standards which are more extensive and provide detailed provisions exceeding Jordanian standards.

Subpart C of 4 CFR, Part 503 provides relevant regulations developed by the USEPA for biosolids monofills. As per Part 503, biosolids monofills are addressed as “surface disposal in biosolids-only facilities”.

Part 503 necessitates that the site meet certain locational restrictions similar to those set in Part 258 of the Landfill Rule. Part 503 also necessitates that measures be taken for closure and post-closure care, leachate collection (if the unit is lined), methane monitoring, and public access restrictions. In addition to these measures, managerial requirements similar to those for MSW landfills must also be met. These include requirements for runoff collection, leachate collection and disposal (if the unit is lined), vector control, methane monitoring, groundwater monitoring or certification, public access restrictions, and restrictions for the growing of crops and grazing of animals. In the case of the unit being unlined, the biosolids must meet concentration limits for arsenic, chromium, and nickel.

#### 6.4.1.2 Disposal Reliability

Landfilling in general is considered to be very reliable. It is dependent on well-established infrastructure and basic earth-moving machinery. It does not require detailed or sophisticated machinery or complex operation and maintenance. The method is simple, reliable and durable. Monofills for biosolids, however, have limited practice in the industry so the design will need to be considered carefully. Two monofill sites were found in literature. The first, in the US, involved dewatered biosolids mixed with sand at a 1:2 ratio. The second was in the UK, and at this site gases caused voids in the landfill which resulted in slope failure.

### 6.4.2 Energy and Mass Flow for the Option

The design life for the biosolids landfill is expected to be 20 years and the design capacity is to be based on average projected biosolids production of approximately 180 dry tonnes per day, though this production varies from 146.6 to 193.9 dry tonnes per day.

The assumed daily solids production, as provided in Sludge Management Plan 2012/2013, is reproduced in Table 6-3 below. Assuming the compacted dry density of the biosolids material (for a solids concentration of 50%) is 0.56 tonne/$m^3$ per O'Kelly (2005), the resulting required landfill capacity is approximately 2.4 million $m^3$. If an additional volume of 15% is added to account for cover soil placement, a design volume of approximately 2.7 million $m^3$ would be required.

This volume could be approximately satisfied with a 30-m-high landfill with 3:1 side slopes, a square footprint, and an outside width of 380 m. This footprint, which assumes no excavation within the existing ground to achieve the landfill base, is approximately 14.5 hectares. If the side slopes are 6:1, the required outside width would be approximately 515 m for a footprint of approximately 26.7 hectares. Depending on the geometry of the landfill, decreasing the side slopes from 3:1 to 6:1 increases the required footprint by 60-90%. Conversely, excavation within existing ground will decrease the required footprint to a degree determined during detailed design. The Energy and Mass diagram for the monofill is provided in Figure 6-2.

**Table 6-3. Dry solids production and equivalent compacted biosolids volume if dried to approximately 50% solids, assuming 0.56 dry tonnes/$m^3$**

| Year | Dry solids production (tonnes/day) | Required Volume ($m^3$/day) | Required Volume ($m^3$/yr) |
|---|---|---|---|
| **2014** | 146.6 | 262 | 95,617 |
| **2015** | 152.5 | 272 | 99,465 |
| **2016** | 156.4 | 279 | 102,009 |
| **2017** | 160.2 | 286 | 104,488 |

**Table 6-3. Dry solids production and equivalent compacted biosolids volume if dried to approximately 50% solids, assuming 0.56 dry tonnes/m$^3$**

| Year | Dry solids production (tonnes/day) | Required Volume ($m^3$/day) | Required Volume ($m^3$/yr) |
|---|---|---|---|
| **2018** | 164.1 | 293 | 107,031 |
| **2019** | 168.0 | 300 | 109,575 |
| **2020** | 171.9 | 307 | 112,119 |
| **2021** | 176.3 | 315 | 114,989 |
| **2022** | 180.7 | 323 | 117,858 |
| **2023** | 185.1 | 331 | 120,728 |
| **2024** | 189.5 | 338 | 123,598 |
| **2025** | 193.9 | 346 | 126,468 |
| **2026** | 193.9 | 346 | 126,468 |
| **2027** | 193.9 | 346 | 126,468 |
| **2028** | 193.9 | 346 | 126,468 |
| **2029** | 193.9 | 346 | 126,468 |
| **2030** | 193.9 | 346 | 126,468 |
| **2031** | 193.9 | 346 | 126,468 |
| **2032** | 193.9 | 346 | 126,468 |
| **2033** | 193.9 | 346 | 126,468 |
| **Total** | **3,596** | **6,422** | **2,345,688** |

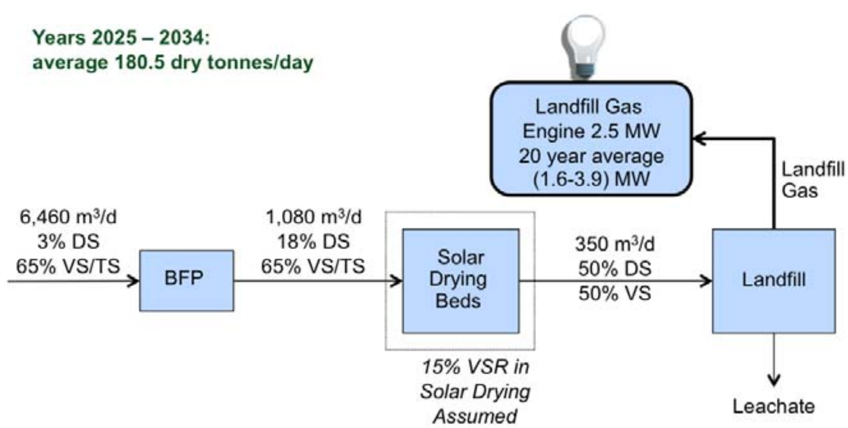



**Figure 6-2. Biosolids Monofill Energy and Mass Diagram**

### 6.4.3 Land Requirements

The total land required for the biosolids monofill is 14.5 to 26.7 hectares, depending on the final side slope design, and lies to the North East of As-Samra wastewater treatment plant. Figure 6-3 shows existing site topography and use.


**Figure 6-3. Existing site topography and use**

It is proposed to construct the landfill by building a berm alongside the southern mountain parallel to the northern mountain as indicated in Figure 6-3. The actual elevation difference between the mountain and the wadi is around 25 to 30 meters. Landfilling the space between the mountain and the berm (after the berm is built) with biosolids up to a height of 15 m will provide enough capacity for approximately 20 years. This area could be divided into four 5-year cells.

A rough sketch of the conceptual landfill layout is shown in Figure 6-4. This conceptual configuration indicates 4 cells with dimensions of approximately 220 meters by 250 meters each. The targeted capacity of this conceptual design is 2.4 million cubic meters.

Based on preliminary stability analyses and volumetric evaluations, the targeted 2.4 million cubic meters of capacity may be achieved for the conceptual footprint configuration by either of the following:

- 14.8 meters total waste depth composed of 2 meters of waste from top of base liner system to top of perimeter berm, 11 meters of waste constructed with a 3H:1V outboard slope, and 1.8 meters of waste constructed at 50H:1V (top deck)
- 20.5 meters total waste depth composed of 4 meters of waste from top of base liner system to top of perimeter berm, 16 meters of waste constructed with a 6H:1V outboard slope, and 0.5 meter of waste constructed at 50H:1V (top deck)

Final configuration for landfilling in the wadi between the two mountains will be developed once the topographic survey of the proposed site has been completed.

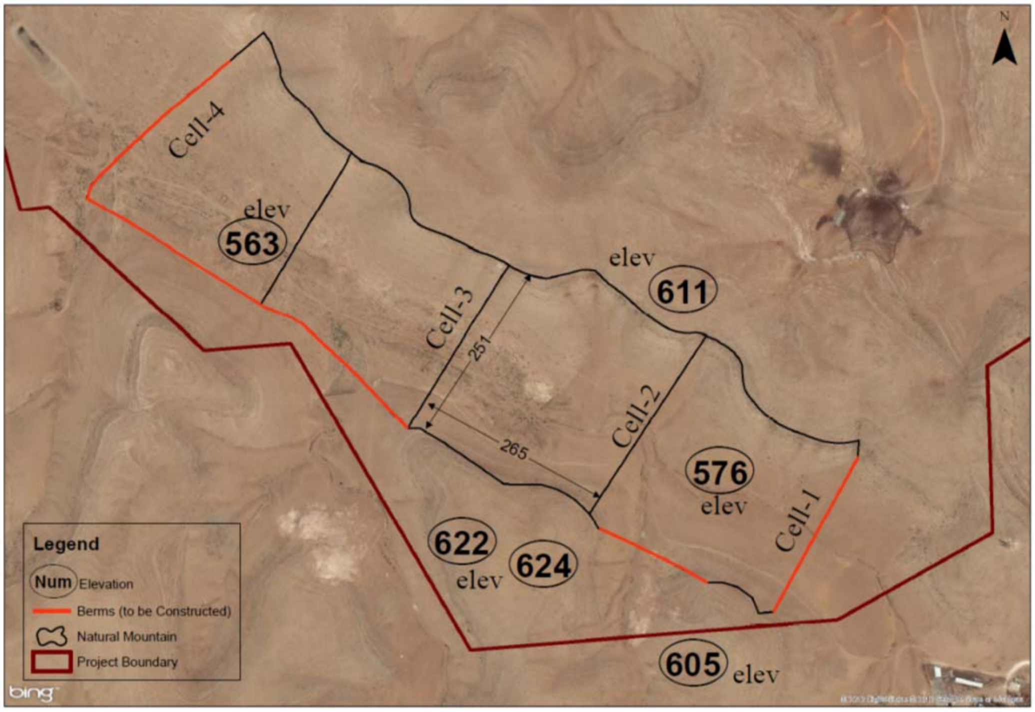



**Figure 6-4. Proposed conceptual landfill layout**

### 6.4.4 Suitability to Meet Required Standards

The regulatory standards that need to be met by the monofill design were outlined in section 6.4.1. The following subsections outline the measures and suitability of the proposed design in meeting those standards. In general, the landfill will be designed in accordance with USEPA standards, which exceed the Jordanian regulations

#### *6.4.4.1 Standards for Subsurface Protection*

The monofill will be constructed with a base liner system composed of natural and/or synthetic liner systems (e.g. clay, GCL, geocomposite, HDPE liner) and a leachate collection system (e.g. perforated collection piping incised within a granular drainage layer).

##### 6.4.4.1.1 Potential Liner Systems and Preferred Liner System

If the leachate produced from the biosolids meets certain minimum regulatory requirements, a liner system is not necessarily required (EPA, 1999). However, if the biosolids produce leachate with unacceptable levels of contaminants such as heavy metals, then a base liner containment system with leachate collection and treatment is required (EPA, 1999). The environmental quality of the biosolids should be determined during the preliminary design stage.

Natural soil liner systems can be built with a layer of relatively impermeable clay (usually with a hydraulic conductivity less than $10^{-7}$ cm/s). The ability to use clay as a base liner component depends on many factors such as availability, thickness required for environmental protection, cost and effort for moisture conditioning, mechanical requirements for installation, and potential desiccation in arid climates. Alternatively, Geosynthetic Clay

Liners (GCLs) can be imported to replace a base clay layer. A GCL is generally described as a thin layer of manufactured clay (i.e. bentonite) supported between layers of geotextile. Use of a geomembrane (GM) as an alternative to a clay liner should be explored. A composite liner (which has a geomembrane in addition to the clay liner or GCL) does not appear to be required under EPA regulations, as it is for municipal solid waste landfills (EPA, 2003). However, since double liners may be required for MSW landfills in Jordan, a composite liner system consisting of 60 mil HDPE and a GCL should be considered for the biosolids landfill at As-Samra.

A drainage layer is typically provided above the impermeable layer(s) to control leachate head levels and to convey collected liquids to the sump. Depending on availability, cost and hydraulic capacity, the drainage layer may be constructed with gravel, sand, or with a geocomposite (typically a HDPE geonet sandwiched between two layers of geotextile).

Availability of clay and gravel borrow near the site will be investigated at the preliminary design stage. Chemical testing will be conducted during preliminary design to investigate leachate quality. Based upon these results and after review of Jordan's regulatory requirements for disposal of biosolids, the preferred liner system for the landfill will be selected. *However, for the purposes of this evaluation, it is assumed that a composite liner system consisting of 60 mil HDPE and a GCL will be used.*

##### 6.4.4.1.2 Groundwater Monitoring

To monitor the performance of the proposed liner system and its effectiveness in protecting the environment from potential leaks, a groundwater monitoring system will be installed. At a minimum, one (1) upgradient and two (2) downgradient groundwater monitoring wells will be installed. The upgradient well will yield water level and water quality information as "background" while the downgradient wells will monitor water level and water quality information as potentially affected by the landfill. Wells will be installed to sufficient depth as determined by a qualified hydro-geologist such that the perforated screen intervals intercept the appropriate subsurface hydraulic system(s). Typically, wells are installed and one full year (quarterly sampling events) of background water level and water quality data is attained prior to landfill construction.

#### *6.4.4.2 Standards for Atmospheric Protection*

Anaerobic decomposition of biosolids contributes to the production of biogas (predominantly methane and carbon dioxide) requiring measures to mitigate gas emissions. Gas emissions can be prevented or minimized by installing passive or active gas collection systems during active filling, a final collection/transmission system when final filling is achieved, and a closure cap. Passive systems generally consist of perforated pipes or granular trenches within the waste mass that are "vented" to the atmosphere. Active systems generally consist of gas wells drilled vertically into the waste mass connected by a series of pipes to a landfill blower/flare station(s). Small utility flares that burn off collected gas may be considered or more environmentally protective enclosed flares that thermally destruct upwards of 98% of collected gas with little to no emissions. In-lieu of destruction at the flare, landfill gas may also be recovered for the generation of heat and/or electricity.

##### 6.4.4.2.1 Potential Final Cover Systems

Cover systems are often constructed after deposition of waste at a landfill has been completed. These typically consist of either a geosynthetic system similar to the base liner system, or of an evapotranspiration layer of soil. Evapotranspiration cover systems are applicable in more arid environments and typically consist of several feet of a loamy soil. Cover systems, however, do not appear to be explicitly required under Part 503 off 40 CFR. Cover systems are described in EPA (2003), but the document does not indicate that they are a regulatory requirement. The purposes of a final cover system typically include reducing the production of leachate by limiting rainwater infiltration (which may not be an issue in Jordan's arid desert) into the landfill after landfill closure, limiting potential fugitive odor and gas emissions, and improving visual appearance of the closed facility. Whether a final cover system consisting of a low permeability layer or an evapotranspiration layer is desired for this project should be determined during the design stage. Availability of on-site and borrow soils near the site for final cover will be investigated at the preliminary design stage.

###### 6.4.4.2.2 Preferred Final Cover System

Selection of the final cover system for the liner will be made during preliminary design based on the borrow source investigation for cover materials and evaluation of regulatory requirements for closure of biosolids landfills in Jordan. This report assumes that a cover will be required and the preferred final cover system would be an evapotranspiration cap utilizing nearby borrow soils. *However, a geosynthetic cap system may be used if appropriate borrow source material is not available*.

##### 6.4.4.3 General Layout

A number of landfill configurations have been historically used for biosolids monofilling. These include the trench, area, and ramp design strategies. In the trench method, trenches are excavated and then filled with biosolids. For area landfills, natural or excavated depressions are backfilled with biosolids in a controlled manner. Biosolids can also be pushed up against slopes in the ramp method. For the remainder of this report, the area method will be assumed to be the design strategy of choice since a trench method would not be appropriate for the large quantities of biosolids expected for this project. However, nearby slopes may make a ramp-like design strategy possible, which will be more fully evaluated at a later design stage.

Depending on the selected landfill layout, space constraints, perimeter berms may be necessary to contain the biosolids. Factors impacting the requirement for perimeter berms include location relative to the water table or geologic features, and prohibitive excavation costs. It is noted that excavation to achieve the base of the landfill can be advantageous as it can increase landfill airspace within the same allotted footprint, allow for a smaller footprint, and provide fill borrow source material. Access roads will likely also be necessary to provide vehicular access to the top deck of the landfill. These may also serve as benches for erosion control, landfill stability, and surface water control.

The base of the landfill will need to be sloped in order to drain leachate collected at the base of the landfill toward an engineered sump. Buildup of liquid head at the landfill base is not desirable as it can lead to waste instability, overtopping of perimeter containment berms, increased head pressure causing leaking through landfill base, watering out of landfill gas extraction systems, and pop-outs of leachate onto closed areas leading to contamination of surface water and adjacent ground surfaces. Pumping of leachate from the sump through a force main or gravity collection of leachate through a liner penetration to an external storage/pumping manhole will be necessary for collection and conveyance of leachate to a wastewater treatment facility. The top deck of the landfill will need to be sloped for surface water drainage purposes.

A general schematic of the envisioned landfill configuration is presented in Figure 6-5 on the next page.

#### *6.4.4.4 Slope Stability*

The slope stability of the monofill depends on the engineering properties of the biosolids, the liner shear strength, cover shear strength and erosion control.

##### 6.4.4.4.1 Biosolids Engineering Properties Related to Monofilling

Literature review was conducted to estimate biosolids characteristics important for monofilling. Limited data exists and O'Kelly (2006) indicates that the shear strength and other geotechnical properties of biosolids can vary significantly from one wastewater treatment facility to another. Therefore, a site-specific geotechnical testing program is recommended. Testing should be conducted on the 50% DS samples of biosolids. The following biosolids tests are recommended for further proper design of the monofill.

- Modified Proctor compaction testing. This test is conducted to assist in determining appropriate water content for optimal workability and compaction of the biosolids in the field. This would assist in determining the desired solids concentration for the material to be landfilled. It would also assist in estimating the expected field density of the compacted biosolids.
- Geotechnical shear strength testing. This testing should be performed on compacted material at target water content. The material may then be tested for shear strength or saturated prior to shear strength testing.
- Shear strength testing. This testing includes the unconsolidated-undrained triaxial compression tests, consolidated-undrained triaxial tests, and lab vane shear tests. This combination of tests will be conducted to establish the undrained and drained shear strengths of the material that would be applicable for slope stability analysis. Simple shear tests would be beneficial to evaluate the effect of a simple shear stress path, which is appropriate for slope stability calculations, compared to triaxial compression. Long-term, creep-induced strength loss, progressive failure, and other considerations should be accounted for before final shear strengths for slope stability analyses are determined.
- Permeability and consolidation testing. This testing is conducted to evaluate how quickly drained conditions will develop and how quickly strength gains due to consolidation will take effect. Strength gains from consolidation can be taken into effect if significant consolidation is expected during the operation of the landfill.
- Seismic testing. Since Jordan is seismically active, bender element shear wave velocity tests and modulus reduction curve testing may be appropriate for final design with respect to earthquake stability and earthquake-induced slope failures.
- Basic geotechnical index and classification tests such as specific gravity, sieve, hydrometer, Atterberg limits, and loss-on-ignition tests.

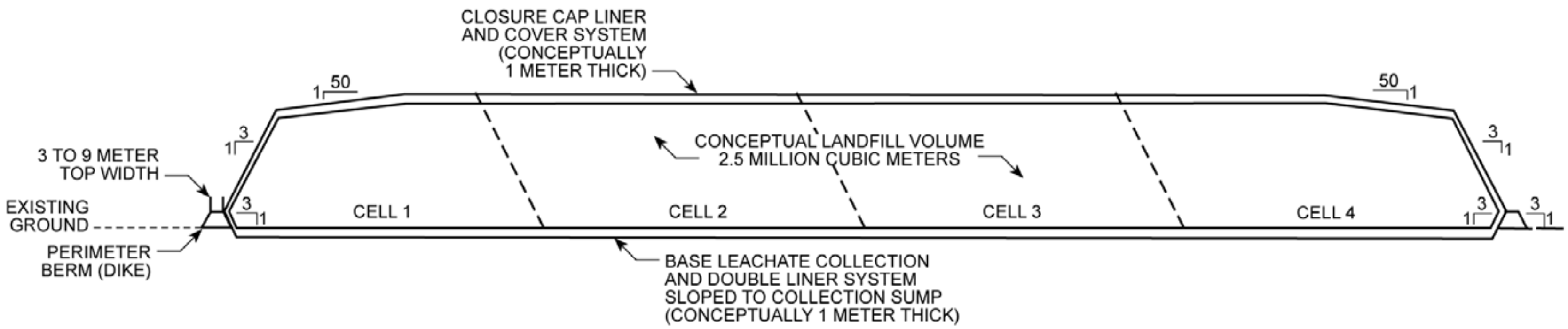



**Figure 6-5. A general schematic of the area disposal method envisioned for this project**

The proposed testing program for determining engineering properties of biosolids from the As-Samra Wastewater Treatment Plant will be implemented during preliminary design. Currently this report includes preliminary slope stability analyses of the biosolids based on the published shear strength data included herein. The testing of biosolids at 50% DS will be used to finalize these slope stability calculations.

###### 6.4.4.4.2 Liner Shear Strength

Liner materials often have weak shear resistance. Once the liner system is selected, appropriate shear strength values can be determined and used for slope stability calculations.

###### 6.4.4.4.3 Cover Shear Strength and Erosion Control

The final cover system may have weak shear strength, and consequently limit the allowable slope inclination. In addition, erosion control of the cover system may necessitate limits to the side slope inclination or require benches, vegetation, or other erosion control practices. Erosion control practices, including typical vegetation and bench details, will be developed for the arid climate of Jordan.

#### 6.4.4.5 Site Geotechnical Investigation

A plan for the investigation of the existing ground conditions at the site will likely be necessary. Data gathered from the geotechnical investigation can be used to evaluate the shear strength and other relevant properties of the base of the landfill, the suitability of the local soil and rock for use as berm fill material, and as borrow material for cover and liner systems. Approximately one to two borings or test pits per acre are typically recommended at the concept or preliminary stages with additional borings conducted at a later stage, if subsurface conditions warrant it. A detailed subsurface investigation program including laboratory testing will be prepared and implemented during preliminary design.

#### 6.4.4.6 Design Conditions

Scenarios to be considered when evaluating slope stability of the monofill should include earthquake loading, loading during rain events, and loading from gas pressure generation in the monofill, in addition to static loading conditions.

Jordan is a seismically active region and therefore consideration of earthquake-induced slope instability may be necessary. In addition, the effect of rainfall activity specific to Jordan's climate may be required. Even if total rainfall in the region is relatively low, short duration precipitation events may be of concern.

