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Author/Contributor:

Peters, G; Lundie, S

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Life-Cycle Assessment of Biosolids Processing Options

Gregory M. Peters
Sydney Water Corporation
Sydney, Australia

Sven Lundie
Centre for Water and Waste Technology
University of New South Wales
Sydney, Australia

Address correspondence to:

Gregory Peters
Sydney Water Corporation
115-123 Bathurst St
Sydney NSW 2000
Australia
gregory.peters@sydneywater.com.au
www.sydneywater.com.au

Summary

Biosolids are the reusable organic materials removed from sewage during treatment. Different options for biosolids handling in Sydney, Australia, are compared using life-cycle assessment. Two key comparisons are made: of system scenarios (scenario one - local dewatering and lime-amendment; scenario two - a centralized drying system) and of technologies (thermal drying versus lime-amendment). The environmental issues addressed are energy consumption, global warming potential (GWP) and human toxicity potential (HTP).

Scenario two would consume 24% more energy than scenario one. This is due to the additional electricity for pumping and particularly the petrochemical methane that supplements biogas in the dryer. A centralized system using the same technologies as scenario one has approximately the same impacts. The GWP and HTP of the different scenarios do not differ significantly.

The assessment of technology choices showed significant differences. The ample supply of endogenous biogas at North Head Sewage Treatment Plant (STP) for the drying option for allows reductions, relative to the lime amendment option, of 68% in energy consumption, 45% in GWP and 23% in HTP.

Technology choices have more significant influence on the environmental profile of biosolids processing than the choice of system configurations. Controlling variables for

environmental improvement are the selection of biogas fuel, avoidance of coal-sourced electrical energy, minimization of trucking distances and raising the solids content of biosolids products.

Keywords

Biosolids, global warming potential, human toxicity potential, lime amendment, sewage sludge, wastewater treatment

Introduction

Ecologically sustainable management of the solid residuals from wastewater treatment, known as biosolids or sewage sludge, is an ongoing challenge in Sydney, Australia, as in many parts of the world. Several components of Sydney Water's legal operating framework require the organisation to act in accordance with the principles of ecologically sustainable development, as defined in the *Protection of the Environment Administration Act, 1991*. According to the *Sydney Water Act, 1994*, Sydney Water is required to demonstrate a reduction in “the combined environmental impact of the per capita amount of energy and water used... and other materials ... discharged”. Environmental life-cycle assessment (LCA) is an obvious means for assessing the potential environmental effects of major capital works, consistent with this stated desire for holistic assessment. Sydney Water has decided to upgrade all biosolids treatment facilities to produce “A” grade biosolids (NSW EPA 1997), a standard that can be reached with several technologies. In early 1999, Sydney Water decided to apply LCA to the examination of particular proposed upgrades to its biosolids treatment infrastructure and potential “A” grade technologies. This presented an opportunity for Sydney Water to examine the application of LCA performed to the ISO 14040 series of standards (ISO 1998, 2000a, 2000b).

The LCA examined two key issues in the further development of Sydney Water's biosolids business: the choice of system configurations, and thermal drying versus lime amendment technologies.

Several studies have been carried out in the area of waste water treatment: Lundin and colleagues (2000) compared large and small conventional wastewater system with separation systems, while Emmerson and colleagues (1995) analysed small-scale sewage treatment processes from an LCA perspective. Other LCA studies on wastewater systems compare alternative treatment options (Bengtsson et al. 1997, Tillman et al. 1998), different sludge treatment and recycling processes (Neumayer et al. 1997), and source separation (Dalemo 1996). Application of LCA of potable water treatment has only recently begun (Crettaz et al. 1999). Dennison and colleagues (1998) compared centralized versus decentralized systems and the influence of composting and digesting on the enhanced greenhouse effect. To our knowledge, this LCA is the first to report on an examination of lime amendment versus thermal drying for biosolids treatment, and to examine biosolids handling in an Australian context.

LCA Goal and Scope Definition

Goal Definition

The goal of the study is to assess the application of life-cycle assessment (LCA) to Sydney Water planning activities by a holistic environmental analysis of selected biosolids processing options for three major sewage treatment plants discharging treated effluent to the Pacific Ocean (see Figure 1). The approach is prospective or change-oriented, looking at the upgrades to plants required to meet future biosolids production rates. Therefore, the study has natural relevance to the ongoing assessment of upgrade options for the ocean plants.

Figure 1: Map of the Sydney region showing catchments of the largest STPs

Functional unit

The functional unit of the study is the treatment of the mass of biosolids which is expected to be captured at the three largest plants in Sydney which serve an estimated population of 2.8 million people and discharge treated effluent to the sea: North Head, Bondi and Malabar. The current estimate of this value for the year 2021, assuming full primary treatment, is 178 dt/d (dry tonsⁱ per day).