Gas pressure resulting from biodegradation of the biosolids may cause increased slope instability and may have caused one historic biosolids monofill landslide (O'Kelly, 2005). Dissipation of generated gas may be possible by incorporating a gas extraction system into the design of the monofill. This effect should be further evaluated during the design portion of this project.

###### 6.4.4.6.1 Acceptable Side Slope Inclinations

Preliminary slope stability analyses were conducted for two separate slope configurations that conceptually achieve the approximate 2.5 million cubic meter targeted monofill capacity within the geometric restrictions set. The two slope configurations analyzed were:

- 14.8 meter total waste depth composed of 2 meters of waste from top of base liner system to top of perimeter berm, 11 meters of waste constructed with a 3H:1V outboard slope, and 1.8 meter of waste constructed at 50H:1V (top deck)

- 20.5 meter total waste depth composed of 4 meters of waste from top of base liner system to top of perimeter berm, 16 meters of waste constructed with a 6H:1V outboard slope, and 0.5 meter of waste constructed at 50H:1V (top deck)

The internal shear strength of site-specific As-Samra WWTP biosolids to be placed within the proposed monofill will be the subject of future work; the shear strength of the biosolids was therefore varied within each stability run until achievement of a minimum factor of safety of 1.5 versus global circular failure through the deposited waste and/or the in-situ foundation soils. Seismic evaluations were not performed. Short term (undrained) shear strength will likely govern the actual achievable fill slopes as the consolidation that will occur overtime will improve the long term (drained) shear strength of the biosolids. Consequently, the undrained shear strengths corresponding to a $\Phi = 0°$ analysis will be used in the stability analysis. The minimum undrained shear strength for the 3H: 1V filling slope is 561 psf (27 kPa) and the minimum undrained shear strength for the 6H: 1V filling slope is 477 psf (23 kPa).

A sliding block failure analysis through the liner system, which could decrease the calculated factor of safety, was evaluated within this report and will be evaluated during the design portion of this project.

##### 6.4.4.6.2 Design Conclusions

The following conclusions were developed based on these results. Slopes of 3:1 (horizontal: vertical) and a height of approximately 15 m may be achievable for biosolids at 50% solids content with an undrained shear strength of approximately 25 kPa, given the literature values for undrained shear strength of 25 to 50 kPa and drained shear strength above 32°. A higher landfill height may be achievable depending on the site-specific shear strength of the biosolids, which could significantly decrease the required landfill area. A comprehensive site-specific shear strength evaluation will be conducted, per the discussion provided above, before a final determination of appropriate biosolids shear strengths can be made. More consideration needs to be given if the 3:1 outboard slopes are achievable for a given landfill height based on undrained shear strength values of the biosolids. The site specific laboratory shear strength results will yield data that can be used in design to further refine the outboard slope and landfill height and footprint.

### 6.4.5 Energy Efficiency

A monofill for biosolids is expected to have high energy efficiency because of the relatively large amount of biogas produced. Biosolids landfills can produce double the amount of biogas as normal municipal solid waste (MSW) landfills because biosolids have higher methane potential. MSW has a methane potential of around 120 $m^3$/Mg whereas biosolids have a methane potential of around 240 $m^3$/Mg. The Land GEM – Landfill Gas Emissions Model (USEPA) was used to project the potential total landfill gas generation quantity, generated quantities for individual pollutants such as methane and carbon dioxide, and the production curves over the active and post-closure period. The collection, flaring or electric generation systems will be designed based on the total estimated landfill gas quantity.

The proposed layout of cells within the monofill involves the construction and filling of four cells each with a 5-year capacity. Each cell is to be closed upon reaching its full capacity at the end of 5 years of operation. Biogas utilization is expected to begin at the closure of the first cell at year 5. The total amount of biogas anticipated to be produced for every cell was calcuated, Figure 6- 6 providing a summary of the methane production and electrical production potential anticipated over the lifespan of the monofill and closure.

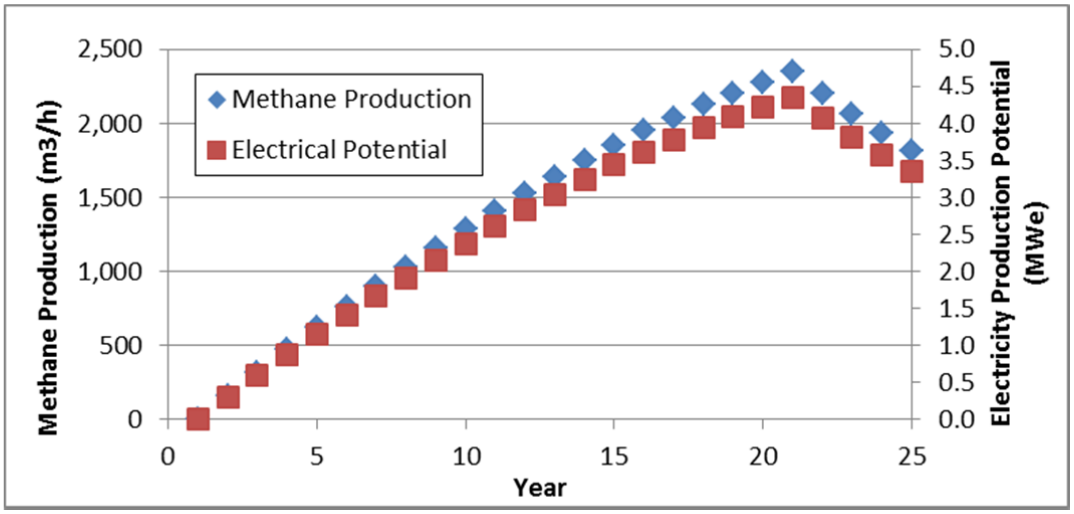



**Figure 6-6. Antipicated methane production and potential electrial production potential over time**

For CHP sizing purposes and for cost estimating, the production potential was considered in 5-year increments as presented in Table 6-4.

**Table 6-4. Power generated from Biogas based on 5 yr averages**

| Years of monofill operation | Power generation |
|---|---|
| 0 to 5 yrs | 0 $MW_e$ |
| 5 to 10 yrs | 1.6 $MW_e$ |
| 10 to 15 yrs | 2.9 $MW_e$ |
| 15 to 20 yrs | 3.9 $MW_e$ |
| 20 yr Average | 2.5 $MW_e$ |

The drying lagoons and landfilling operation consume energy in the form of diesel fuel for biosolids transportation. Table 6-5 summarizes the energy consumption and production for the monofill option.

**Table 6-5. Monofill Energy Efficiency**

| Parameter | Energy Consumption |
|---|---|
| Consumption | |
| Onsite Hauling[1] | 12,200 L/yr (420 GJ/yr) |
| Landfill Operation | 270,000 L/yr (9,800 GJ/yr) |
| Total Consumed | 10,220 GJ/yr |
| Production | |
| Electrical Production - Landfill Gas[2] | 2.5 MWe |

1. Assumes 1 km round trip of 20 $m^3$ each at 2.13 km/L for transporting from the BFPs to the lagoons and from the lagoons to monofill.
2. Based on 20-year average

### 6.4.6 Climate Impact (Methane and CO2 emissions)

Several protocols exist internationally for Green House Gas (GHG) accounting created by several organizations around the world. Each protocol has slightly different approaches and ways of accounting for GHG. It is important therefore when comparing the different options for climate impact to use the same protocol. Some of the widely used protocols are the Intergovernmental Panel on Climate Change protocol, Clean Development Mechanism protocol, the greenhouse gas protocol, ISO 14064, California climate action registry, and the climate registry.

The GHG accounting in this report was performed in accordance to the Biosolids Emissions Assessment Model, which is specifically developed for biosolids based on the climate registry as it is one of the most widely adopted protocols in North America. The emissions accounting includes three scopes of compiled direct and indirect emissions:

- Scope 1 – Direct within the fence of the WWTP
- Scope 2 – Indirect resulting from purchased electricity, steam or heat
- Scope 3 – Emissions associated with purchased chemicals and offsite hauling

It should be noted that using biogas for generating electricity is considered biogenic and $CO_2$ emissions present in the flue gas are not accounted for. However, $NO_X$ and methane emissions are included in the analysis. The analysis presented for CO2 equivalent is based on the operating parameters only.

GHG emissions for the activities associated with landfill construction and operation were calculated and converted to tonnes $CO_2$ eq/yr. Table 6-6 summarizes the anticipated GHG emissions for the landfill options based on a 20-year average of methane production and electrical generation and using the three above mentioned scopes. Although a gas collection and management system is planned, a significant portion of methane and carbon dioxide produced at the landfill is expected to be emitted, which is typical to all landfills.

**Table 6-6. Landfill Greenhouse Gas Analysis**

| Parameter | Landfill |
|---|---|
| Units | Tonnes $CO_2$ eq/yr |
| Scope 1 | |
| Fugitive Methane | 5,900,000 |
| Fugitive CO2 | 770,000 |
| Onsite Hauling | 34 |
| Diesel | 747 |
| **Total Scope 1** | **6,670,781** |
| Scope 2 | |
| Electricity Consumption | 0 |
| Electricity Production | -11,868 |
| **Total Scope 2** | **-11,868** |
| **Total Scope 3** | **0** |
| **Total** | **6,667,964** |

### 6.4.7 Environmental Impacts

Landfills permanently scar the locations they are constructed in as the disposed waste will stay in its place permanently. An environmental impact assessment study is required in most cases to get permission for landfill construction in Jordan. Landfills can have several environmental impacts if not carefully designed, constructed, and operated. Table 6-7 summarizes the environmental impacts associated with implementing the landfill in terms of traffic, noise, odor, impact on neighborhood and impact on soil and water (including both surface and underground water).

**Table 6-7. Landfill Environmental Impacts**

| Parameter | Impact |
|---|---|
| Traffic | Requires hauling of cover material from surrounding areas |
| Noise | Low Noise as medium and small landfill equipment will be used |
| Odor | Low potential odor from solar drying and landfilling with digested biosolids that are lagoon dried to 50% DS |
| Impact on Neighborhood | Access to the landfill area neighboring residents will be controlled. Landfill should be carefully operated to minimize impact on the surrounding areas |
| Impact on soil and water | Installation of engineered liners should result in little to no impact on the soil and groundwater |

### 6.4.8 Use of the Existing Treatment Facilities

The monofill option will continue to use the existing dewatering and solar drying system; the new landfill is simply an “add-on” to the existing and currently planned processes.

### 6.4.9 Investment and O&M Costs

The cost for monofill includes the initial cost for construction, closure and post closure, and O&M costs.

#### *6.4.9.1 Initial Investment Cost for Construction*

The initial phase of landfill construction will include other preparatory work in addition to actual construction of the first landfill disposal cell. Each cell should be constructed as it is needed. Therefore the initial investment cost should include landfill infrastructure as well as the construction of cell 1. Afterwards, cells are to be constructed and paid for every 5 years. Typical costs include the following:

- Site access roads (gravel surface)
- Site security fencing and lockable gates
- Site office (building, container or trailer) and convenience facilities
- Weighing facilities (if applicable)
- Extension of existing utilities
- Stormwater run-on/runoff controls
- Leachate treatment facility (single lined evaporation pond or other treatment)
- Landfill gas management facility (flare station or small utility flares)
- Solar panels and other sustainable energy practices (if applicable)
- Earthworks contractor mobilization
- Excavation
- Structural fill (import if required) placement
- Perimeter liner anchor trench
- Liner system (single composite liner system): controlled subgrade layer, GCL, HDPE liner, geocomposite drainage layer
- Leachate collection system – 460 mm (18-inch) protective soil and incised PVC collection pipes
- Leachate collection sump
- Leachate gravity pipe or collection manhole, or sideslope riser to sump house
- Perimeter utility corridor (gas piping, electrical, forcemain).

#### *6.4.9.2 Closure and Post-Closure*

Final landfill closure consists of construction of the incomplete final cap areas, and the decontamination/removal of equipment and facilities not required in the post-closure monitoring period. Costs typically considered for closure of a landfill mainly include:

- Closure cap system which is proposed to be an evapotranspiration final cover system
- Final landfill gas extraction and lateral/header pipe installation
- Installation of vegetative stabilization or other erosion and sediment control systems
- Decontamination of facility (cleaning of equipment and removal of contaminated liquids)
- Removal of support facilities (weigh station, offices, fuel dispensary, solar drying facility, etc.)

Costs typically considered for post-closure inspection, monitoring and maintenance of the landfill mainly include:

- General inspections (perimeter security features, access road condition, drainage structures, etc.)
- Closure cap inspection and maintenance (erosion damage, soil and liner component replacement)
- Groundwater monitoring system (inspect/sample/report) and maintenance
- Landfill gas collection monitoring (monthly well field balancing) and maintenance (flare system)
- Leachate collection and leachate treatment system inspection, monitoring (sampling/analysis/reporting) and maintenance (leachate evaporation pond repairs, pump maintenance)

#### 6.4.9.3 Operations and Maintenance Costs

Operations and Maintenance (O&M) costs have been developed based on the labor, fuel and electricity costs needed to operate the monofill over a period of 20 years. The major costs included are:

- Landfill equipment: it is assumed that the landfill equipment will be purchased and replaced every 6 years.
- Fuel consumption: Construction vehicles during monofill cell construction (subgrade, perimeter berm, sub-base).
- Energy use for daily disposal of biosolids, daily cover activities, closure cap construction.
- Waste and soil placement, leachate collection and disposal, and landfill gas monitoring. The estimate includes landfill equipment operator salaries, annual fuel consumption for landfill operations equipment, compliance personnel salaries, general maintenance costs, biogas and leachate technician salaries, costs for leachate pumping and maintenance, off-site leachate disposal if required, and cost for landfill gas monitoring equipment.
- Landfill gas production estimates and electrical generation: It is understood that gas at the local wastewater treatment plant is collected and electricity is generated. The option of piping the gas back to the treatment plant and expanding the generation facility at the plant should be explored and may be more viable then building a new plant. In almost all cases concerning landfills, it is preferable to send the gas to the local electric facility, or a third party vender, than to build a new plant. However, for this report, a gas electric generation plant is accounted for.

Table 6-8 summarizes the capital and O&M costs for the landfill based on five-year increments of operation. As illustrated, the majority of the investment occurs upfront in the first five years. Over time, however, the electrical production from the methane generated will have the potential to generate revenue.

**Table 6-8. Cost Estimates for the Biosolids Landfill Option (in JD)**

| Year Increment | 0-5 | 6-10 | 11-15 | 16-20 | Closure |
|---|---|---|---|---|---|
| Construction Cost | 2,510,000 | 5,430,000 | 3,750,000 | 3,750,000 | 0 |
| Closure Cost | 0 | 890,000 | 890,000 | 890,000 | 890,000 |
| **Total Construction Cost (20 yr) is 18,100,000** | | | | | |
| Annualized Cost | | | | | |
| Direct (Operating) | 380,000 | 380,000 | 380,000 | 380,000 | 0 |
| Direct (Closure) | 0 | 120,000 | 120,000 | 120,000 | 120,000 |

**Table 6-8. Cost Estimates for the Biosolids Landfill Option (in JD)**

| Year Increment | 0-5 | 6-10 | 11-15 | 16-20 | Closure |
|---|---|---|---|---|---|
| Indirect | 30,000 | 100,000 | 150,000 | 210,000 | 190,000 |
| Revenue | 0 | (1,490,000) | (2,670,000) | (3,580,000 | (3,490,000) |
| Capital (Operating + Closure) | 180,000 | 620,000 | 950,000 | 1,270,000 | 1,160,000 |
| Total | 580,000 | (270,000) | (1,070,000) | (1,590,000) | (2,010,000) |
| Total Cost per tonne | JD 8.2 | (JD 3.8) | (JD 15.1) | (JD 22.5) | (JD 28.5) |
| **Average Cost per Tonne (20 yr) is JD (12.3) including closure costs** | | | | | |

### 6.4.10 Requirements for Operating Staff

To manage the landfill operations, there must be at least one trained manager as well as two to three skilled machinery operators. There are several certifications available internationally for landfill managers including a well-known certification program in North America called Manager of Landfill Operation (MOLO). In Jordan there are no requirements for landfill manager certification but the manager should be trained and have knowledge of:

- The fundamental features of the sanitary landfill and how the engineering controls were designed and constructed to protect human health and the environment
- Methods of waste disposal, compaction and management in order to maximize use of landfill space in a safe way that provides maximum environmental protection
- The types and conditions of the biosolids to be disposed of in order to prohibit problematic and unwanted wastes or unprocessed biosolids
- Methods of applying cover material daily or long term in addition to controlling run off during landfill operations
- Techniques for safe management of landfill leachate and gas
- Methods of environmental monitoring for ground water, surface water and landfill gas

All the items above and more are included in training courses provided by solid waste associations such as the Solid Waste Association of North America.

### 6.4.11 Recycling of Biosolids

The monofill is a disposal facility and any biosolids landfilled are ultimately not recycled for a beneficial purpose. Over time, however, the landfill will generate a useful byproduct in the form of methane which can be captured for energy production.

### 6.4.12 Preliminary Stakeholder Information

There is no apparent reluctance in stakeholder willingness to cooperate other than preference for economically viable, environmentally sound options.

### 6.4.13 Risks of Option

Although landfilling, in general, is a well-established process, monofilling of biosolids is not widely practiced and limited design references are available. It is also noted that there have been some issues with previous installations.

Having an onsite landfill reduces the disposal risk as the control of the entire process remains “within the fence.” The liner installation will also help control leachate to ensure safe disposal.

The monofill option has low to moderate socio economic risks and should be a socially acceptable practice as long as it is away from residential and environmentally sensitive areas. The project also provides the local community a benefit by creating jobs, but local operators should be trained on safe and proper operation practices.

The environmental impact will be moderate but can be managed with proper practices. The design of the landfill should include all the required environmental protection techniques for ground water, surface water, and atmosphere. Risks which should be carefully managed include:

- Defects that occur during the landfill construction. This risk should be managed by assigning experienced engineers and quality assurance staff to supervise the construction process.
- Issues that may arise during operation by untrained staff. This can be mitigated by training the landfill manager and operators.
- Co-Disposal of other types of waste. Since the landfill is designed based on the disposal of biosolids with specific moisture content, it may be risky to accept biosolids with other moisture contents or other types of waste that may react with the biosolids or may be of a more hazardous nature. This can be managed by careful control and supervision of the disposal process and prohibition of all unwanted material.
- Unforeseen conditions that may cause landfill contamination. This can be addressed by monitoring of environmental contamination of the ground water, surface water, and atmosphere.

There is high risk from carbon footprint since there will be fugitive methane escaping the process, making it a relatively large GHG emitter as shown in Table 6-6.

#### 6.4.14 Use of Monofill as a Contingency Biosolids Outlet

Monofill was evaluated as standalone option for the produced biosolids and as a contingency outlet for the other options, including cement kiln, gasification and incineration. Table 6-9 shows the monofill options as a standalone or as a contingency. Gas recovery and electricity production is considered only for the standalone monofill option and not when the monofill is used as a contingency for other options. As a contingency, monofill will be used for a single five-year-cell facility. For the incineration and gasification, this monofill will also be used for disposal of the generated ash.

**Table 6-9. Landfill options as a standalone option and a contingency for other options**

| Option | Content | Capital Cost of Landfill for Option Life Cycle | | | |
|---|---|---|---|---|---|
| | | Landfill | Initial | Life | Gas Recovery |
| Landfill Option | Biosolids | Complete | 5 yr | 20 yr | Yes |
| Cement Kiln | Biosolids | 1st Cell | 5 yr | 5 yr | No |
| Incineration or Gasification for Energy Recovery | Biosolids | 1st Cell | 5 yr | 5 yr | No |
| | Ash | Complete | 5 yr | 20 yr | No |

## 6.5 Incineration

### 6.5.1 Technical Standard and Disposal Reliability

Incineration is well established technology for dewatered cake in the 20-35% DS range but not as common for incinerating biosolids with DS > 50% mainly because upstream thermal drying is required, which is cost prohibitive. However, in the case of As-Samra, since achieving greater than 50% DS is based on low tech solar drying, incineration is one favored option.

Multiple types of furnaces such as fluid bed, circulating fluid bed, bubbling fluid bed and reciprocating grates are feasible for biosolids >50% DS. According to the USEPA there are 60 fluid bed units installed in the US. Infilco Degremont, one of the main US suppliers, has constructed 26 plants worldwide since 1995. Andritz, another major supplier with a focus on large plants, has constructed three plants that combust solely biosolids and three additional plants that co-combust biosolids along with other wastes.

The new developments in biosolids incineration are mostly related to control of combustion emissions to meet stringent air quality regulatory requirements in Europe and USA. There are also developments associated with recovering the excess heat produced from incineration for thermal energy recovery (plume suppression, thermal drying, etc.) or for electricity production via steam turbines or the organic rankine cycle (ORC).

Incineration is a reliable technology for processing/disposal of biosolids and recovering energy as well. Incinerating dryer biosolids improves the heat balance and should not negatively impact system reliability. The incineration process can operate reliably continuously with greater than 85% annual average up time. Andritz specifically recommends a one-week shut down after 4,000 hours of operation for cleaning and an annual two-week shutdown to complete routine maintenance tasks.

The byproduct of incineration is an inert ash product with a volume of less than 5% of the dewatered biosolids leaving the belt filter press. The inert ash has a low risk of disposal and is typically landfilled although there may be opportunities for beneficial use in road aggregate or in cement manufacturing.

Incinerating As-Samra biosolids for energy recovery was evaluated with 50% and 75% DS. Since processing biosolids at 75% DS was favorable when compared to processing 50% DS, the following sections describe the 75% DS option.

### 6.5.2 Energy and Mass Flow for the Option

The incineration process was designed for 193.9 dry tonnes per day with 75% DS. Figure 6-7 shows the energy and mass balance for incineration.

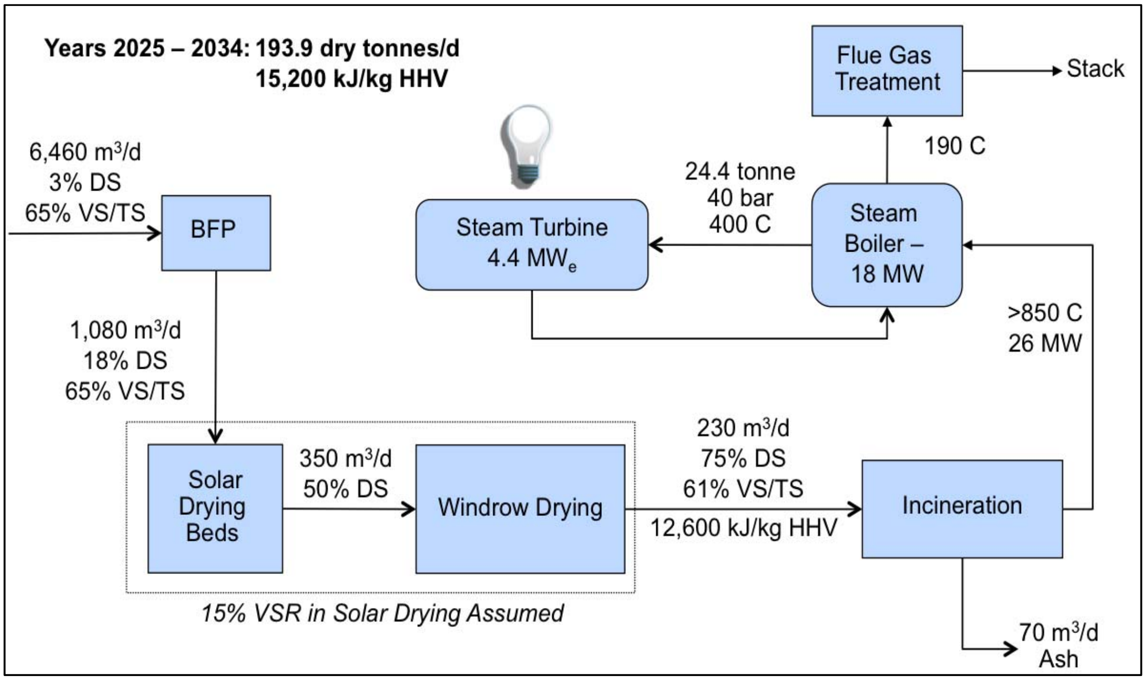



**Figure 6-7. Incineration Energy and Mass Balance Diagram**

### 6.5.3 Land Requirements

Table 6-10 summarizes the land requirements for the incineration option components.

**Table 6-10. Incineration option footprint requirements**

| Parameter | Incinerating 75% DS |
|---|---|
| Windrow Drying Beds | 10 Hectares |
| Incineration System (including boiler house, flue gas treatment and ash silo) | 36m long x 19m wide |
| Steam Turbine for Electricity Generation | 5.5 m long x 4m wide |
| Ash Contingency – Monofill | 5.5 Hectares |

### 6.5.4 Suitability to Meet Required Standards

There are currently no defined standards for biosolids incineration in Jordan and the system will be designed based on EU standards for performance and emissions.

### 6.5.5 Energy Efficiency

The drying and incineration processes consume energy in the form of diesel fuel for biosolids transportation and turning, natural gas or fuel oil for incineration start up and electricity to run incineration equipment such as pumps, compressors and fans. The incineration process also generates excess energy which will be recovered through the generation of 40 bar steam used to generate electricity. Table 6-11 summarizes the energy consumption and production for the incineration options. As the table shows, incinerating 75% DS will generate 4.3 MWe.

**Table 6-11. Incineration Energy Efficiency**

| Parameter | Incinerating 75% DS |
|---|---|
| Consumption | |
| Onsite Hauling[1] | 12,200 L/yr (420 GJ/yr) |
| Windrow Drying – Diesel Fuel | 87,000 L/yr (3,150 GJ/yr) |
| Incineration (start-up)[2] | 910 GJ/yr |
| Electrical | 3,540 MWh/yr (12,742 GJ/yr) |
| Total Consumed | 17,220 GJ/yr |
| Generation | |
| Electrical Production - Steam Turbines | 4.3 $MW_e$ |

1. Assumes 1 km round trip of 20 $m^3$ each at 2.13 km/L for transporting from the BFPs to the lagoons and from the lagoons to either the incineration system or Windrow drying system.
2. Assuming two cold starts and four warm starts per year.

### 6.5.6 Climate Impact (Methane and $CO_2$ Emissions)

The climate impact for incineration was estimated in a way similar to the methodology discussed previously under the monofill option. It should be noted that using dried biosolids as a fuel source for generating electricity is considered biogenic and $CO_2$ emissions present in the flue gas are not accounted for. However, $NO_X$ and methane emissions are included in the analysis. Table 6-12 summarizes the GHG analysis for the two incineration options (including gasification). The analysis shows that incineration with electrical production will result in GHG negative emissions or carbon credit.

**Table 6-12. Incineration Greenhouse Gas Analysis**

| Parameter | Incinerating 75% DS |
|---|---|
| Units | Tonnes $CO_2$ eq/yr |
| Scope 1 | |
| Incineration $NO_X$ + $CH_4$ | 4,915 |
| Start-up Fuel | 72 |
| Onsite Hauling | 34 |
| Windrow Turning Diesel | 254 |
| **Total Scope 1** | **5,275** |
| Scope 2 | |
| Electricity Consumption | 2,279 |
| Electricity Production | -26,181 |
| **Total Scope 2** | **-23,902** |
| Scope 3 | |
| FGT Chemicals | 1,952 |
| **Total** | **-16,675** |

### 6.5.7 Environmental Impacts

Table 6-13 summarizes the environmental impacts associated with implementing the drying and incineration process in terms of traffic, noise, odor, impact on neighborhood and impact on soil and water (including both surface and underground water).

**Table 6-13. Incineration Environmental Impacts**

| Parameter | Impact |
|---|---|
| Traffic | Requires hauling of chemicals for emission control (sodium bicarbonate, carbon, etc.) to site |
| Noise | Low noise |
| Odor | Low potential odor from solar and windrow drying with digested biosolids that are lagoon dried to 50% DS |
| Impact on Neighborhood | Facility will be considered energy recovery and should have little impact on neighbors |
| Impact on Soil and Water | Should be little to no impact on soil and water compared to current practice |

### 6.5.8 Use of the Existing Treatment Facilities

The incineration option will continue to use the existing solar drying system; new equipment is simply an "add-on" to the existing and currently planned processes.

### 6.5.9 Investment and O&M Costs

Table 6-14 summarizes the capital investment and O&M cost for the incineration option. The costs presented include the costs of windrow drying. The incineration costs are based on input provided by Andritz, and the steam turbine costs are based on input provided by Siemens. Specific assumptions used to develop the capital and O&M costs include:

- Incineration capital cost of JD 15,250,000 and refractory installation of JD 345,000
- Steam turbine cost of JD 1,340,000
- Eight employees for operation and maintenance of the incineration plant
- Incineration equipment maintenance costs equal to 2% of the initial capital cost

**Table 6-14. Incineration Capital and O&M Cost**

| Parameter | Incinerating 75% DS |
|---|---|
| Construction Costs | |
| Incineration | JD 53,100,000 |
| Windrow Drying | JD 8,930,000 |
| Onsite Monofill | JD 2,510,000 |
| **Total Construction Cost** | **JD 64,540,000** |
| Annual O&M | |
| Incineration | JD 1,990,000 |
| Revenue – Electricity | (JD 5,990,000) |
| Windrow Drying | JD 360,000 |
| Landfill | JD 70,000 |
| **Total Annual O&M** | **(JD3,570,000)** |
| **Total Annual O&M Cost per dry tonne** | **(JD 50.4)** |
| Annualized Capital[1] | |
| Incineration + Windrow Drying | JD 4,360,000 |
| Onsite Landfill | JD 180,000 |
| **Total Cost with Ash Disposal** | **JD 990,000** |

**Table 6-14. Incineration Capital and O&M Cost**

| Parameter | Incinerating 75% DS |
|---|---|
| **Total Cost per dry tonne with Ash Disposal** | **JD 13.8** |

1. Assuming 20 year financing at an effective interest rate of 3.5%

#### 6.5.10 Requirements for Operating Staff

The requirements and necessary skill level will vary depending on the considered process. The windrow drying turning process requires only a low-skill-type operator. However, the incineration process with steam boiler and steam turbine would require a highly skilled operator. Boiler's license or boiler engineers may also be required depending on local codes.

#### 6.5.11 Recycling of Biosolids

With the incineration process, all biosolids would be beneficially used as a renewable fuel source for power production. The final ash, approximately 70 tonne/d, could potentially be beneficially used for concrete, road aggregate or another purpose. Further study and market analysis would be required before it is known if any markets exist locally to use this material. A major advantage of this option is that the control of biosolids beneficial use remains "within the fence."

#### 6.5.12 Preliminary Stakeholder Information

There is no apparent reluctance in stakeholder willingness to cooperate other than preference for economically viable, environmentally sound options.

#### 6.5.13 Risks of Option

Although windrow drying and incineration are well-established technologies, there are risks associated with implementing this process. The risks from the windrow drying can be mitigated with proper piloting of the process to fine tune design parameters. The risks were analyzed based on disposal safety, technology, socio-economic and environmental impacts.

In terms of disposal safety, there is only low risk in reducing biosolids to an inert ash and disposing of them in an onsite contingency landfill or other outlet such as nearby cement kiln, nearby landfill or via other beneficial use. Having an onsite landfill further reduces the risk as the control of the entire process remains "within the fence."

Incineration is a well proven technology, but a high level of skilled operators is required because of complexity and high temperature. Generation of steam to produce electricity by steam turbines may further complicate the operational and licensing requirements. The operational risk, however, could be reduced if the process was operated by a third party or the project implemented under public-private partnership (P3) project implementation.

The project has low socio-economic risks and should provide the local community a benefit by creating jobs. The environmental impact will be low as long as the flue gas treatment system is properly designed and maintained. There is no risk from carbon footprint, since with electricity production the project will be GHG negative as shown in Table 6-12.

## 6.6 Gasification

### 6.6.1 Technical Standard and Disposal Reliability

Gasification is a well-established technology for biomass but considered an innovative technology for biosolids. The gasification system evaluated in this project is a close-coupled gasification system which is more established than the two-stage gasification system presented earlier. In the close-coupled system, the generated syngas is combusted to produce hot flue gas that is used as energy source. There are two known facilities operating worldwide: one system is successfully operating in Sanford, FL, and the other is in Japan.

Gasification is a still a new technology for processing/disposal of biosolids and has a higher risk than incineration due to the "newness" of the process but technology improvements have progressed significantly over the last few years. If properly designed and maintained, the gasification process should operate reliably and continuously with greater than 85% annual average up time.

Similar to incineration, the byproduct of gasification is an inert ash/slag/char product that will have a volume of less than 5% of the dewatered biosolids leaving the belt filter press. The inert ash/slag/char has a low risk of disposal and is typically landfilled although there may be opportunities for beneficial use as road aggregate or in cement manufacturing.

### 6.6.2 Energy and Mass Flow for the Option

The gasification process will be designed for 193.9 dry tonnes per day and 75% DS. Figure 6-8 is an energy and mass flow diagram for the process.

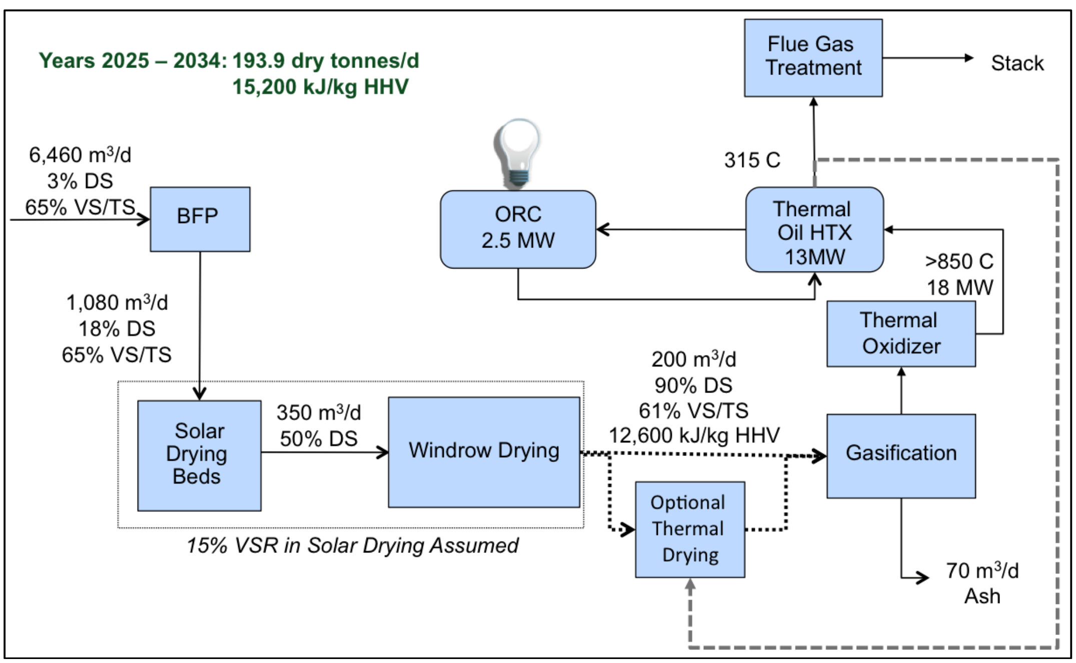



**Figure 6-8 Gasification Energy and Mass Flow Diagram**

### 6.6.3 Land Requirements

Table 6-15 summarizes the land requirements for the gasification option components.

**Table 6-15. Gasification option footprint requirements**

| Parameter | Area Required |
|---|---|
| Windrow Drying Beds | 10 Hectares |
| Gasification System | Not provided |
| Organic Rankine Cycle | Not provided |
| Ash Contingency – Monofill | 5.5 Hectares |

### 6.6.4 Suitability to Meet Required Standards

There are currently no defined standards for biosolids gasification in Jordan and limits worldwide are not well defined since it is still a new application for the technology. Table 6-16 presents the observed emissions from Sanford, FL facility stack testing.

**Table 6-16. Observed Gasification Emissions at Sanford, FL**

| Pollutant | Emissions levels @ 7% O2 feed rate of 1000 lbs/hr |
|---|---|
| SO2 | 0 |
| NOx | 2 TPY |
| VOC | 0.44 TPY |
| CO | 1.29 TPY |
| PM | 0.51 TPY |
| HCl | 0.048 TPY |
| Hg | 1 lb/yr |

### 6.6.5 Energy Efficiency

The drying and gasification processes consume energy in the form of diesel fuel for biosolids transportation and turning, natural gas for gasification start-up and operation, and electricity to run gasification equipment such as pumps and fans. The gasification process also generates excess energy which will be recovered with thermal oil for electricity production via an organic rankine cycle. Table 6-17 summarizes the energy consumption and production for the gasification options.

**Table 6-17. Gasification Energy Efficiency**

| Parameter | Energy Consumption |
|---|---|
| Consumption | |
| Onsite Hauling[1] | 12,200 L/yr (420 GJ/yr) |
| Windrow Drying – Diesel Fuel | 87,000 L/yr (3,150 GJ/yr) |
| Gasification (Start-up/Operation)[2] | 500 GJ/yr |
| Electrical[3] | 10,420 MWh/yr (37,500 GJ/yr) |
| Total Consumed | 41,570 GJ/yr |
| Production | |
| Electrical Production - Organic Rankine Cycle | 2.5 $MW_e$ |

[1] Assumes 1 km round trip of 20 $m^3$ each at 2.13 km/L for transporting from the BFPs to the lagoons and from the lagoons to either the incineration system or Windrow drying system.
[2] Estimated from older projects, specific consumption for Jordan was not provided
[3] Estimated from older projects, specific consumption for Jordan was not provided

### 6.6.6 Climate Impact (Methane and $CO_2$ emissions)

The methodology used to estimate the GHG emissions is the same as discussed in section 6.5.6. Table 6-18 summarizes the GHG analysis for the gasification option.

**Table 6-18. Gasification Greenhouse Gas Analysis**

| Parameter | Carbon Dioxide Equivalent |
|---|---|
| Units | Tonnes $CO_2$ eq/yr |
| Scope 1 | |
| Gasification NOx + $CH_4$ | 4,915 |
| Start-up/Operating Fuel | 25 |
| Onsite Hauling | 34 |
| Windrow Turning Diesel | 254 |
| **Total Scope 1** | **5,228** |
| Scope 2 | |
| Electricity Consumption | 6,708 |

**Table 6-18. Gasification Greenhouse Gas Analysis**

| Parameter | Carbon Dioxide Equivalent |
|---|---|
| Electricity Production | -14,269 |
| **Total Scope 2** | **-7,561** |
| Scope 3 | |
| FGT Chemicals[1] | 1,500 |
| **Total** | **-833** |
| [1] Estimated from older projects; specific consumption for Jordan was not provided | |

Table 6-18 shows gasification with electrical production will be GHG negative but since less electricity is produced from gasification than incineration it is less of a GHG reducer than incineration.

### 6.6.7 Environmental Impacts

Table 6-19 summarizes the environmental impacts associated with implementing the drying and gasification process in terms of traffic, noise, odor, impact on neighborhood and impact on soil and water (including both surface and underground water).

**Table 6-19. Gasification Environmental Impacts**

| Parameter | Impact |
|---|---|
| Traffic | Requires hauling of chemicals for emission control (sodium bicarbonate, carbon, etc.) to site |
| Noise | Low Noise |
| Odor | Low potential odor from solar and windrow drying with digested biosolids that are lagoon dried to 50% DS |
| Impact on Neighborhood | Facility will be considered energy recovery and should have little impact on neighbors |
| Impact on soil and water | Should be little to no impact on soil and water compared to current practice |

### 6.6.8 Use of the Existing Treatment Facilities

The gasification option will continue to use the existing solar drying system; new equipment is simply an “add-on” to the existing and currently planned processes.

### 6.6.9 Investment and O&M Costs

Table 6-20 summarizes the capital investment and O&M cost for the gasification option. The costs presented include the costs of windrow drying. The gasification costs are based on input provided by Max West, and the Organic Rankine Cycle costs are based on input provided by Turboden.

- Gasification Capital Cost – three units total – JD 25,500,000
- Organic Rankine Cycle Cost – JD 2,800,000
- Gasification plant is assumed to have eight operation and maintenance staff
- Gasification equipment maintenance costs are equal to 2% of the initial capital cost

**Table 6-20. Gasification Capital and O&M Cost**

| Parameter | |
|---|---|
| Construction Cost | |
| Gasification | JD 81,860,000 |
| Windrow Drying | JD 8,930,000 |
| Onsite Monofill | JD 2,510,000 |
| **Total Project Cost** | **JD 93,300,000** |
| Annual O&M | |
| Gasification | JD 2,360,000 |
| Revenue – Electricity | (JD 3,490,000) |
| Windrow Drying | JD 360,000 |
| Landfill | JD 70,000 |
| **Total Annual O&M** | **(JD 700,000)** |
| **Total Annual O&M Cost per dry tonne** | **(JD 9.9)** |
| Annualized Capital[1] | |
| Incineration + Windrow Drying | JD 6,390,000 |
| Onsite Landfill | JD 180,000 |
| **Total Annualized Cost with Ash Disposal** | **JD 5,870,000** |
| **Total Cost per dry tonne with Ash Disposal** | **JD 82.9** |

1. Assuming 20-year financing at an effective interest rate of 3.5%

Compared to incineration, the costs for gasification are higher and there is less potential to produce electricity.

#### 6.6.10 Requirements for Operating Staff

The requirements and necessary skill level will vary depending on the considered process. The Windrow drying turning process would require only a low-skill-type operator. However, the gasification process would require a highly skilled operator due to high temperature and complexity of the equipment.

#### 6.6.11 Recycling of Biosolids

With the gasification process, all biosolids would be beneficially used as a renewable fuel source for power production. The final ash/slag/char, approximately 70 tonne/d, could potentially be beneficially used for concrete, road aggregate or another purpose, and a further study and market analysis would be required before it is known if any markets exist locally to use this material. Like incineration, a major advantage of this option is that the control of biosolids beneficial use remains "within the fence."

#### 6.6.12 Preliminary Stakeholder Information

There is no apparent reluctance in stakeholder willingness to cooperate other than preference for economically viable, environmentally sound options.

#### 6.6.13 Risks of Option

Since gasification is still a new and innovative technology for processing biosolids, there are risks associated with implementing this process. The risks were analyzed based on disposal safety, technology, socio-economic and environmental impacts.

In terms of disposal safety, there is only low risk in reducing biosolids to an inert ash/slag/char and disposing of them in an onsite contingency landfill or other outlet such as nearby cement kiln, nearby landfill or via other beneficial use. Having an onsite landfill further reduces the risk as the control of the entire process remains "within the fence."

Operators with a high level of skill are required for gasification because of complexity and high temperature. The operational risk, however, could be reduced if the process were operated by a third party.

The project has low socio-economic risks and should provide the local community a benefit by creating jobs. The environmental impact will be low as long as the flue gas treatment system is properly designed and maintained. The carbon footprint risk is also low and with electrical production, the project will be a GHG negative as shown in Table 6-18.

### 6.7 Cement Kiln

#### 6.7.1 Technical Standard and Disposal Reliability

Using dry biosolids in a cement kiln as a fuel source is a technically sound concept but requires agreement between MWI and the cement kiln owner. The concept is gaining more popularity due to increasing cost of energy for cement manufacturing and requirements imposed on cement kilns to use renewable energy sources to offset the use of coal and other fossil fuels. Use is limited to replacing only approximately 20% of the fossil fuel by dried biosolids.

The concept is currently practiced in Back River (Maryland, USA) and Encina (California, USA) for a portion of the dried biosolids but neither plant uses a cement kiln as the sole beneficial use outlet. Instead the cement kiln provides an alternative beneficial use outlet along with land application.

The cement kiln option is reliable as long as the cement kiln is accepting the dried material. Ash material is used within the cement kiln processing so there is no additional byproduct generated at the cement kiln that would require disposal.

### 6.7.2 Energy and Mass Flow for the Option

The onsite windrow drying process will be designed for 193.9 dry tonnes per day to increase the solid content of the biosolids from 50% DS to 75% DS. The dried biosolids would then be hauled offsite 10 km to the cement kiln. Figure 6-9 shows the energy and mass balance for the cement kiln option.