System Boundaries

In this study, two functionally equal system and technology configurations are compared with each other:

- *System configuration comparison: status quo (scenario one) versus drying at a central location (scenario two).* Thermal biosolids drying at a proposed central biosolids treatment facility (CBTF) is compared with treatment of solids according to current practices. In order to examine the consequences of building a possible central drying facility, calculations were performed for both a central system with drying and pelletization, and for a central system producing the current ratio of lime stabilized and dewatered biosolids (these systems are described in more detail in the next section).
- *Technology comparison: lime stabilization versus drying of biosolids.* Alternative technologies for treatment of sludge were compared on a decentralized basis only. The environmental impacts of the application of thermal drying and the alternative of lime amendment at North Head STP were assessed. These systems are described in more detail in the next section. The functional unit was consistent with the comparison of system configurations: biosolids capture expected in 2021, currently estimated at 70.8 dt/d for North Head.

The foregroundⁱⁱ system boundary of this LCA runs from the outlet of the primary sedimentation tanks to delivery at the land application site. All of the unit operations between these boundaries are considered, including the ancillary services of odor abatement and (at Malabar) cogeneration with biogas. The processes were analysed at the level of individual unit operations for the foreground system whenever possible. Using national and international databases embedded in the LCA software “GaBi 3v2” (GaBi 2001) additional background systems processes were modelled.

The inventory for the foreground system included construction and operational impacts. Process impacts of the background systems were included, but the “cut-off” rule of not including the impacts resulting from the installation of the background systems was applied.ⁱⁱⁱ Equipment is assumed to have an average operating lifespan of 20 years. As the materials used in construction of the plant and equipment (primarily concrete and steel) are recyclable and considered to reduce environmental impact in other product systems, the disposal of equipment is not considered in this LCA. Additionally, the material and energy flows associated with construction are considerably smaller than those associated with operation of the plants, and it is therefore to be expected that operational issues dominate the total environmental impact of the system relative to construction and disposal.^{iv}

System configuration comparison

A conceptual diagram of scenario one is given as Figure 2. In this system, the unit operations at the STPs are substantially the same as those currently in operation: lime amendment without digestion at North Head, and digestion and dewatering at Bondi and Malabar. At all sites, vapor scrubbers are used to treat the air drawn from the enclosed facilities.

```

graph LR
    A[gravity thickening] --> B[centrifuge dewatering]
    B --> C[lime stabilization]
    C --> D[on-site storage]
    D --> E[truck transport]
    E --> F[agricultural application]
  
```

```

graph LR
    A[centrifuge thickening] --> B[anaerobic digestion]
    B --> C[centrifuge dewatering]
    C --> D[on-site Storage]
    D --> E[truck transport]
    E --> F[agricultural application]
  
```

Malabar STP

The process flow is as follows:

- centrifuge thickening**: Initial stage of sludge processing.
- anaerobic digestion**: Sludge is digested, and **power generation** occurs.
- centrifuge dewatering**: Further processing of the digested sludge.
- on-site Storage**: Temporary storage of the dewatered sludge.
- truck transport**: Sludge is transported by truck.
- agricultural application**: Final use of the sludge as fertilizer.

At North Head, the primary settling tank underflow is thickened by gravity prior to centrifuge dewatering. Physical and microbial stabilization occurs via subsequent lime amendment. The biosolids are trucked to an agricultural application site 250 km away using covered 25 ton articulated trucks. For the purposes of this study, 50 km of the journey is assumed to be in urban traffic, with the remainder under rural or motorway conditions.

At Malabar and Bondi, thickening occurs by centrifugation. Prior to centrifuge dewatering, the biosolids are digested. In the case of Malabar, the biogas is burnt in a cogeneration set and the waste heat is used to warm the digesters, while at Bondi the biogas combustion supplies the heat for the digesters via a boiler. The digested, dewatered biosolids from these STPs are also delivered to an agricultural site 250 km away.

The materials for construction of the STPs included in this LCA are only those required to upgrade the facilities for the capture and treatment of a higher proportion of the influent suspended solids. This includes additional thickening centrifuges and digesters at North Head and Malabar, additional dewatering centrifuges at Bondi and Malabar and additional storage for treated biosolids at North Head and Malabar. Additional odor scrubbing equipment is required at Malabar.

Scenario two would maintain the use of the thickening and digestion units at Bondi and Malabar, with the associated uses of biogas, but the other unit operations would be located at a central processing facility. (There are several alternative locations at which

biosolids handling could be centralized, if the decision to centralize were made.) Raw sewage would be pumped from North Head to the CBTF for gravity-thickening and digestion, both to enhance its stability and to provide biogas fuel for the drier. This fuel would be insufficient for the total heat load of the direct drier, and is supplemented with (fossil) natural gas for this study. Figure 3 depicts the system configuration of scenario two.