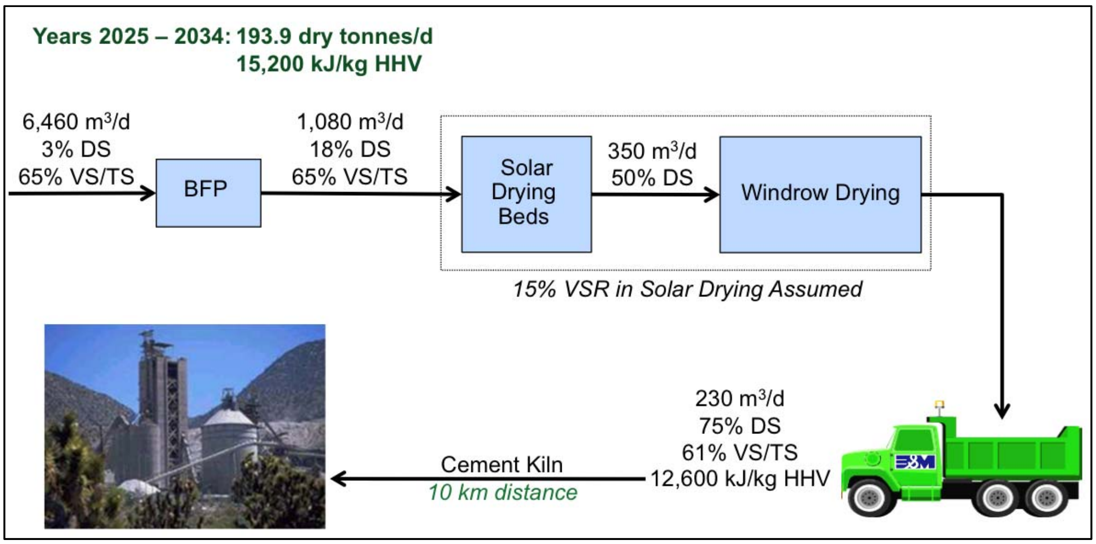



**Figure 6-9. Cement Kiln Energy and Mass Diagram**

### 6.7.3 Land Requirements

Table 6-21 summarizes the land requirements for the cement kiln option components which will only consist of the drying beds and **contingency** landfill

**Table 6-21. Gasification option footprint requirements**

| Parameter | Area Required |
|---|---|
| Windrow Drying Beds | 10 Hectares |
| Contingency – Monofill | 5.5 Hectares |

### 6.7.4 Suitability to Meet Required Standards

The process is practiced in other parts of the world and regulations usually depend on local permitting authority. The cement kiln owner will be the entity responsible for meeting any existing limits, if any, associated with burning dried biosolids.

### 6.7.5 Energy Efficiency

The drying processes consume energy in the form of diesel fuel for biosolids transportation (both onsite and to the cement kiln) and turning, but the process does not require any additional onsite combustion or electrical requirements beyond what is currently onsite or already in the planning phase. Table 6-22 summarizes the energy consumption including that for the onsite drying process and hauling. The energy produced from the dried biosolids is at the cement kiln site and thus no energy is produced at As-Samra site from this option.

**Table 6-22. Drying to Cement Kiln Energy Efficiency**

| Parameter | Energy Consumption |
|---|---|
| Consumption | |
| Onsite Hauling[1] | 12,200 L/yr (420 GJ/yr) |
| Windrow Drying – Diesel Fuel | 87,000 L/yr (3,150 GJ/yr) |
| Hauling to Cement Kiln[2] | 40,000 L/yr (1,400 GJ/yr) |
| Total Consumed | 4,970 GJ/yr |

[1] Assumes 1-km round trip of 20 $m^3$ each at 2.13 km/L for transporting from the BFPs to the drying lagoons and from the drying lagoons to either the incineration system or Windrow drying system.
[2] Based on 20-km round trip of 20 $m^3$ each at 2.13 km/L for transporting from the WWTP to the cement kiln.

### 6.7.6 Climate Impact (Methane and $CO_2$ Emissions)

The methodology used to estimate the GHG emissions is the same as discussed in section 6.5.6. The scope three emissions also include the offset for avoided coal at the cement kiln. The offset is based on the value of 0.95 kg of $CO_2$ equivalent per gigajoule (GJ) of coal burned assuming that the dried biosolids will have a dry high heating value of 12,600 kJ/kg and an as-burned heating value of 9,450 kJ/kg at 75% DS. Table 6-23 summarizes the GHG analysis for the drying to cement kiln option.

**Table 6-23. Drying to Cement Kiln Greenhouse Gas Analysis**

| Parameter | Carbon Dioxide Equivalent |
|---|---|
| Units | Tonnes $CO_2$ eq/yr |
| Scope 1 | |
| Onsite Hauling | 34 |
| Windrow Turning Diesel | 254 |

**Table 6-23. Drying to Cement Kiln Greenhouse Gas Analysis**

| Parameter | Carbon Dioxide Equivalent |
|---|---|
| **Total Scope 1** | **288** |
| Scope 2 | |
| **Total Scope 2** | **0** |
| Scope 3 | |
| Trucking to Cement Kiln [1] | 399 |
| Coal Offset[2] | -57,371 |
| **Total Scope 3** | **-56,971** |
| **Total** | **-56,683** |

[1]. Based on average round trip hauling of 71 km (see Table 6-25)
[2] Assumed based on energy credit avoided by not burning coal

Table 6-23 shows that although the carbon footprint at the WWTP will increase marginally, the total carbon footprint impact will be a net $CO_2$ reducer since it will offset coal burning.

### 6.7.7 Environmental Impacts

Table 6-24 summarizes the environmental impacts associated with implementing the drying and hauling to the cement kiln in terms of traffic, noise, odor, impact on neighborhood and impact on soil and water (including both surface and underground water).

**Table 6-24. Drying to Cement Kiln Environmental Impacts**

| Parameter | Impact |
|---|---|
| Traffic | Most hauling requirements (~260 tonne/day) |
| Noise | Low Noise |
| Odor | Low potential odor from solar and windrow drying with digested biosolids that are lagoon dried to 50% DS |
| Impact on Neighborhood | The option would increase traffic through the neighborhood but the option would also be considered beneficial use and could be viewed positively by the neighbors |
| Impact on soil and water | Should be little to no impact on soil and water compared to current practice |

### 6.7.8 Use of the Existing Treatment Facilities

The option will continue to use the existing solar drying system; an additional windrow drying process is simply an “add-on” to the existing and currently planned process. The option uses an existing third party cement kiln for final beneficial use of the dried biosolids.

### 6.7.9 Investment and O&M Costs

The drying to cement kiln option does not require additional capital equipment beyond the cost of windrow drying beds presented in Table 6-2 for normal operation. The option does include the cost for one landfill cell for back up and contingency at a project cost of JD 2,510,000. The hauling costs presented in Table 6-25 assume that 75% of the dried biosolids will go to Al Rajhi and 25% will go to Modern Cement Company. The costs presented in Table 6-26 summarize the cement kiln costs for two options: one where biosolids are given away and one where 10 JD per ton revenue is generated from the sale of biosolids.

**Table 6-25. Cement Kiln Capital and O&M Cost**

| | **Round Trip (km)** | **JD/tonne** |
|---|---|---|
| Al Rajhi | 18 | 2 |
| Modern | 230 | 7.5 |
| Weighted tipping Fee | | 3.375 |

**Table 6-26. Cement Kiln Capital and O&M Cost**

| **Parameter** | **Option 1: Zero Tipping Fee** | **Option 2: JD 10/tonne revenue** |
|---|---|---|
| Construction Cost | | |
| Windrow Drying | JD 8,930,000 | JD 8,930,000 |
| Onsite Monofill | JD 2,510,000 | JD 2,510,000 |
| **Total Project Cost** | **JD 11,440,000** | **JD 11,440,000** |
| Annual O&M | | |
| Tipping Fee | JD 0 | (JD 940,000) |
| Hauling | JD 320,000 | JD 320,000 |
| Windrow Drying | JD 360,000 | JD 360,000 |
| Landfill | JD 0 | JD 0 |
| **Total Annual O&M** | **JD 680,000** | **(JD 260,000)** |
| **Total Annual O&M Cost per dry tonne** | **JD 9.6** | **(JD 3.7)** |
| Annualized Capital[1] | | |
| Windrow Drying | JD 630,000 | JD 630,000 |

**Table 6-26. Cement Kiln Capital and O&M Cost**

| Parameter | Option 1: Zero Tipping Fee | Option 2: JD 10/tonne revenue |
|---|---|---|
| Onsite Landfill (contingency) | JD 180,000 | JD 180,000 |
| **Total Annualized Cost** | **JD 1,490,000** | **JD 550,000** |
| **Total Cost per dry tonne** | **JD 21.0** | **JD 7.7** |
| [1] Assuming 20-year financing at an effective interest rate of 3.5% | | |

The actual costs and potential revenue from the option will be dependent on the terms negotiated with the local cement kilns.

### 6.7.10 Requirements for Operating Staff

The Windrow drying turning process would require only a low-skill-type operator. The more complicated high temperature combustion process is operated by the cement kiln staff and not the WWTP staff.

### 6.7.11 Recycling of Biosolids

With the drying and cement kiln option, all biosolids could potentially be beneficially used as a fuel replacement at a cement kiln. Furthermore the ash produced from biosolids combustion is beneficially used for the cement making. The process, however, relies on a third party to provide the beneficial use outlet and the option is subject to factors outside of the municipality's control. If the cement kiln was unable to accept dried biosolids for an extended period, the biosolids would require disposal in the onsite monofill that is currently planned as a backup for contingency.

### 6.7.12 Preliminary Stakeholder Information

There is no apparent reluctance in stakeholder willingness to cooperate other than preference for economically viable, environmentally sound options.

### 6.7.13 Risks of Option

Since the beneficial use outlet is dependent on a third party, reliability is outside of MWI control which increases the risk for outlet disposal. Before deciding to move forward with this as the main outlet option, a long-term reliability partnership with a cement kiln will have to be determined. Risk should be reduced by negotiating a tight agreement with a cement kiln.

This option does not require a new, innovative or complicated process so the onsite operational risk is low.

The project has low socio-economic risks and should provide the local community a benefit by creating jobs. The environmental impact associated with this case should be positive and mutually beneficial to two different entities. The carbon footprint risk is also low and with a significant coal offset, the project will be GHG negative as shown in Table 6-23.

There could be a risk with capacity limitations, and as noted in section 4.6 there may not be enough capacity for the cement kiln to take all of As-Samra's dried biosolids. The onsite landfill and potential development of other beneficial use outlets could mitigate the capacity limitation risk with this option.

# 7. CRITERIA FOR EVALUATION AND SELECTION OF ALTERNATIVES

This section provides an overview of the criteria used to evaluate the various biosolids management alternatives presented in this report. The criteria have been categorized into technical, environmental, financial, and socio-economic considerations. Each criterion is assigned a weighting factor (as described below) which, when combined with a score assigned for each technical alternative, results in an overall score for that alternative. Where possible at this stage of project development, quantitative data will be used as the basis for evaluation of the various criteria. This will be combined with a qualitative assessment for other criteria where quantitative assessment is not yet possible. The following sections provide a general discussion of each criterion along with the factors or sub-criteria that have also been considered in assessing the final ranking.

## 7.1 Technical Considerations

### 7.1.1 Process Reliability

This is an inherent quality of the biosolids management process or technology and is based on whether the alternative is technically sound and robust and whether it has been in widespread use for some time. Newer technologies with less proven experience would be rated lower than older, proven, and more conventional methods.

### 7.1.2 Complexity of Technology

This consideration addresses relative technical complexity. Given the challenges of retention of trained/skilled operations and maintenance staff, and the need to periodically replace staff and conduct necessary training, the issue of technical complexity is important as it relates to overall sustainability. Alternatives that are less technically complex will be ranked more favorably.

### 7.1.3 Operational Considerations

In Jordan, a key factor in the category of technical considerations is the level of skill or training required to operate the biosolids management system, and the relative ease of maintaining that system in accordance with manufacturer recommendations. One consideration is the experience and familiarity that operators in the country have with the specific technology. Such experience and familiarity would foster a faster learning curve for the ultimately selected alternative. Another consideration is operational flexibility; this refers to the ability of the particular technology to adapt to changes in circumstances such as swings in influent biosolids characterization. Technologies that are able to easily respond to such situations quickly will be rated higher than those that are not.

### 7.1.4 Infrastructure Requirements

This factor relates to the reliance of an alternative on support infrastructure such as roadways and utilities. Alternatives that are less infrastructure-intensive will be ranked more favorably.

## 7.2 Environmental Considerations

### 7.2.1 Land Use and Area Requirements

Land use and compatibility with the surrounding area will be considered in the evaluation. Part of this assessment will also consider land area or footprint to be occupied by the facilities and equipment specified for each alternative versus the available land area: in general, the more consistent land usage combined with lesser space requirements, the more desirable the option.

### 7.2.2 Emissions to Air, Soil, and Water

The objective of environmental control projects is to minimize uncontrolled emissions to air, soil, and water. The degree to which an alternative can be designed to mitigate such emissions – particularly as these may relate to health and safety of workers and nearby populations – and the ease with which such measures can be implemented will be considered in the evaluation.

### 7.2.3 Noise and Odor Control

Due to the nature of wastewater and biosolids treatment in general, odor abatement is typically very important. Noise levels can also be of concern – both to workers and adjacent populations. The degree to which the given alternative requires odor and noise abatement and/or the ease with which such control measures can be implemented will be considered important factors.

### 7.2.4 Traffic Requirements

This factor addresses traffic requirements for workers, delivery of consumables, and transfer/transport of biosolids and is related to infrastructure requirements included under Technical Considerations. A traffic-intensive alternative will generally be ranked lower than less traffic-intensive alternatives.

### 7.2.5 Regulatory Approval and Non-Compliance Risks

Any biosolids management scenario considered for the project will require regulatory approval before it can be implemented. The likelihood of approval and/or the ease with which such approval can be obtained will be considered important. The risk of non-compliance with applicable regulations and/or authorizations is also considered as part of the evaluation process. The likely impact of any non-compliance will also be considered.

## 7.3 Financial Considerations

### 7.3.1 Capital Investment Cost

One of the primary factors in technical evaluations is the total installed cost (TIC) or capital investment cost. For equipment-intensive alternatives, the total process equipment (TPE) cost is determined including biosolids turners, furnaces, gasifiers, heat exchangers, flue gas treatment devices, electricity generation equipment and other key system components. Then, common industry factors are used to adjust the TPE for such items as sitework, installation, piping electrical and instrumentation, to arrive at a total capital cost (TCC). Additional factors are then used to account for engineering, contractor overhead and profit and freight to enable calculation of the TIC. For earth/concrete intensive alternatives, the TIC will be based on reasonable design assumptions and associated quantity estimates. The basis for the capital investment costs is discussed in section 6.1.

### 7.3.2 Operating Cost

Another key financial factor to consider is the annual operating cost for the given alternative. This cost consists of both direct operating costs (labor, maintenance and utilities) and indirect operating costs (overhead, taxes, insurance, administrative costs and consumables). In addition, for this evaluation, a second annual operating cost is considered which includes the cost of capital recovery, based on a certain life expectancy for the equipment and an assumed interest rate. The annual operating cost obviously includes fuel consumption, electrical power requirements, chemical usage and annual maintenance.

### 7.3.3 Tariff

This consideration addresses the anticipated impact on the tariff for wastewater collection, treatment, and disposal.

## 7.4 Socio-economic Considerations

### 7.4.1 Sustainability to the Local Situation

This criterion addresses the relative sustainability of the alternatives with local practices.

### 7.4.2 Ability to Pay Tariff

The extent to which an alternative will add to the existing tariff for wastewater collection, treatment, and disposal and potentially impose a hardship to customers will be assessed. An alternative that adds less to this tariff will be ranked more favorably.

### 7.4.3 Required Subsidization

In general terms, sustainability is the capacity to endure. For this project, sustainability will be considered to include management of resources, which is typically based on economic considerations such as subsidies. Alternatives that reduce the consumption of resources – including supplemental/subsidized resources (e.g., grants or reduced energy rates) will be highly rated. The reuse potential for biosolids associated with the alternatives for As-Samra will also be considered in this context. In addition to the physical properties of the biosolids processed under each alternative, the quality of the treated biosolids will be quite important, as this will determine the degree to which the biosolids can be reused.

### 7.4.4 Job Creation

Job creation considers both long-term employment opportunities associated with the biosolids management alternatives as well as construction-related employment. Alternatives deemed to contribute more to job creation will be ranked more favorably. Anticipated contributions toward employment and sustainability of end-user operations (in the context of beneficial use of biosolids) will also be considered.

### 7.4.5 Public Acceptance

This criterion addresses the perceived likelihood of gaining public acceptance of the alternative. For example, an alternative that would result in lower impacts (odor, noise, traffic, etc.) to neighboring uses compared to others would likely be deemed more publicly acceptable.

#### 7.4.6 End-user Education and Awareness

End-user education and awareness may be essential for the implementation of certain biosolids management alternatives. This may introduce an element of risk to the biosolids management operation as the end-user may not be under the direct control of the operator of the biosolids management system. Alternatives with less reliance on end-user education and awareness for implementation will be ranked more favorably.

### 7.5 Technology Rating Scheme

Determination of the best alternative will be based on all of the criteria discussed in this section and will make use of a standard methodology referred to as a K-T analysis. K-T analysis stands for Kepner-Tregoe analysis, for the authors who originally pioneered the approach. The approach involves three steps – weighting, rating and scoring.

#### 7.5.1 Weighting Factors

Each criterion discussed above will be assigned a weighting factor based on its importance in the overall evaluation process. Weighting factors from 1 to 10 are used, with 1 assigned to criteria having relatively little importance and 10 being assigned to factors that are most important. It should be noted that not all of the weightings need to be used. For example, a 10 could be assigned to every criterion being considered if all were deemed equally important. The assignment of weighting factors also considers the likelihood of achieving differentiation between alternatives for a given criterion; if it is likely that little differentiation in rating can be achieved, then the criterion will tend to be viewed as less important. Assigning evaluation criteria and sub-criteria weight factors is discussed in section 8.2.1.

#### 7.5.2 Rating Scale

The second step in the evaluation process is to rate each criterion in terms of its effectiveness and/or score. For this process, ratings of 1 to 5 are used as defined below:

- 1 = worst
- 2 = below average
- 3 = average
- 4 = good (above average)
- 5 = best

As with the weighting factors, not all of the ratings need to be used. For example, any number of criteria could be considered “good (above average)” for the alternatives being considered. Assigning the rating scale is discussed in section 8.2.2.

#### 7.5.3 Detailed Matrix Evaluation and Scoring

The final step in the process is to determine the overall score for the alternative. This is done by multiplying the rating by the weighting factor (for each criterion) and then summing all of the scores over all of the criteria considered. The alternative with the highest overall score is the preferred alternative. Scoring and ranking of options is discussed in section 8.2.2.

# 8. COMPARISON OF OPTIONS AND RECOMMENDATIONS

## 8.1 Summary conclusions for options

Section 6 provided detailed evaluations of the monofill, incineration, gasification and cement kiln options. Table 8-1 summarizes the detailed evaluation for the four options according to the required assessments identified in Part 4.1.2.5 of the TOR. Stakeholders have in general appeared open to consideration of all four options with a preference for economically viable, environmentally sound options.

Table 8-2 presents a comparison of the options in terms of capital cost, electricity production, annual operating cost, 20 years present worth, cost per dry tonne, and carbon footprint. To summarize:

- The cement kiln option represents the lowest capital investment cost followed by monofill and incineration.

- As previously discussed in section 6.7.9, the actual costs and potential revenue from the cement kiln option will depend on the terms negotiated with the cement kiln. The hauling costs presented in Table 6-25 assume that 75% of the dried biosolids are going to Al Rajhi and 25% are going to Modern. Two cement kiln options were considered; one where biosolids are given away and one where 10 JD per ton revenue is generated from the sale of biosolids.

- The incineration option provides the highest electricity generation followed by gasification and monofill. As indicated, incineration provides the highest revenue in terms of annual operating cost, followed by gasification and then monofill. The cement kiln option does not provide any electricity generation on site.

- The least cost alternative per dry tonne of biosolids processed incorporating capital and operating costs is the monofill option, followed by the cement kiln option with JD 10/tonne revenue, followed by incineration, followed by cement kiln with no revenue, and then gasification.

- The carbon footprint is a significant environmental impact indicator for the respective options. The cement kiln would result in the highest carbon credit followed by incineration. The monofill has the highest carbon footprint even with the electricity generation, primarily as the result of methane gas escaping during landfilling of the biosolids and prior to construction of a cover for the respective landfill cells.

- The gasification option for the design biosolids loading is estimated to be approximately 1.5 times the cost of the incineration option while providing only 60% of the electricity production of incineration. Given that environmental, social, and technical considerations for the two options are essentially the same, and the significant difference in cost and electricity generation, gasification will not be considered further in the selection process.

**Table 8-1. Comparison of Biosolids Processing Options**

| Option Assessment | Monofill | Mono-Incineration (75%DS) | Gasification | Cement Kiln |
|---|---|---|---|---|
| **Technical Standard and Disposal Reliability**<br>• Information on implementation history of technology<br>• Experience in other projects<br>• New developments in the technology and further experience will be highlighted<br>• Disposal reliability assessment | • Landfilling of dewatered biosolids (20% DS or above) is a well-established practice with municipal solid waste landfill. Monofills for biosolids have limited practice.<br>• Two monofill sites were found in literature. The first in the US was dewatered sludge mixed with sand at 1:2 ratio. The second was in the UK; at this site, gases caused voids in the landfill and resulted in slope failure.<br>• State-of-the art liners and gas collection systems are used currently to further protect the environment.<br>• Some uncertainties exist, given limited monofill applications and design experience. | • Incineration is well-established technology for dewatered sludge in 20-35% DS range but is not as common for biosolids with DS > 50% mainly because upstream thermal drying is required.<br>• Multiple types of furnaces such as fluid bed, circulating fluid bed and reciprocating grate are feasible for biosolids >50% DS. According to the EPA, 60 FBI units are installed in the US. IDI has constructed 26 plants worldwide since 1995, and Andritz has constructed three plants that combust solely sewage sludge and three additional plants that co-combust sewage sludge with other wastes.<br>• The incineration technology is well-established and new development is related only to the need to control combustion emissions to meet stringent new regulations.<br>• Incineration is a reliable technology for processing/disposal of biosolids. Incinerating dryer biosolids improves heat balance and should not negatively impact system reliability.<br>• Generated ash has the lowest risk of disposal. | • Gasification is well-established technology for biomass but considered an innovative technology for biosolids. The gasification system evaluated in this project is close-coupled gasification system, which is more established than the two-stage gasification system.<br>• Two worldwide operating facilities: one system is successfully operating in Sanford, FL, and the other is in Japan.<br>• Gasification has a higher risk than incineration due to the "newness" of the process but technology improvements have progressed significantly over the last few years.<br>• Generated ash has the lowest risk of disposal. | • Using dry biosolids in cement kiln as a fuel source is technically sound concept, but requires agreement between municipality and third party.<br>• The concept is gaining more popularity due to increasing cost of energy for cement manufacturing and requirements imposed on cement kilns to use renewable energy sources rather than fossil fuel.<br>• Use is limited to replacing only ~20% of the fossil fuel by dried biosolids.<br>• Concept practiced in Back River, MD and Encina, CA for a portion of the dried biosolids, but neither plant uses a cement kiln as the sole disposal option.<br>• This option is reliable as long as the cement kiln is accepting the dried biosolids.<br>• Ash material is used within the cement manufacture processing and therefore does not require an ash landfill. |
| **Land Requirements**<br>• Land use and consumption<br>• Indicate separate land for landfills and land used for treatment | • Landfill cells (20 yrs) – 25 Hectares | • Windrow Drying Beds – 10 Hectares<br>• Incineration System including boiler house, flue gas treatment and ash silos – 36m L x 19m W<br>• Steam Turbine<br>• Landfill for ash - 5.5 Hectares | • Windrow Drying Beds – 10 Hectares<br>• Gasification System<br>• Organic Rankine Cycle<br>• Landfill for ash/slag/char - 5.5 Hectares | • Windrow Drying Beds – 10 Hectares<br>• Contingency Landfill for biosolids - 5.5 Hectares |
| **Suitability to Meet Required Standard**<br>• Meeting Technical and environmental standards in Jordan | • Monofill will be designed in accordance with USEPA standards, which exceed the Jordanian regulations | • Currently no defined standards for sewage sludge incineration in Jordan<br>• System will be designed to meet EU limits | • Currently no defined standards for sewage sludge gasification in Jordan<br>• Limits worldwide are not well-defined since it is still a new application for the technology | • Practiced in other parts of the world and regulations usually depend on local permitting authority<br>• Cement kiln owner will be entity responsible for meeting any environmental and discharge limits |
| **Energy Efficiency**<br>• Energy consumption<br>• Potential energy generation | • Diesel fuel 270,000 L/yr (9,800 GJ/yr)<br>• ~2.5 MW 20 yr average for electrical generation (1.6 – 3.9 MW range) | • Windrow Drying – 87,000 L/yr (3,150 GJ/yr)<br>• Incinerator Start-up – 910 GJ/yr<br>• Electrical – 3,540 MWh/yr (12,742 GJ/yr)<br>• Total – 16,800 GJ/yr<br>• Combustion with energy recovery through steam turbines can generate at future design capacity 4.8 MW (net) | • Windrow Drying – 87,000 L/yr (3,150 GJ/yr)<br>• Gasifier Start-up/Operation – 500 GJ/yr<br>• Electrical – 10,420 MWh/yr (37,500 GJ/yr)<br>• Total – 41,500 GJ/yr<br>• Combustion with energy recovery through ORC can generate 2.8 MW at future design capacity | • Windrow Drying – 87,000 L/yr (3,150 GJ/yr)<br>• Hauling ~ 40,000 L/yr (1,400 GJ/yr)<br>• Total 4,500 GJ/yr<br>• Using dried biosolids can help reduce coal and fuel consumption at that cement kiln, but this will need to be determined by the specific facility |

| | | | | |
|---|---|---|---|---|
| **Environmental Impacts**<br>• Traffic<br>• Noise<br>• Odor<br>• Impact on neighborhood<br>• Impact on soil and water (surface and underground water) | • Requires hauling of cover material from surrounding areas<br>• Low noise as medium and small landfill equipment will be used<br>• Low potential odor from windrow drying and landfilling with digested biosolids that are lagoon dried to 50% DS<br>• Controlled access to landfill area for neighboring residents. Landfill should be carefully operated to minimize impact on the surrounding area<br>• Installation of engineered liners should result in little to no impact on soil and groundwater | • Requires hauling of chemicals for emission control (sodium bicarbonate, carbon, etc.) to site<br>• Low noise<br>• Low potential odor from windrow drying with digested biosolids that are lagoon dried to 50% DS<br>• Facility will be considered energy recovery and should have little impact on neighbors<br>• Should be little to no impact on soil and water compared to current practice | • Requires hauling of chemicals for emission control (sodium bicarbonate, carbon, etc.) to site<br>• Low noise<br>• Low potential odor from windrow drying with digested biosolids that are lagoon dried to 50% DS<br>• Facility will be considered energy recovery and should have little impact on neighbors. Should be little to no impact on soil and water compared to current practice | • Most hauling requirements (~260 tonnes/day)<br>• Low noise<br>• Low potential odor from windrow drying with digested biosolids that are lagoon dried to 50% DS<br>• Should be little to no impact on soil and water compared to current practice |
| **Use of Existing Treatment Facilities**<br>Existing facilities that can be used and integrated | • Continues to make most use of existing solar drying system<br>• Possibility of pumping biogas produced from landfill to biogas electrical generators | • Continues to make most use of existing solar drying system | • Continues to make most use of existing solar drying system | • Continues to make most use of existing solar drying system<br>• Uses an existing third party cement kiln for final use |
| **Requirements for Operation Staff**<br>Qualification of the operating staff and especially where differences with respect to the various options are to be considered | • Windrow drying turning operator would be low skill<br>• Landfill operation requires at least one skilled operator to maintain safe and environmentally sound disposal practices | • Windrow drying turning operator would be low skilled<br>• Combustion process with steam boiler and steam turbine would require a highly skilled operator.<br>• Boiler's license or boiler engineers may also be required, depending on local codes. | • Windrow drying turning operator would be low skilled<br>• Gasification operator with steam boiler and steam turbine would require a highly skilled operator<br>• Boiler's license or boiler engineers may also be required, depending on local codes<br>• Organic rankine cycle in lieu of a steam turbine could eliminate boiler licensing requirements | • Windrow drying turning operator would be low skill |
| **Recycling of Sludge**<br>Recycling refers to use in agriculture or energy generation<br>• The quantities of sludge recycled<br>• Differences in recycling and possible impacts from recycling | • Landfill is a disposal option for biosolids. However, after closure, remaining volatile organic material in biosolids will be beneficially used as a renewable fuel source for power production if landfill gas is utilized<br>• Fugitive emission during landfilling operation reduces the beneficial use aspects of the landfilled biosolids | • All biosolids beneficially used as a renewable fuel source for power production<br>• Final Ash (~ 70 tonne/d) could potentially be beneficially used for concrete, road aggregate or another purpose (requires further studying)<br>• All biosolids are used as an energy source with only ash remaining<br>• Control of biosolids beneficial use "within the fence" | • All biosolids beneficially used as a renewable fuel source for power production<br>• Ash/Slag/Char (~ 70 tonnes/d) could be beneficially used for concrete, road aggregate or another purpose (requires further studying). Could also be some left over carbon, depending on gasification technology<br>• All biosolids are used as an energy source with only ash/slag/char remaining<br>• Control of biosolids beneficial use "within the fence" | • All biosolids beneficially used as a fuel replacement at a cement kiln<br>• Ash is beneficially used for the cement making<br>• Relies on third party for beneficial use outlet and subject to factors outside of the municipality's control |
| **Major Risk**<br>• Disposal safety<br>• Technology<br>• Socio-economic<br>• Environmental aspects<br>Any local specific situation in Jordan shall be considered | • Liner installation will provide safe disposal in the landfill<br>• Monofill not widely practiced, limited design reference with some issues with previous installations.<br>• Socially acceptable practice as long as it is away from residential and environmentally sensitive areas<br>• Creates jobs for local communities but local operators should be trained in safe and proper operation practices | • Reduced biosolids to an inert ash that is disposed of in-contingency landfill or other outlet such as nearby cement kiln, nearby landfill or other beneficial use<br>• Well proven technology, but a high level of skilled operators is required because of complexity and high temperatures.<br>• Use of steam may complicate the operational requirements<br>• Creates jobs for local communities<br>• Assume risk is minimal as would likely be P3 | • Reduced biosolids to an inert ash that is disposed of in contingency landfill or other outlet such as nearby cement kiln, nearby landfill or other beneficial use<br>• Innovative technology and requires a high level of skilled operators because of complexity and high temperature<br>• Use of steam may complicate the operational requirements<br>• Creates jobs for local communities<br>• Assume risk minimal as would likely be P3 | • Disposal dependent on third party and reliability is outside of the municipality's control<br>• Long term reliability partnership with cement kiln will have to be determined. Risk should be reduced by negotiating a tight agreement with cement kiln<br>• No new, innovative or complicated process required |

**Table 8-2. Metric comparison of the four evaluated options (M represents Million JD)**

| | Monofill | Incineration | Gasification | Cement Kiln (Zero Revenue)[1,2] | Cement kiln (JD 10 /tonne revenue) [1,2] |
|---|---|---|---|---|---|
| Capital Cost, M JD | 19.0 | 64.5 | 93.3 | 11.4 | 11.4 |
| Electricity, MW | 2.5 | 4.3 | 2.5 | 0 | 0 |
| Annual Operating Cost, M JD | (1.34) | (3.6) | (0.70) | 0.68 | (0.26) |
| 20 year PW, M JD | (11.7) | 19.5 | 117.3 | 29.8 | 10.9 |
| Cost, JD/dry tonne | (12.3) | 13.8 | 82.9 | 21.0 | 7.7 |
| CO2 eq. tonnes/yr | 6,668,000 | - 16,675 | - 833 | -56,970 | -56,683 |

[1] Based on JD120/tonne coal cost with a 6,000 kCal/kg calorific value
[2] Operating Cost for Cement Kiln option without revenue is 1.25 M per year. Does not include transportation costs to cement kin.

The results presented in Table 8-2 indicate that energy consumption and electricity generation play a significant role in the annual operating cost and the effective cost of per dry tonne biosolids processed. If all the baseline energy costs (consumption and generation) were to on average increase by 50% in the future, Table 8-3 presents the results comparing monofill with incineration option. As the table shows, increasing the cost of energy as is anticipated, and accordingly increasing revenue created through energy generation, makes the incineration option a more attractive economic solution in the future.

**Table 8-3. Impact of increasing all baseline energy costs and revenues on operating cost of monofill and incineration options**

| Option | Monofill (JD) | Incineration (JD) |
|---|---|---|
| **Baseline** | | |
| Cost per dry tonne | (12.3) | 13.8 |
| 20 yr PW | (11.7 M) | 19.5 M |
| **Increasing Baseline Energy Costs and Revenues by 50%** | | |
| Cost per dry tonne | (26.7) | (25.0) |
| 20 yr PW | (28.9 M) | (35.4 M) |

To further compare the options – applying the ranking criteria described in Section 7 – the four options are discussed Subsection 8.2.

## 8.2 Options ranking

### 8.2.1 Evaluation Criteria Weights

The criteria discussed in section 7 were given weights as shown in Table 8-4. The weights assigned to the 4 evaluation criteria are consistent with weights previously assigned to the 5 evaluation criteria in Section 5.2.1 by the various stakeholders. Financial considerations were given 30%, followed by environmental consideration (25%), socio-economic consideration (23%) and technical considerations (22%). The sub-criteria per each major criterion were further assigned weights as shown in Table 8-4.

**Table 8-4. Weights for options evaluation criteria**

| Evaluation Criteria | Weight (100% total) |
|---|---|
| **Technical Considerations (22%)** | |
| Process reliability | 7 |
| Complexity of technology | 5 |
| Operational consideration | 5 |
| Infrastructure requirements | 5 |
| **Environmental Considerations (25%)** | |
| Land use/area | 4 |
| Emissions to air, soil, water | 7 |
| Noise and odor | 6 |
| Traffic requirements | 3 |
| Regulatory approval/compliance risk | 5 |
| **Financial Considerations (30%)** | |
| Capital investment | 10 |
| Operating cost | 10 |
| Tariff (operating costs only) | 10 |
| **Socio-Economic Considerations (23%)** | |
| Sustainability to local situation | 3 |
| Ability to pay tariff | 4 |
| Reliance on subsidies | 4 |
| Job creation | 5 |
| Public acceptance | 5 |
| End-user education | 2 |

### 8.2.2 Rating and ranking of options

The rating scale for the options as discussed in section 7.5.2 was applied to the criteria for the various options. The incineration option was considered to be implemented as Public Private Partnership (P3) and the rating was estimated accordingly. The ratings and ranking shown in Table 8-5 were conducted by AECOM.

**Table 8-5. Rating and ranking of the three technical options**

| Evaluation Criteria | Weight Factor | Rating of Technical Alternatives: Incineration (P3) Rating | Incineration (P3) Score | Monofill Rating | Monofill Score | Cement Kiln Rating | Cement Kiln Score |
|---|---|---|---|---|---|---|---|
| *total weight factor* | **100** | | | | | | |
| **Technical Considerations** | **22** | | **95** | | **81** | | **110** |
| Process Reliability | 7 | 5 | 35 | 3 | 21 | 5 | 35 |
| Complexity of Technology | 5 | 3 | 15 | 4 | 20 | 5 | 25 |
| Operational Considerations | 5 | 5 | 25 | 4 | 20 | 5 | 25 |
| Infrastructure Requirements | 5 | 4 | 20 | 4 | 20 | 5 | 25 |
| **Environmental Considerations** | **25** | | **104** | | **75** | | **97** |
| Land Use and Area Requirements | 4 | 5 | 20 | 3 | 12 | 5 | 20 |
| Emissions to Air, Soil, Water | 7 | 4 | 28 | 1 | 7 | 3 | 21 |
| Noise and Odor Control | 6 | 4 | 24 | 4 | 24 | 4 | 24 |
| Traffic Requirements | 3 | 4 | 12 | 4 | 12 | 4 | 12 |
| Regulatory Approval and Non-compliance Risks | 5 | 4 | 20 | 4 | 20 | 4 | 20 |
| **Financial Considerations** | **30** | | **100** | | **100** | | **100** |
| Capital Investment Cost | 10 | 2 | 20 | 4 | 40 | 5 | 50 |
| Operating Cost | 10 | 4 | 40 | 3 | 30 | 2 | 20 |
| Tariff (assumes operating costs only) | 10 | 4 | 40 | 3 | 30 | 3 | 30 |
| **Socio-economic Considerations** | **23** | | **86** | | **81** | | **84** |
| Sustainability to the Local Situation | 3 | 5 | 15 | 5 | 15 | 3 | 9 |
| Ability to Pay Tariff | 4 | 4 | 16 | 3 | 12 | 3 | 12 |
| Reliance on Subsidies/Sustainability | 4 | 3 | 12 | 4 | 16 | 5 | 20 |
| Job Creation | 5 | 3 | 15 | 3 | 15 | 3 | 15 |
| Public Acceptance | 5 | 4 | 20 | 3 | 15 | 4 | 20 |
| End-user Education and Awareness | 2 | 4 | 8 | 4 | 8 | 4 | 8 |
| **OVERALL SCORES:** | | | **385** | | **337** | | **391** |

## 8.3 Consideration for the preferred option

As the resulting ranking in Table 8-5, total score shows, the incineration and cement kiln options are essentially equal. However, the three options ranked within 15% of each other and all of them will be considered further. Notable differentiators for the three ranked options are as follows:

Incineration:
- Greatest capital cost required to initiate program.
- Based on the sensitivity analysis, the net return on the investment would increase notably with increase in energy costs and revenue.
- Greatest carbon credit and would be available to the GoJ.
- Reliable technology in a P3 scenario.
- No risk associated with reliance on outside industries.

Monofill:
- Medium capital investment.
- Lowest overall cost option assuming 50% methane gas recovery for energy generation.
- Additional drying beyond current SPC requirement of 50% not anticipated.
- Could strategically begin as an interim option.
- Not likely to be viable as a BOT opportunity.
- High operations risk requires involvement of a services operator contract due to complexity of methane gas extraction in a sludge/biosolids only landfill. Not recommended to be operated by public entity. As previously discussed, monofills are generally not practiced.

Cement Kiln
- Least capital investment required for the GoJ.
- Requires negotiation with a limited number of cement companies and possibly as few as one given the significant distance to transport biosolids for most companies, and some could use only a relatively small percentage of the generated biosolids.
- Required dryness and desire to transport varies between cement companies complicating negotiations. To limit effort of MWI in the drying process, the process of drying from 50% to 75% or as desired could be deferred to the cement companies, and performed either on their own sites, or on a dedicated area of land provided by MWI at the As Samra facility.
- Some risk associated with the solvency of the cement companies.
- Would not require landfill of ash as the ash would likely be utilized in the final cement product.
- The cement company nearest to As-Samra is modifying their facilities to accept alternate fuels such as biosolids. Modifications should be complete in late 2014.

### 8.3.1 RPA requirements

The conditions of the Restated Project Agreement would need to be reviewed for potential modification, particularly with respect to management of the biosolids in the solar drying area should modifications be required. Windrow drying if necessary could be incorporated into SPC's scope, operated by WAJ, privatized as a separate contract, or included as part of the incineration or cement kiln option operations contracts.

### 8.3.2 Phased implementation and immediate activities

Upon selection of the preferred biosolids end use option, potential phasing of activities to expedite efforts should be considered. Examples include:

- The contingency or ash landfill could be designed and the procurement process should begin ahead of the design of and procurement of an incineration facility or ahead of cement kiln option startup.
- For both the incineration and cement kiln options, the solar drying option process would need to be modified including potentially a paved area to avoid degradation of the biosolids calorific value. Further, the windrow drying area would need to be designed and constructed for both options.

Further discussions in this regard will be necessary if one of either the cement kiln or incineration options is selected.

#### 8.3.3 Existing and compliance requirements

Should incineration be part of the selected alternative, committees should be developed by the GoJ to establish emissions requirements specific to this application. This may involve amendment of existing Jordanian Standards or development of a new standard. In any event, the activity should be initiated once selection of the alternatives is finalized as the process required to amend or develop standards within the Jordanian Standards and Metrology Organization (JSMO) would likely take several months to a year. Resolution of the standards would be prerequisite to finalizing any design and procurement effort as it could impact the design and cost of constructing and operating the incineration facility. In the interim, facility planning and design could proceed, using established USEPA emissions requirements.

### 8.4 Consideration for end use diversification

In principal, consideration of multiple end use outlets would reduce the potential risk associated with relying on a single outlet should the single outlet no longer be viable. For example, a portion of the generated biosolids could be incinerated for energy recovery, the remaining portion used in cement kilns, while the monofill remains as a contingency only. However, certain factors need to be considered when using multiple outlets that include incineration:

1. Based on communications with vendors for incinerating dry biosolids >75%, an approximate minimum of 100 dry tonnes per day should be processed based on the commercial size of these units.
2. The capital cost of the smaller unit is not significantly lower than the cost of a full sized unit able to process the design capacity of approximately194 dry tonnes per day.
3. Less energy recovery and electricity would be generated from processing less biosolids, resulting in significantly less revenue from the incineration option while the capital and operation costs are not significantly reduced.
4. The financial aspects of diverting biosolids from incineration and energy recovery to cement kiln or other end use options need to be evaluated in order to arrive at the proper value of biosolids when processing smaller amount of biosolids in incineration.
5. Finally, and perhaps most notably, the risk of incineration no longer being viable during the 20 design/operations period is very unlikely, so the risk of incineration as a single outlet is not significant.

For multiple outlets including monofill for energy production, an operations type contract would be required and should be incentive based. Once an agreement is reached, and for an approach that would attract operations companies, input quantities of biosolids should remain as planned and originally agreed to.

## 8.5 Preliminary Financial Analysis

For a clearer understanding of the potential financial implications to MWI for the remaining three options, a preliminary financial analysis was performed. Options considered (including two each for monofill and cement kiln alternatives) were as follows:

1. **Incineration** at 75% dryness
2. Monofill without energy production, for the purpose of presenting a minimal disposal option
3. Monofill with energy production
4. Cement kiln option with biosolids at 75% dryness with no fee to the cement companies
5. Cement kiln option with biosolids at 75% dryness and a 10JD per tonne fee

Table 8.6 below presents the results of the analysis.

**Table 8-6. Preliminary financial analysis of the technical options**

| | **Incineration with Energy Production** | **Monofill without Energy Production** | **Monofill with Energy Production** | **Cement Kiln with zero fee** | **Cement Kiln with JD 10 fee** |
|---|---|---|---|---|---|
| Total Capital (millions JD) | 64.5 | 13.1 | 19.8 | 11.4 | 11.4 |
| Total O&M (millions JD) | 46.7 | 10.2 | 22.4 | 13.7 | 13.7 |
| Total Income (millions JD) | 118.6 | 0 | 59.9 | 0 | 18.4 |
| Salvage Value (millions JD) | 10.6 | n/a | n/a | n/a | n/a |
| Internal Rate of Return | 2.0% | Negative | 6.2% | Negative | Negative |
| Net Present Value (millions JD) | (19.1) | (12.9) | 0.7 | (18.5) | (8,.3) |

**Assumptions**

1. Cost of Capital for NPV= 5.6% Jordanian Interest Rate (DOT 2012 & 2013)
2. 20 year sludge/biosolids treatment for all alternatives
3. Monofill options include cost/benefit for 4th cell for years 21-25.

Associated cash flow charts are included in Appendix C of this report. From a financial standpoint, the following conclusions can be drawn:

- Incineration, if grant funded by a donor, would provide continuous revenue with very little risk. However, through discussions with MWI, we understand that grant funding is not available for this activity. Because of the low internal rate of return (IRR), the option would not be attractive as a BOT opportunity.
- Cement kiln option would be costly to the MWI given the cement companies unwillingness to pay an equitable amount for the dried biosolids.
- Monofill option with energy production is the best cost alternative. However, as is evident in the associated cash flow chart in Appendix C, cost recovery does not begin until year six of the program, and peaks in the later stages of the program. Note that,

based on the resulting IRR, the Monofill option would not be attractive to potential investors as a BOT opportunity.

## 8.6 Recommendations

As is apparent, all three final options are technically viable and could be carried forward. While incineration and cement kiln options scored the highest in the evaluation, the monofill scored a reasonably close third with no notable obstacles in its implementation provided it is operated by the private sector. Financially, the monofill with energy production option is currently significantly more viable. Accordingly, it is recommended that MWI move forward with the Monofill with energy production alternative. In parallel, with the early stages of the feasibility study, discussions may continue with the cement companies to determine whether they may be willing to reconsider their current valuation of biosolids produced and dried at As Samra so that it becomes a more financially viable option for MWI.

# REFERENCES

Brown Bear Corporation website http://www.brownbearcorp.com/testimonials/Chicago%20Speed%20Dries%20Its%20Sludge.pdf, November 13, 2013.

BRP (2013), Community Action Plan, Badia Restoration Program

EPA (1999). “Biosolids Management Handbook.” US Environmental Protection Agency, Denver, CO.

EPA (2003). “Biosolids Technology Fact Sheet.” US Environmental Protection Agency, Washington, DC.

MoA (2013), Rangelands Reserves, Ministry of Agriculture (Information including data and maps provided by MoA via email)

O’Kelly, Brendan C. (2005) “Sewage Sludge to Landfill: Some Pertinent Engineering Properties.” *Air & Waste Management Association,* Vol. 55, 765–771.

O’Kelly (2006). “Geotechnical Properties of Municipal Sewage Sludge.” *Geotechnical and Geological Engineering,* Vol. 24, 833–850.

Sogreah, Study on Sludge Management at Samra Wastewater Treatment Plant, July, 2011.

Samra Plant Company (2012), Environmental and Social Impact Assessment Study for the Expansion of As-Samra WasteWater Treatment Plant, Final ESIA Report 2012.

Samra Plant Company (SPC) and the Ministry of Water and Irrigation (MWI). Sludge Management Plan 2012/2013 (SMP), for the As Samra Wastewater Treatment Plant Expansion BOT Project.

Sogreah (2011) Study On Sludge Management At Samra Wastewater Treatment Plant, Final Report, Samra Plant Operation & Maintenance Co. Ltd.

WAJ (2013), Wastewater in Jordan Report, Water Authority of Jordan

Zotarelli, L, M. Dukes, C. Romero, K. Migliaccio, K Morgan; “Step By Step Calculation of the Penman Monteith Evapotranspiration (FAO-56 Method)” University of Florida IFAS Extension, 2009.

# APPENDICES

The following appendices are attached:

Appendix 1 Windrow Drying Sizing

Appendix 2 Mass and Energy Balances

Appendix 3 Preliminary Financial Analyses Charts

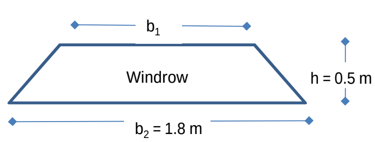
# APPENDIX 1

# WINDROW DRYING SIZING

Windrow Drying, Preliminary Sizing

| | Option 1 | Option 2 | Option 3 | | Comments |
|---|---|---|---|---|---|
| *Mass Balance* | | | | | |
| Biosolids Mass | 195 | 195 | 195 | tonne/d | |
| Solid Content Start | 18% | 30% | 50% | DS | |
| Specific Gravity | 1 | 1 | 1 | | |
| Volume throughput | 1,083 | 650 | 390 | $m^3/d$ | |
| *Windrow Cross-section* | | | | | |
| Height, m | 0.5 | 0.5 | 0.5 | m | Assumed from Chicago feedback (18" tall) |
| Base, m | 1.8 | 1.8 | 1.8 | m | From Brown Bear Feedback of 6 ft |
| Cross Sectional Area | 0.63 | 0.63 | 0.63 | $m^2$ | Assume trapezoid w/1:1 sides |
| Drying Surface Area | 2.21 | 2.21 | 2.21 | $m^2/m$ | Area exposed to air for drying per linear meter |
| ***Windrow Requirements*** | | | | | |
| Daily Length | 1727.5 | 1036.5 | 621.9 | m | |
| Drying Time Requirement | 120 | 90 | 60 | days | Estimated |
| Total Length | 207,301 | 93,286 | 37,314 | m | |
| | *129* | *58* | *23* | *miles* | |
| Desired Length per windrow | 90 | 90 | 90 | m | Assumed |
| Number of Windrows (per day) | 19.2 | 11.5 | 6.9 | | |
| Total Number of Windrows | 2,303.3 | 1,036.5 | 414.6 | | |
| Space Between Windrows | 0.30 | 0.3 | 0.3 | m | Feedback from Chicago was a couple of inches to a foot |
| Total Width Requiremed | 4,924 | 2,221 | 894 | m | Assume 5 m clearance on each side |
| Rough Area | 492,418 | 222,121 | 89,430 | $m^2$ | |
| Rough Area | 49.24 | 22.21 | 8.94 | Ha | |
| *Windrow Design* | | | | | |
| Selected Number of Windrow Bays | 55 | 25 | 10 | | Targeting several 100m x 100 m areas |
| Min. Drying Area Length (per bay) | 100 | 100 | 100 | m | |
| Min. Drying Area Width (per bay | 100 | 100 | 100 | m | |
| Area, $m^2$ | 10,000 | 10,000 | 10,000 | $m^2$ | |
| Area, Ha | 1.00 | 1.00 | 1.00 | Ha | |
| Total Area | 550,000 | 250,000 | 100,000 | $m^2$ | |
| Total Area | 55 | 25 | 10 | Ha | |
| Total Area | 135.9 | 61.8 | 24.7 | Ac | |
| Total Area | 5,920,007 | 2,690,912 | 1,076,365 | $ft^2$ | |
| *Area (Parkson Comparison)* | *1,995,840* | *1,108,800* | *753,984* | *$ft^3$* | 22,176 $ft^2$ per Chamber from Parkson |
| | 18.5 | 10.3 | 7.0 | Ha | |
| *Area Increase from Parkson* | *297%* | *243%* | *143%* | | |
| Tractor / Brown Bear Requirements | | | | | |
| Brown Bear Speed | 3.5 | 3.5 | 3.5 | miles/hr | Estimate from Brown Bear |
| | 5,632 | 5,632 | 5,632 | m/hr | |
| Mixing Amount | 3,532 | 3,532 | 3,532 | $m^3/hr$ | |
| | 4,620 | 4,620 | 4,620 | $yd^3/hr$ | |
| Working Day | 7 | 7 | 7 | hrs/day | Not including 1 hr for mobilizing/demobilizing |
| Turns per Day | 1 | 1 | 1 | | |
| Number of Brown Bears Required | 7 | 4 | 2 | | |
| Total Brown Bear Operation | 13,434 | 6,045 | 2,418 | hrs/yr | Cummulative for all Brown Bears |
| Design Checks | | | | | |
| Annual Evaporation | 300,517 | 142,350 | 47,450 | tonne/yr | |
| Specific Evaporation | 5,464 | 5,694 | 4,745 | tonne/Ha | |
| | 2,438 | 2,541 | 2,117 | ton/Ac | Chicago Paper Lists 2,600 tons $H_2O$ evaporated per acre |
| Total Drying Surface Area | 457,634 | 205,935 | 82,374 | $m^2$ | |
| Evapotranspiration Estimate (Annual Average) | 6.0 | 6.0 | 6.0 | mm/d | Based on Penman - Monteith equation estimate |
| | 2,760 | 1,242 | 497 | $m^3/d$ = tonne/d | |
| | 1,007,360 | 453,312 | 181,325 | tonne/yr evaporation | |
| Safety | 335% | 318% | 382% | | |
| Evapotranspiration Estimate (Winter) | 2.7 | 2.7 | 2.7 | mm/d | Based on Penman - Monteith equation estimate |
| | 1,255 | 565 | 226 | $m^3/d$ = tonne/d | |
| | 458,087 | 206,139 | 82,456 | tonne/yr evaporation | |
| Safety | 152% | 145% | 174% | | |

Windrow Dimentions




$A = 1/2 * h * (b_1 + b_2)$

Assuming 1:1 sides

$b_1 = b_2 - 2 * h$

$A = 1/2 * h * ((b_2 - 2 * h) + b_2)$

Evapotranspiration Data

| | Annual Average | Summer (Jun - Aug) | Winter (Dec - Feb) | | Comments/Source |
|---|---|---|---|---|---|
| $ET_o$ (Penman) | 7.5 | 10.9 | 4.2 | mm/d | |
| $ET_o$ (Penman - Monteith) | 6.0 | 10.0 | 2.7 | mm/d | Used for Calculation Check |
| $ET_o$ (Blaney-Criddle) | 6.3 | 10.3 | 3.2 | mm/d | (ETo = p ·(0.46·Tmean + 8) |
| $ET_o$ (Priestley-Taylor) | 6.6 | 10.5 | 3.2 | mm/d | |
| Pan Evaporation | 6.2 | 10.8 | 2.1 | mm/d | |
| Precipitation | 0.7 | 0 | 1.9 | mm/d | |
| | | | | | |
| From Amman, Jordan Climate Data | | | | | |
| Temperature (T) | 18.9 | 26.7 | 10.0 | C | |
| Slope of Saturation Vapor Curve (m or Δ) | 0.136 | 0.206 | 0.082 | kPa/C | Used for Penman Equation |
| Slope of Saturation Vapor Curve (Δ) | 1.018 | 1.557 | 0.608 | mmHg/K | Equation from Zotarelli et. al. (http://edis.ifas.ufl.edu/ae459) |
| Net Solar Radiation Flux (Rn) | 18.55 | 26.36 | 10.82 | $MJ/m^2$-d | |
| Psychrometric Constant (γ) | 0.0615 | 0.0613 | 0.0617 | kPa/K | Equation from Zotarelli et. al. (http://edis.ifas.ufl.edu/ae459) |
| Heat of Vaporization (λv) | 2.45 | 2.45 | 2.45 | MJ/kg | At 20 C |
| Pressure (P) | 92.52 | 92.17 | 92.77 | kPa | |
| Wind Speed ($U_2$) | 3.1 | 3.0 | 3.3 | m/s | |
| Vapor Pressure Deficit (δe) | 0.94 | 1.92 | 0.34 | kPa | Equation from Zotarelli et. al. (http://edis.ifas.ufl.edu/ae459) |
| Saturation Vapor Pressure (es) | 2.18 | 3.50 | 1.23 | kPa | Equation from Zotarelli et. al. (http://edis.ifas.ufl.edu/ae459) |
| Actual Vapor Pressure (ea) | 1.24 | 1.58 | 0.88 | kPa | Equation from Zotarelli et. al. (http://edis.ifas.ufl.edu/ae459) |
| Relative Humidity | 57% | 45% | 72% | | |
| Soil Heat Flux Density (G) | 0 | 0 | 0 | $MJ/m^2$-d | Assumed to be zero and not significant |
| Priestley-Taylor coefficient (a) | 1.26 | 1.26 | 1.26 | | http://agsys.cra-cin.it/tools/evapotranspiration/help/Priestley-Taylor.html |
| Sunlight Percentage (p) | 37.7% | 50.8% | 25.1% | | Allen et. al (http://en.wikipedia.org/wiki/Blaney%E2%80%93Criddle_equation) |

Penman Equation (from http://www.hydrol-earth-syst-sci.net/11/210/2007/hess-11-210-2007.pdf)

$$E_{mass} = \frac{mR_n + \gamma * 6.43\,(1 + 0.536 * U_2)\,\delta e}{\lambda_v\,(m + \gamma)}$$

Penman-Monteith (http://edis.ifas.ufl.edu/ae459)

$$ET_o = \frac{0.408\Delta\,(R_n - G) \;+\; \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)}$$

Priestley-Taylor (http://agsys.cra-cin.it/tools/evapotranspiration/help/Priestley-Taylor.html)

$$ET_0 = \frac{l}{\lambda} \cdot \frac{s \cdot (R_n - G)}{s + \gamma} \cdot \alpha$$

Climate Data

Metrological Parameters at the Study Area (from 10/31/13 email from Eyad Batarseh)

| Amman Airport Metrological Station: E 35 59', N 31 59', Elevation= 780 m | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean Air Temp "C°" During 1923-2000 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 9.2 | 10.2 | 13.9 | 17.5 | 22.3 | 25.5 | 27.4 | 27.3 | 25.2 | 22 | 15.4 | 10.5 | 18.9 |
| Mean Total Rainfall Amount "mm" During 1922-2000 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 58.2 | 61.2 | 31.2 | 16.2 | 4.5 | 0 | 0 | 0 | 0 | 2.8 | 24.5 | 48.4 | 246.9 |
| Mean No. of Rainy Days (Rainfall Amount >=0.1 mm) During 1923-2000 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 10.9 | 11 | 6.3 | 4.6 | 1.8 | 0 | 0 | 0 | 0 | 2.2 | 4.9 | 7.7 | 50.6 |
| Total Evaporation, Class A Pan "mm" During 1962-2000 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 57.4 | 71 | 121 | 173.1 | 274.4 | 318.8 | 356.2 | 316.2 | 241.5 | 175.4 | 97.2 | 61.7 | 777.6 |
| Daily Mean Relative Humidity "%" During 1966-2000 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 73.9 | 72.4 | 62.8 | 53.8 | 43.6 | 42.6 | 43.3 | 49.3 | 53.6 | 56.1 | 61.4 | 69.8 | 56.9 |
| Mean Wind Speed "Knot" During 1977-2000 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 4.7 | 5.6 | 5.2 | 5.9 | 5.7 | 6 | 6.8 | 5.5 | 4.4 | 3.1 | 3.5 | 4 | 5.1 |
| Prevailing Wind Direction "Degree" During 1977-2007 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 227 | 231.4 | 256.3 | 262.4 | 267.4 | 283.8 | 277.8 | 284.8 | 287.1 | 265 | 209.3 | 216.1 | 268 |
| Mean Pressure at Station Level "Hpa" During 1977-2000 | | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
| 928 | 926.5 | 925.8 | 924.3 | 923.8 | 922.6 | 920.8 | 921.6 | 924.6 | 926.9 | 928.4 | 928.7 | 925.2 |

247

49.4

2263.9

Data Converted to Other Units

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) | 2.4 | 2.9 | 2.7 | 3.0 | 2.9 | 3.1 | 3.5 | 2.8 | 2.3 | 1.6 | 1.8 | 2.1 | 2.6 |
| Pressure (kPa) | 92.8 | 92.65 | 92.58 | 92.43 | 92.38 | 92.26 | 92.08 | 92.16 | 92.46 | 92.69 | 92.84 | 92.87 | 92.52 |

Solar Radiation Data - https://eosweb.larc.nasa.gov/

Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/$m^2$/day)

| Lat 31.9<br>Lon 35.9 | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22-year Average | 2.85 | 3.54 | 4.76 | 6.08 | 6.98 | 7.77 | 7.53 | 6.67 | 5.7 | 4.17 | 3.17 | 2.63 | 5.16 |

Monthly Averaged Wind Speed At 10 m Above The Surface Of The Earth For Terrain Similar To Airports (m/s)

| Lat 31.9<br>Lon 35.9 | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10-year Average | 4.45 | 4.59 | 4.72 | 4.36 | 4.09 | 4.13 | 4.13 | 3.92 | 3.64 | 3.65 | 3.65 | 4.13 | 4.12 |

https://eosweb.larc.nasa.gov/cgi- bin/sse/grid.cgi?&num=216122&lat=31.9&hgt=100&submit=Submit&veg=17&sitelev=&email=skip@larc.nasa.gov&p=grid_id&p=swv_dwn&p=wspd10arp

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Solar Radiation Data (MJ/$m^2$-d) | 10.26 | 12.74 | 17.13 | 21.89 | 25.13 | 27.97 | 27.11 | 24.01 | 20.52 | 15.01 | 11.41 | 9.47 | 18.55 |
| Windspeed @ 2m | 3.33 | 3.43 | 3.53 | 3.26 | 3.06 | 3.09 | 3.09 | 2.93 | 2.72 | 2.73 | 2.73 | 3.09 | 3.08 |

Equation from Zotarelli et. al. (http://edis.ifas.ufl.edu/ae459)

http://en.wikipedia.org/wiki/Amman

Climate data for Amman

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Record high °C (°F) | 23.6<br>-74.5 | 28.9<br>-84 | 30.4<br>-86.7 | 36.2<br>-97.2 | 37.9<br>-100.2 | 40.3<br>-104.5 | 44<br>-111.2 | 43.8<br>-110.8 | 40<br>-104 | 38.2<br>-100.8 | 34.6<br>-94.3 | 26.3<br>-79.3 | 44<br>-111.2 |
| Average high °C (°F) | 12.3<br>-54.1 | 13.7<br>-56.7 | 17.2<br>-63 | 22.6<br>-72.7 | 27.8<br>-82 | 30.8<br>-87.4 | 32<br>-89.6 | 32.4<br>-90.3 | 30.7<br>-87.3 | 27.1<br>-80.8 | 20.4<br>-68.7 | 14.4<br>-57.9 | 23.5<br>-74.2 |
| Average low °C (°F) | 3.6<br>-38.5 | 4.2<br>-39.6 | 6.1<br>-43 | 9.5<br>-49.1 | 13.5<br>-56.3 | 16.6<br>-61.9 | 18.5<br>-65.3 | 18.6<br>-65.5 | 16.6<br>-61.9 | 13.8<br>-56.8 | 9.3<br>-48.7 | 5.2<br>-41.4 | 11.3<br>-52.3 |
| Record low °C (°F) | −10.0<br>-14 | −9.5<br>-14.9 | −8.2<br>-17.2 | −2.6<br>-27.3 | −0.9<br>-30.4 | 3.2<br>-37.8 | 7<br>-44.6 | 5.4<br>-41.7 | 0<br>-32 | −1.8<br>-28.8 | −4.5<br>-23.9 | −7.8<br>-18 | −10<br>-14 |
| Precipitation mm (inches) | 63.4<br>-2.496 | 61.7<br>-2.429 | 43.1<br>-1.697 | 13.7<br>-0.539 | 3.3<br>-0.13 | 0<br>0 | 0<br>0 | 0<br>0 | 0.3<br>-0.012 | 6.6<br>-0.26 | 28<br>-1.102 | 49.2<br>-1.937 | 269.3<br>-10.602 |
| Avg. precipitation days | 11 | 10.9 | 8 | 4 | 1.6 | 0.1 | 0 | 0 | 0.1 | 2.3 | 5.3 | 8.4 | 51.7 |
| Mean monthly sunshine hours | 179.8 | 182 | 226.3 | 266.6 | 328.6 | 369 | 387.5 | 365.8 | 312 | 275.9 | 225 | 179.8 | 3,298.30 |

17.4

*Source #1: World Meteorological Organization* [12]

*Source #2: Hong Kong Observatory(sun, 1961–1990)* [13]

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Yearly |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Days in Month | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 | |
| Sunlight Hour Percentage | 24.2% | 27.1% | 30.4% | 37.0% | 44.2% | 51.3% | 52.1% | 49.2% | 43.3% | 37.1% | 31.3% | 24.2% | 37.6% |

# APPENDIX 2

# MASS AND ENERGY BALANCES

**Jordan Alternatives - Year 2034 (Design for Equipment Sizing)**

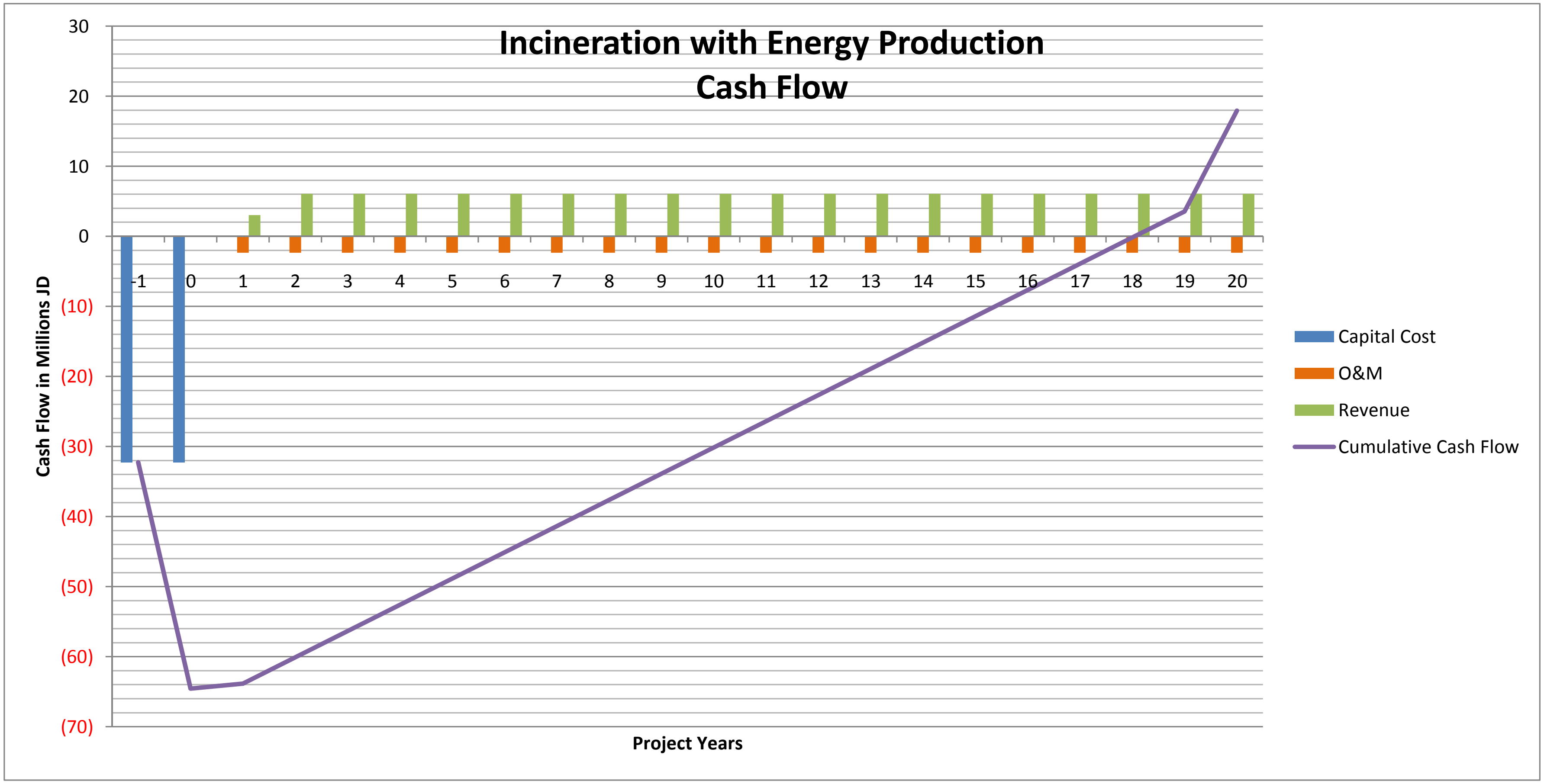
| Input Parameters | Unit | BFP(18%) -> SDB(50%) -> Inc | BFP (18%) -> Win(75%) -> Inc/Gas | BFP (18%) -> SDB (30%) -> Win(75%) -> Inc/Gas | BFP (18%) -> SDB (50%) -> Win(75%) -> Inc/Gas | BFP (18%) -> SDB (50%) -> Win(90%) -> Inc/Gas | Assumptions/Notes |
|---|---|---|---|---|---|---|---|
| Mass (Dry) | dry tonne/d | 195.0 | 195.0 | 195.0 | 195.0 | 195.0 | |
| Mass (Dry) | kg/d | 195,000 | 195,000 | 195,000 | 195,000 | 195,000 | |
| Mass (Volatiles Dry) | kg/d | 126,165 | 126,165 | 126,165 | 126,165 | 126,165 | |
| Volatile Solids | %VS/TS | 64.7% | 64.7% | 64.7% | 64.7% | 64.7% | |
| Solid Content | %TS | 18.00% | 18.00% | 18.00% | 18.00% | 18.00% | |
| S.G | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| Volume | $m^3/d$ | 1,083 | 1,083 | 1,083 | 1,083 | 1,083 | |
| Inlet Temperature | C | 20 | 20 | 20 | 20 | 20 | |
| Reference Temperature | C | 0 | 0 | 0 | 0 | 0 | |
| **Calculations** | | | | | | | |
| Volatile Solids Reduction - Air Drying | % VSR | 0% | 0% | 0% | 0% | 0% | Assumed to Occur During Drying Process |
| Mass (Dry) | kg/d | 195,000 | 195,000 | 195,000 | 195,000 | 195,000 | |
| Mass (Volatiles Dry) | kg/d | 126,165 | 126,165 | 126,165 | 126,165 | 126,165 | |
| Volatile Solids | %VS/TS | 64.7% | 64.7% | 64.7% | 64.7% | 64.7% | |
| HHV Estimate (dry) | kcal/kg | 3,000 | 3,000 | 3,000 | 3,000 | 3,000 | Based on ATEX samples from RSS and Hazen Research assuming 15% Loss during drying / storage |
| HHV Estimate (dry) | kJ/kg | 12,600 | 12,600 | 12,600 | 12,600 | 12,600 | |
| ***Solar Drying Beds*** | | | | | | | |
| Desired Solid Content | %TS | 50% | 18% | 30% | 50% | 50% | |
| S.G | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| Volume | $m^3/d$ | 390 | 1,083 | 650 | 390 | 390 | |
| Water Evaporated | kg/d | 693,333 | 0 | 433,333 | 693,333 | 693,333 | Not accounting for VSR |
| ***Windrow Dryer*** | | | | | May require a thermal dryer | | |
| Desired Solid Content | %TS | 50% | 75% | 75% | 75% | 90% | |
| S.G | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| Volume | $m^3/d$ | 390 | 260 | 260 | 260 | 217 | |
| Water Evaporated | kg/d | 0 | 823,333 | 390,000 | 130,000 | 173,333 | Not accounting for VSR |
| ***Incineration*** | | | | | | | |
| Inlet Solids Fuel Value | MJ/d | 2,457,000 | 2,457,000 | 2,457,000 | 2,457,000 | 2,457,000 | |
| Inlet Solids Sensible Heat | MJ/d | 5,850 | 5,850 | 5,850 | 5,850 | 5,850 | 1.5 kJ/kg-C Dry Solid Heat Capacity |
| Inlet Water Sensible Heat | MJ/d | 16,302 | 5,434 | 5,434 | 5,434 | 1,811 | 4.18 kJ/kg-C Water Heat Capacity |
| Total Energy to Incinerator | MJ/d | 2,479,152 | 2,468,284 | 2,468,284 | 2,468,284 | 2,464,661 | |
| Excess Air | % | 40% | 40% | 40% | 40% | 40% | Based on MOP-8 criteria |
| Theoretical Oxygen | kg O2/kg fuel (dry) | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | |
| Stoichiometric Air Requirement | kg air/kg fuel (dry) | 4.86 | 4.86 | 4.86 | 4.86 | 4.86 | |
| Combustion Air Requirement | kg/d (dry) | 1,326,223 | 1,326,223 | 1,326,223 | 1,326,223 | 1,326,223 | |
| Humidity | kg H2O/kg D.A. | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 | |
| Ambient Air Temperature | C | 25 | 25 | 25 | 25 | 25 | |
| Preheat Temperature | C | 25 | 25 | 25 | 25 | 25 | No Air Preheating Assumed |
| Energy to Air Preheater | MJ/d | 0 | 0 | 0 | 0 | 0 | 1.0 kJ/kg-C Dry Air Heat Capacity |
| Inlet Combustion Air Sensible Heat | MJ/d | 73,750 | 73,750 | 73,750 | 73,750 | 73,750 | 2.03 kJ/kg-C Water Vapor Heat Capacity |
| Preheated C.A. Sensible Heat | MJ/d | 73,750 | 73,750 | 73,750 | 73,750 | 73,750 | 2500 kJ/kg Latent Heat of Water |
| Water From Combustion | kg H2O/kg dry sludge | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | |
| Water From Combustion | kg H2O/d | 80,072 | 80,072 | 80,072 | 80,072 | 80,072 | |
| Flue Gas Production | kg/d (dry) | 1,372,315 | 1,372,315 | 1,372,315 | 1,372,315 | 1,372,315 | |
| Flue Gas Water Vapor | kg/d | 290,987 | 160,987 | 160,987 | 160,987 | 117,654 | |
| Ash | kg/d | 68,835 | 68,835 | 68,835 | 68,835 | 68,835 | |
| Humidity | kg H2O/kg D.A. | 0.212 | 0.117 | 0.117 | 0.117 | 0.086 | |
| Oxygen Content | % O2 (mass basis) | 6.4% | 6.4% | 6.4% | 6.4% | 6.4% | |
| Total Energy Produced | MJ/d | 2,552,902 | 2,542,034 | 2,542,034 | 2,542,034 | 2,538,411 | 1.05 kJ/kg-C Dry Flue Gas Heat Capacity |
| Total Energy Produced | MMBtu/hr | 101 | 100 | 100 | 100 | 100 | |
| Adiabatic Temperature | C | 871 | 1,168 | 1,168 | 1,168 | 1,288 | 0.92 kJ/kg-C Ash Heat Capacity |
| Heat Loss Factor | % | 2% | 2% | 2% | 2% | 2% | |
| Heat Loss | MJ/d | 51,058 | 50,841 | 50,841 | 50,841 | 50,768 | |
| Flue Gas Temperature | C | 847 | 1,141 | 1,141 | 1,141 | 1,258 | Target about 850 C |
| Heat Exchanger Heat Loss | % | 2% | 2% | 2% | 2% | 2% | |
| Energy to Air Preheater | MJ/d | 0 | 0 | 0 | 0 | 0 | |
| Cooled Flue Gas Temperature 1 | C | 847 | 1,141 | 1,141 | 1,141 | 1,258 | |
| Secondary Heat Recovery | MJ/d | 1,376,333 | 1,740,823 | 1,740,823 | 1,740,823 | 1,862,320 | |
| Total Energy Produced | MMBtu/hr | 54 | 69 | 69 | 69 | 74 | |
| Cooled Flue Gas Temperature 2 | C | 190 | 190 | 190 | 190 | 190 | Set equal to cooled flue gas temperature 1 if no secondary heat recovery is included |
| Steam Turbine Electrical Efficiency | % | 29.1% | 27.2% | 27.2% | 27.2% | 27.2% | Based on information from Siemens |
| Steam Turbine Electrical Production (gross) | kW | 4,638 | 5,490 | 5,490 | 5,490 | 5,873 | Adjusted to match Siemens output |
| Steam Turbine Parasitic Electrical Load | kW | 557 | 659 | 659 | 659 | 705 | |
| Steam Turbine Electrical Production (net) | kW | 4,081 | 4,831 | 4,831 | 4,831 | 5,168 | |
| Steam Turbine Electrical Production (net) | kWh/d | 97,955 | 115,949 | 115,949 | 115,949 | 124,041 | |
| Energy to Flue Gas Treatment | MJ/d | 1,125,511 | 750,370 | 750,370 | 750,370 | 625,323 | |
| Flue Gas Density | kg/Nm3 | 1.28 | 1.30 | 1.30 | 1.30 | 1.30 | @ STP (0 C & 1 atm) |
| Flue Gas Flow | m3/h | 54,144 | 49,144 | 49,144 | 49,144 | 47,755 | @ STP (0 C & 1 atm) |
| Flue Gas Flow | SCFM | 31,868 | 28,925 | 28,925 | 28,925 | 28,108 | |
| Flue Gas Flow (Incinerator Outlet) | m3/hr | 222,031 | 254,379 | 254,379 | 254,379 | 267,764 | |
| | ACFM | 130,682 | 149,721 | 149,721 | 149,721 | 157,599 | |
| | ACFM | 130,682 | 149,721 | 149,721 | 149,721 | 157,599 | |
| Flow Gas Flow (Out of Steam Boiler) | m3/hr | 91,806 | 83,329 | 83,329 | 83,329 | 80,974 | |
| | ACFM | 54,035 | 49,045 | 49,045 | 49,045 | 47,659 | |
| | ACFM | 54,035 | 49,045 | 49,045 | 49,045 | 47,659 | |
| **Steam Production** | | | | | | | |
| Steam Pressure | bara | 40 | 40 | 40 | 40 | 40 | |
| Superheated Steam Tempereråture | C | 400 | 400 | 400 | 400 | 400 | |
| Specific Enthalpy | kJ/kg | 3,214 | 3,214 | 3,214 | 3,214 | 3,214 | From Steam Tables |
| Feedwater Temperature | C | 130 | 130 | 130 | 130 | 130 | |
| Feedwater Enthalpy | kJ/kg | 546 | 546 | 546 | 546 | 546 | |
| Steam Produced | kg/d | 516,004 | 652,656 | 652,656 | 652,656 | 698,207 | |
| Steam Produced | kg/h | 21,500 | 27,194 | 27,194 | 27,194 | 29,092 | |
| | tonnes/h | 21.50 | 27.19 | 27.19 | 27.19 | 29.09 | |
| Steam Produced | lb/hr | 47,408 | 59,963 | 59,963 | 59,963 | 64,148 | |
| **Operating Cost Factors** | | | | | | | |
| Electrical Consumption | kW | 450 | 450 | 450 | 450 | 450 | Based on 450 kW per Andritz estimate at 195 tonne/d |
| Carbon Consumption | kg/h | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | Based on 4 kg/hr per Andritz estimate at 195 tonne/d |
| Sodium Bicarbonate Consumption | kg/hr | 580 | 580 | 580 | 580 | 580 | Dry Fuel contains 1.2% sulfur, all to SO2. Stoic rate for bicarbonate addition for SO2 removal is 2.63 lb NaCO3/lb SO2. Added 13% S.F. to match Andritz estimate of 580 kg/hr |
| Start-up Fuel Requirement | MWh per cold start-up | 84 | 84 | 84 | 84 | 84 | From Andritz |
| Start-up Fuel Oil Requirement | L/start-up | 8,700 | 8,700 | 8,700 | 8,700 | 8,700 | Based on 131.5 kJ/gal heating value |
| Annual Start Up Requirement | L fuel oil | 26,100 | 26,100 | 26,100 | 26,100 | 26,100 | Andritz recommendation of 2 cold starts and 4 warm starts (25% of cold start fuel consumption) |
| Ash Production | tonne/d (dry) | 69 | 69 | 69 | 69 | 69 | |
| ***Max West Gasification*** | | | | | | | |
| Energy Generation Efficiency | % | -- | 53% | 53% | 53% | 71% | Set to match estimations provided by Max West |
| Total Energy Produced | MJ/d | -- | 1,292,678 | 1,292,678 | 1,292,678 | 1,738,522 | |
| Total Energy Produced | MBtu/hr | -- | 51,050 | 51,050 | 51,050 | 68,657 | |
| Heat Recovery Efficency | % | -- | 72% | 72% | 72% | 70% | |
| Energy Available For Electricity | MJ/d | -- | 927,284 | 927,284 | 927,284 | 1,216,966 | |
| Energy Available For Electricity | MBtu/hr | -- | 36,620 | 36,620 | 36,620 | 48,060 | |
| Energy Available For Drying / Electricity | kW | -- | 10,732 | 10,732 | 10,732 | 14,085 | |
| **Electrical Production Potential - 20% eff** | **kW** | -- | **2,146** | **2,146** | **2,146** | **2,817** | |
| **Electrical Production Potential - 10% eff** | **kW** | -- | **1,073** | **1,073** | **1,073** | **1,409** | |
| Total Energy to Flue Gas Treatment | MJ/d | -- | 365,394 | 365,394 | 365,394 | 521,557 | |
| Total Energy to Flue Gas Treatment | MBtu/hr | -- | 14,430 | 14,430 | 14,430 | 20,597 | |
| Natural Gas Input to Process Heater | kg/d | -- | 24 | 24 | 24 | 24 | Based on input from previous Max West mass and energy balances |
| Natural Gas Input to Process Heater | $m^3/d$ | -- | 33 | 33 | 33 | 33 | |
| Natural Gas Input to Process Heater | $ft^3/hr$ | -- | 49 | 49 | 49 | 49 | |
| Natural Gas Fuel Value | MJ/d | -- | 1,346 | 1,346 | 1,346 | 1,346 | |
| Natural Gas Fuel Value | kW | | 16 | 16 | 16 | 16 | |
| Natural Gas Fuel Value | MBtu/hr | -- | 53.2 | 53.2 | 53.2 | 53.2 | |
| Electrical Consumption Factor | kW/mton | -- | ~~163~~ | ~~163~~ | ~~163~~ | ~~163~~ | |
| Electrical Consumption | kWh/d | -- | ~~31785~~ | ~~31785~~ | ~~31785~~ | ~~31785~~ | |
| Electrical Consumption | kW | -- | ~~1324~~ | ~~1324~~ | ~~1324~~ | ~~1324~~ | |

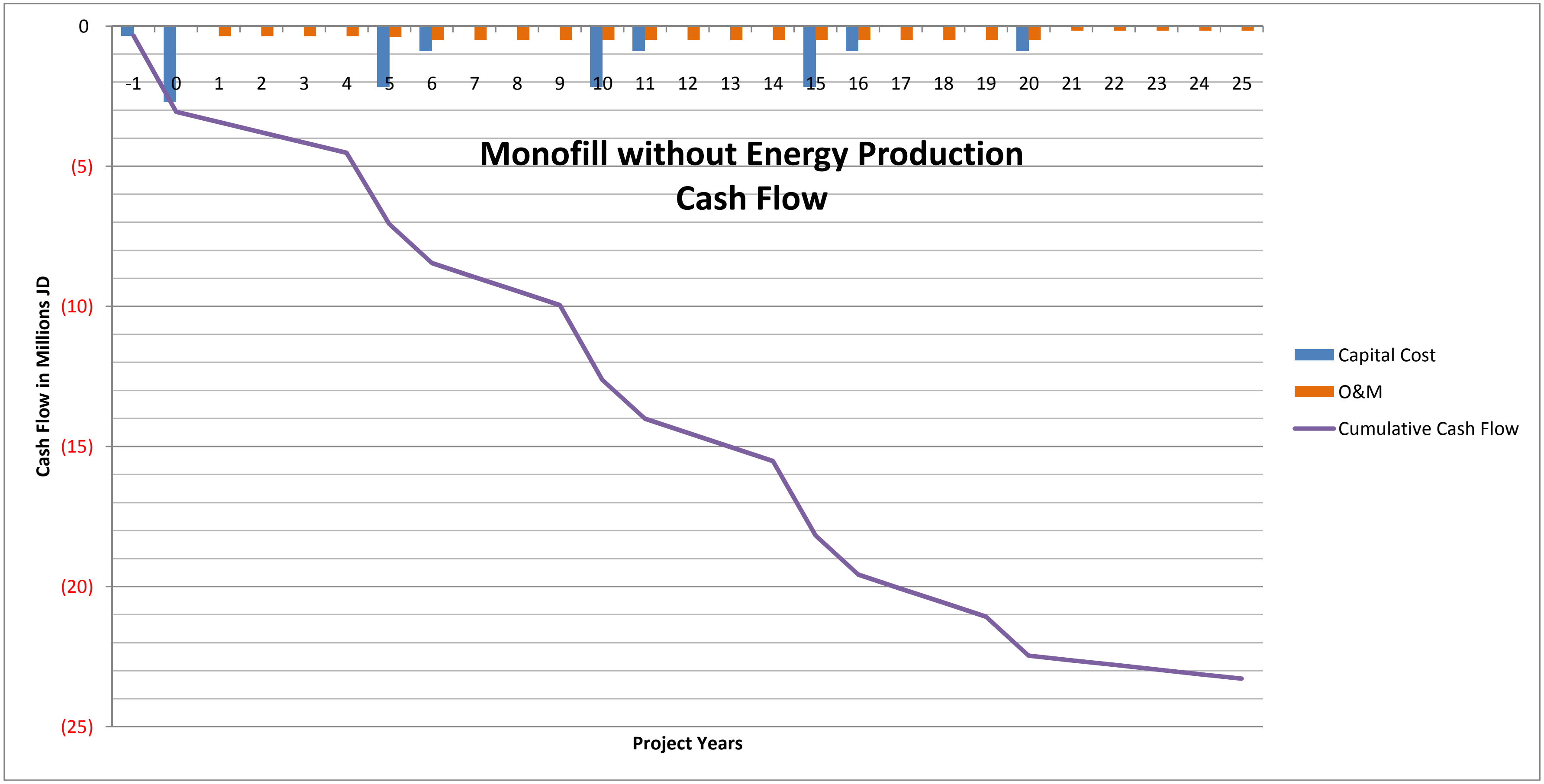
**Jordan Alternatives - Year 2034 (For Operation Cost Estimates)**

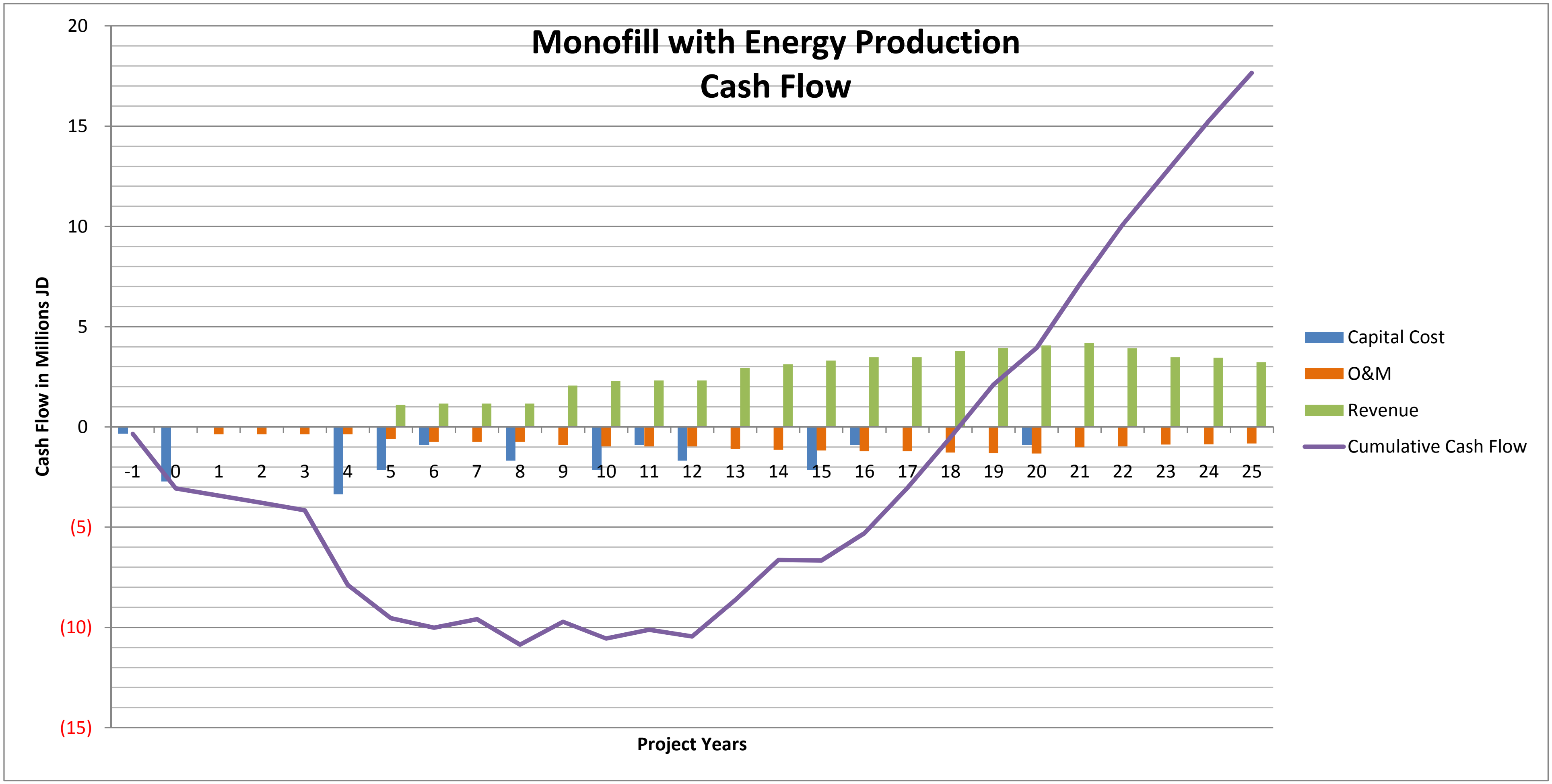
| Input Parameters | | BFP(18%) -> SDB(50%) -> Inc | BFP (18%) -> Win(75%) -> Inc/Gas | BFP (18%) -> SDB (30%) -> Win(75%) -> Inc/Gas | BFP (18%) -> SDB (50%) -> Win(75%) -> Inc/Gas | BFP (18%) -> SDB (50%) -> Win(90%) -> Inc/Gas | *Assumptions/Notes* |
|---|---|---|---|---|---|---|---|
| Mass (Dry) | dry tonne/d | 193.9 | 193.9 | 193.9 | 193.9 | 193.9 | |
| Mass (Dry) | kg/d | 193,900 | 193,900 | 193,900 | 193,900 | 193,900 | |
| Mass (Volatiles Dry) | kg/d | 125,453 | 125,453 | 125,453 | 125,453 | 125,453 | |
| Volatile Solids | %VS/TS | 64.7% | 64.7% | 64.7% | 64.7% | 64.7% | |
| Solid Content | %TS | 18.00% | 18.00% | 18.00% | 18.00% | 18.00% | |
| S.G | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| Volume | $m^3$/d | 1,077 | 1,077 | 1,077 | 1,077 | 1,077 | |
| Inlet Temperature | C | 20 | 20 | 20 | 20 | 20 | |
| Reference Temperature | C | 0 | 0 | 0 | 0 | 0 | |
| **Calculations** | | | | | | | |
| Volatile Solids Reduction - Air Drying | % VSR | 15% | 15% | 15% | 15% | 15% | *Assumed to Occur During Drying Process* |
| Mass (Dry) | kg/d | 175,082 | 175,082 | 175,082 | 175,082 | 175,082 | |
| Mass (Volatiles Dry) | kg/d | 106,635 | 106,635 | 106,635 | 106,635 | 106,635 | |
| Volatile Solids | %VS/TS | 60.9% | 60.9% | 60.9% | 60.9% | 60.9% | |
| HHV Estimate (dry) | kcal/kg | 3,000 | 3,000 | 3,000 | 3,000 | 3,000 | *Based on ATEX samples from RSS and Hazen Research assuming 15% Loss during drying / storage* |
| HHV Estimate (dry) | kJ/kg | 12,600 | 12,600 | 12,600 | 12,600 | 12,600 | |
| ***Solar Drying Beds*** | | | | | | | |
| Desired Solid Content | %TS | 50% | 18% | 30% | 50% | 50% | |
| S.G | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| Volume | $m^3$/d | 350 | 973 | 584 | 350 | 350 | |
| Water Evaporated | kg/d | 689,422 | 0 | 430,889 | 689,422 | 689,422 | *Not accounting for VSR* |
| ***Windrow Dryer*** | | | | | | *May require a thermal dryer* | |
| Desired Solid Content | %TS | 50% | 75% | 75% | 75% | 90% | |
| S.G | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| Volume | $m^3$/d | 350 | 233 | 233 | 233 | 195 | |
| Water Evaporated | kg/d | 0 | 818,689 | 387,800 | 129,267 | 172,356 | *Not accounting for VSR* |
| ***Incineration*** | | | | | | | |
| Inlet Solids Fuel Value | MJ/d | 2,206,033 | 2,206,033 | 2,206,033 | 2,206,033 | 2,206,033 | |
| Inlet Solids Sensible Heat | MJ/d | 5,252 | 5,252 | 5,252 | 5,252 | 5,252 | *1.5 kJ/kg-C Dry Solid Heat Capacity* |
| Inlet Water Sensible Heat | MJ/d | 14,637 | 4,879 | 4,879 | 4,879 | 1,626 | *4.18 kJ/kg-C Water Heat Capacity* |
| Total Energy to Incinerator | MJ/d | 2,225,923 | 2,216,165 | 2,216,165 | 2,216,165 | 2,212,912 | |
| Excess Air | % | 40% | 40% | 40% | 40% | 40% | *Based on MOP-8 criteria* |
| Theoretical Oxygen | kg O2/kg fuel (dry) | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | |
| Stoichiometric Air Requirement | kg air/kg fuel (dry) | 4.86 | 4.86 | 4.86 | 4.86 | 4.86 | |
| Combustion Air Requirement | kg/d (dry) | 1,190,758 | 1,190,758 | 1,190,758 | 1,190,758 | 1,190,758 | |
| Humidity | kg H2O/kg D.A. | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 | |
| Ambient Air Temperature | C | 25 | 25 | 25 | 25 | 25 | |
| Preheat Temperature | C | 25 | 25 | 25 | 25 | 25 | *No Air Preheating Assumed* |
| Energy to Air Preheater | MJ/d | 0 | 0 | 0 | 0 | 0 | *1.0 kJ/kg-C Dry Air Heat Capacity* |
| Inlet Combustion Air Sensible Heat | MJ/d | 66,217 | 66,217 | 66,217 | 66,217 | 66,217 | *2.03 kJ/kg-C Water Vapor Heat Capacity* |
| Preheated C.A. Sensible Heat | MJ/d | 66,217 | 66,217 | 66,217 | 66,217 | 66,217 | *2500 kJ/kg Latent Heat of Water* |
| Water From Combustion | kg H2O/kg dry sludge | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | |
| Water From Combustion | kg H2O/d | 71,894 | 71,894 | 71,894 | 71,894 | 71,894 | |
| Flue Gas Production | kg/d (dry) | 1,225,500 | 1,225,500 | 1,225,500 | 1,225,500 | 1,225,500 | |
| Flue Gas Water Vapor | kg/d | 261,265 | 144,543 | 144,543 | 144,543 | 105,636 | |
| Ash | kg/d | 68,447 | 68,447 | 68,447 | 68,447 | 68,447 | |
| Humidity | kg H2O/kg D.A. | 0.213 | 0.118 | 0.118 | 0.118 | 0.086 | |
| Oxygen Content | % O2 (mass basis) | 6.4% | 6.4% | 6.4% | 6.4% | 6.4% | |
| Total Energy Produced | MJ/d | 2,292,139 | 2,282,382 | 2,282,382 | 2,282,382 | 2,279,129 | *1.05 kJ/kg-C Dry Flue Gas Heat Capacity* |
| Total Energy Produced | MMBtu/hr | 91 | 90 | 90 | 90 | 90 | |
| Adiabatic Temperature | C | 872 | 1,169 | 1,169 | 1,169 | 1,288 | *0.92 kJ/kg-C Ash Heat Capacity* |
| Heat Loss Factor | % | 2% | 2% | 2% | 2% | 2% | |
| Heat Loss | MJ/d | 45,843 | 45,648 | 45,648 | 45,648 | 45,583 | |
| Flue Gas Temperature | C | 847 | 1,141 | 1,141 | 1,141 | 1,259 | *Target about 850 C* |
| Heat Exchanger Heat Loss | % | 2% | 2% | 2% | 2% | 2% | |
| Energy to Air Preheater | MJ/d | 0 | 0 | 0 | 0 | 0 | |
| Cooled Flue Gas Temperature 1 | C | 847 | 1,141 | 1,141 | 1,141 | 1,259 | |
| Secondary Heat Recovery | MJ/d | 1,235,914 | 1,563,174 | 1,563,174 | 1,563,174 | 1,672,260 | |
| Total Energy Produced | MMBtu/hr | 49 | 62 | 62 | 62 | 66 | |
| Cooled Flue Gas Temperature 2 | C | 190 | 190 | 190 | 190 | 190 | *Set equal to cooled flue gas temperature 1 if no secondary heat recovery is included* |
| Steam Turbine Electrical Efficiency | % | 29.1% | 27.2% | 27.2% | 27.2% | 27.2% | *Based on information from Siemens* |
| Steam Turbine Electrical Production (gross) | kW | 4,165 | 4,930 | 4,930 | 4,930 | 5,274 | *Adjusted to match Siemens output* |
| Steam Turbine Parasitic Electrical Load | kW | 500 | 592 | 592 | 592 | 633 | |
| Steam Turbine Electrical Production (net) | kW | 3,665 | 4,338 | 4,338 | 4,338 | 4,641 | |
| Steam Turbine Electrical Production (net) | kWh/d | 87,961 | 104,116 | 104,116 | 104,116 | 111,382 | |
| Energy to Flue Gas Treatment | MJ/d | 1,010,383 | 673,560 | 673,560 | 673,560 | 561,286 | |
| Flue Gas Density | kg/Nm3 | 1.28 | 1.30 | 1.30 | 1.30 | 1.30 | @ STP (0 C & 1 atm) |
| Flue Gas Flow | m3/h | 48,397 | 43,912 | 43,912 | 43,912 | 42,665 | @ STP (0 C & 1 atm) |
| Flue Gas Flow | SCFM | 28,485 | 25,845 | 25,845 | 25,845 | 25,111 | |
| Flue Gas Flow (Incinerator Outlet) | m3/hr | 198,534 | 227,390 | 227,390 | 227,390 | 239,328 | |
| | ACFM | 116,852 | 133,836 | 133,836 | 133,836 | 140,863 | |
| | ACFM | 116,852 | 133,836 | 133,836 | 133,836 | 140,863 | |
| Flow Gas Flow (Out of Steam Boiler) | m3/hr | 82,062 | 74,456 | 74,456 | 74,456 | 72,342 | |
| | ACFM | 48,300 | 43,823 | 43,823 | 43,823 | 42,578 | |
| | ACFM | 48,300 | 43,823 | 43,823 | 43,823 | 42,578 | |
| **Steam Production** | | | | | | | |
| Steam Pressure | bara | 40 | 40 | 40 | 40 | 40 | |
| Superheated Steam Tempererature | C | 400 | 400 | 400 | 400 | 400 | |
| Specific Enthalpy | kJ/kg | 3,214 | 3,214 | 3,214 | 3,214 | 3,214 | *From Steam Tables* |
| Feedwater Temperature | C | 130 | 130 | 130 | 130 | 130 | |
| Feedwater Enthalpy | kJ/kg | 546 | 546 | 546 | 546 | 546 | |
| Steam Produced | kg/d | 463,359 | 586,053 | 586,053 | 586,053 | 626,951 | |
| Steam Produced | kg/h | 19,307 | 24,419 | 24,419 | 24,419 | 26,123 | |
| | tonnes/h | 19.31 | 24.42 | 24.42 | 24.42 | 26.12 | |
| Steam Produced | lb/hr | 42,571 | 53,844 | 53,844 | 53,844 | 57,601 | |
| **Operating Cost Factors** | | | | | | | |
| Electrical Consumption | kW | 404 | 404 | 404 | 404 | 404 | *Based on 450 kW per Andritz estimate at 195 tonne/d* |
| Carbon Consumption | kg/h | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | *Based on 4 kg/hr per Andritz estimate at 195 tonne/d* |
| Sodium Bicarbonate Consumption | kg/hr | 520 | 520 | 520 | 520 | 520 | *Dry Fuel contains 1.2% sulfur, all to SO2. Stoic rate for bicarbonate addition for SO2 removal is 2.63 lb NaCO3/lb SO2. Added 13% S.F. to match Andritz estimate of 580 kg/hr* |
| Start-up Fuel Requirement | MWh per cold start-up | 84 | 84 | 84 | 84 | 84 | *From Andritz* |
| Start-up Fuel Oil Requirement | L/start-up | 8,700 | 8,700 | 8,700 | 8,700 | 8,700 | *Based on 131.5 kJ/gal heating value* |
| Annual Start Up Requirement | L fuel oil | 26,100 | 26,100 | 26,100 | 26,100 | 26,100 | *Andritz recommendation of 2 cold starts and 4 warm starts (25% of cold start fuel consumption)* |
| Ash Production | tonne/d (dry) | 68 | 68 | 68 | 68 | 68 | |
| ***Max West Gasification*** | | | | | | | |
| Energy Generation Efficiency | % | -- | 53% | 53% | 53% | 71% | *Set to match estimations provided by Max West* |
| Total Energy Produced | MJ/d | -- | 1,160,639 | 1,160,639 | 1,160,639 | 1,560,943 | |
| Total Energy Produced | MBtu/hr | -- | 45,836 | 45,836 | 45,836 | 61,644 | |
| Heat Recovery Efficency | % | -- | 72% | 72% | 72% | 70% | |
| Energy Available For Electricity | MJ/d | -- | 832,568 | 832,568 | 832,568 | 1,092,660 | |
| Energy Available For Electricity | MBtu/hr | -- | 32,880 | 32,880 | 32,880 | 43,151 | |
| Energy Available For Drying / Electricity | kW | -- | 9,636 | 9,636 | 9,636 | 12,647 | |
| **Electrical Production Potential - 20% eff** | **kW** | -- | **1,927** | **1,927** | **1,927** | **2,529** | |
| **Electrical Production Potential - 10% eff** | **kW** | -- | **964** | **964** | **964** | **1,265** | |
| Total Energy to Flue Gas Treatment | MJ/d | -- | 328,071 | 328,071 | 328,071 | 468,283 | |
| Total Energy to Flue Gas Treatment | MBtu/hr | -- | 12,956 | 12,956 | 12,956 | 18,493 | |
| Natural Gas Input to Process Heater | kg/d | -- | 24 | 24 | 24 | 24 | *Based on input from previous Max West mass and energy balances* |
| Natural Gas Input to Process Heater | $m^3$/d | -- | 33 | 33 | 33 | 33 | |
| Natural Gas Input to Process Heater | $ft^3$/hr | -- | 49 | 49 | 49 | 49 | |
| Natural Gas Fuel Value | MJ/d | -- | 1,346 | 1,346 | 1,346 | 1,346 | |
| Natural Gas Fuel Value | kW | | 16 | 16 | 16 | 16 | |
| Natural Gas Fuel Value | MBtu/hr | -- | 53.2 | 53.2 | 53.2 | 53.2 | |
| Electrical Consumption Factor | kW/mton | -- | ~~163~~ | ~~163~~ | ~~163~~ | ~~163~~ | |
| Electrical Consumption | kWh/d | -- | ~~28538~~ | ~~28538~~ | ~~28538~~ | ~~28538~~ | |
| Electrical Consumption | kW | -- | ~~1189~~ | ~~1189~~ | ~~1189~~ | ~~1189~~ | |

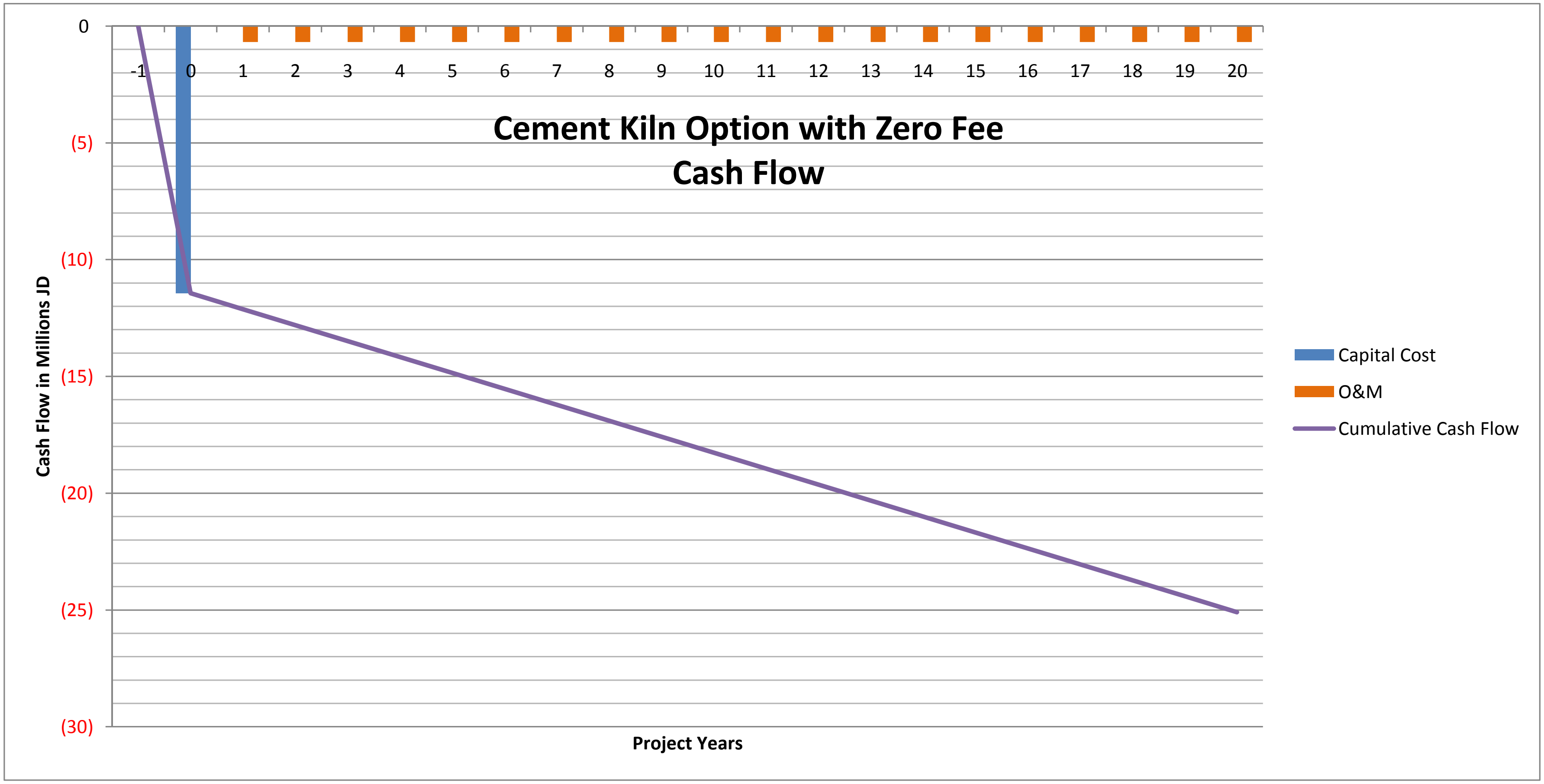
# APPENDIX 3

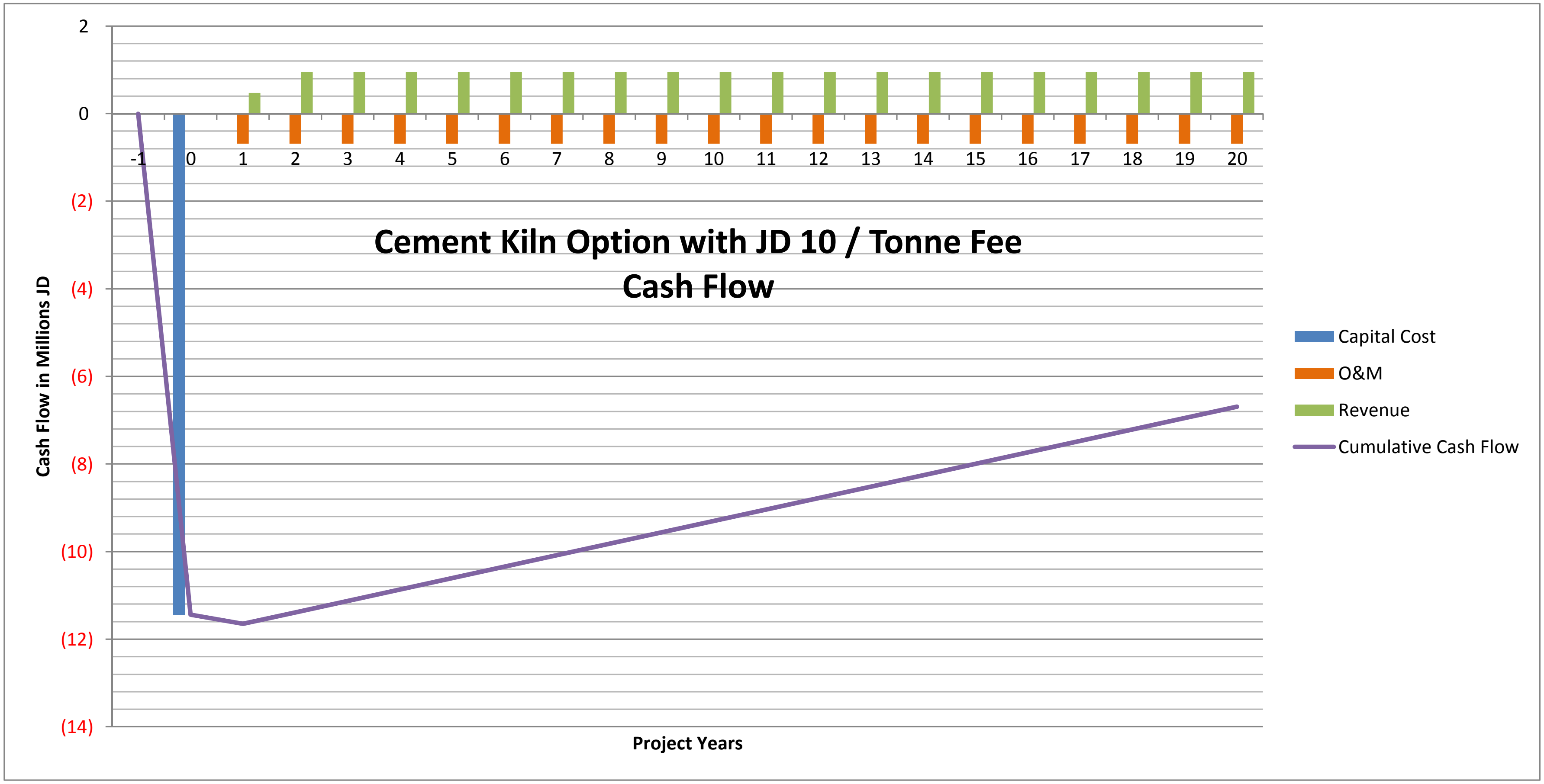
## PRELIMINARY FINANCIAL ANALYSES CHARTS


Incineration with Energy Production
Cash Flow
30
20
10
0
(10)
(20)
(30)
(40)
(50)
(60)
(70)
Cash Flow in Millions JD
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Project Years
Capital Cost
O&M
Revenue
Cumulative Cash Flow


Monofill without Energy Production
Cash Flow
0
(5)
(10)
(15)
(20)
(25)
Cash Flow in Millions JD
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Project Years
Capital Cost
O&M
Cumulative Cash Flow


Monofill with Energy Production
Cash Flow
20
15
10
5
0
(5)
(10)
(15)
Cash Flow in Millions JD
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Project Years
Capital Cost
O&M
Revenue
Cumulative Cash Flow


Cement Kiln Option with Zero Fee
Cash Flow
Cash Flow in Millions JD
0
(5)
(10)
(15)
(20)
(25)
(30)
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Project Years
Capital Cost
O&M
Cumulative Cash Flow


Cement Kiln Option with JD 10 / Tonne Fee
Cash Flow
Cash Flow in Millions JD
2
0
(2)
(4)
(6)
(8)
(10)
(12)
(14)
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Project Years
Capital Cost
O&M
Revenue
Cumulative Cash Flow