Construction materials required for this system are predominantly concrete and steel. Locating a digester at the CBTF would imply the installation of further digestion equipment in addition to that envisaged for scenario one. The transfer of sewage to the CBTF would require the laying of new concrete-lined, ductile iron pipes between the three STPs and the new plant. A corrosion-resistant, fusion-bonded epoxy coated stainless steel pipe would be required for the submerged crossing of Sydney Harbour by the pipeline from North Head. The CBTF would require new dewatering centrifuges, connected to new direct drying and storage equipment.

Figure 3: Conceptual system - scenario two

The system shown in Figure 3 was also examined without the CBTF digester and with the direct drying unit replaced by a lime amendment unit sized to treat the North Head biosolids only. This approach allowed the significance of the act of centralization to be examined (predominantly, the significance of pumping impacts) independently of the consequences of the differences of technology chosen for scenarios one and two.

Technology comparison: lime stabilization versus drying

For the comparison of drying technologies, the process units required for lime stabilization and drying of biosolids at North Head were compared. These are shown in Figure 4.

The lime stabilization system at North Head is exactly as described as part of scenario one. The drying system would be similar to that employed in scenario two. However, as a consequence of the reduced thermal load of the direct drier, it is possible to supply its entire thermal needs by burning the biogas produced from digestion of the sludge captured at North Head. In fact, surplus biogas would be produced in the digesters and this is assumed to be used in heating the digesters, with the remainder flared.

The materials required for the lime option are the same as those described in the comparison of configuration scenarios. For the drying option, thickening centrifuges, digesters, driers and additional storage facilities are required.

North Head (lime stabilization)

North Head (drying & pelletization)

Figure 4: Conceptual alternative North Head biosolids systems

Comparison of the systems

The main function of the systems under study is the treatment of biosolids. As only one product is considered to leave the plant (treated biosolids) all impacts are attributed to it. However, electricity generated from anaerobic digestion at Malabar STP is a byproduct that crosses the system boundary. The electricity is exported to other parts of the sewage treatment process other than the biosolids processing. This energy export is taken into account by including the avoided environmental impacts which would otherwise result from coal-fired electricity generation - the supply alternative to the Malabar STP cogeneration facility.

Methodological choices and assumptions

In this study, several methodological choices and assumptions have been made that might influence the results. The most relevant choices are:

- *System boundaries.* The system starts at the outlet of the primary sedimentation tanks to delivery of biosolids at the land application site. The application of biosolids is excluded from this study due to the complexity of its impacts on interrelated soil chemical processes.
- *Capital equipment.* Non-recurrent (construction) impacts associated with long-lived equipment are considered only for the upgrade of the facilities. Environmental impacts from construction of existing facilities are excluded.
- *Impact assessment models.* In this study, impact categories and environmental indicators have been selected that are most relevant to Sydney Water, that is, energy consumption, global warming potential and human toxicity of air emissions.
- *Energy consumption.* In regards to primary energy consumption, all energy flows entering the defined system (consumed energy) and all energy flows leaving the defined system (produced energy) are considered. If energy is produced within one system and at the same time consumed, no energy flows occur across the system boundary. Therefore, the net energy consumption / production is shown only. In the case of Malabar, there is a net production of *electricity* under scenario one, as a consequence of its generation in the cogeneration plant. However, despite the electricity exported to other parts of the STP, the biosolids process is a net consumer of *energy* due to the high energy demand of the trucking operations. By contrast, in scenario two, this trucking occurs from the CBTF site, and the additional energy saved at Malabar due to the absence of dewatering operations makes the biosolids process a net producer of both electricity and energy.
- *Greenhouse effect.* Carbon dioxide and nitrous oxide emissions resulting from the combustion of fossil fuels contribute to global warming and other climate change effects. However, carbon dioxide emissions from the microbial degradation of biosolids, or the combustion of biogas, merely complete a biological cycle which begins with the conversion of atmospheric CO₂ to biomass by photosynthesis in crops. These carbon emissions are not derived from the lithosphere but return carbon to the atmosphere. Therefore, greenhouse gas emissions resulting from the combustion or emission of gases generated by the metabolizing of biosolids are excluded from the calculation of contributions to the enhanced greenhouse effect in this LCA, consistent with the approach used by other LCA practitioners (US EPA 1997).

Life-Cycle Inventory Data Collection

After validation of annual mass and energy balances, the data were related to unit processes and the functional unit (see the previous description of the functional unit and system boundaries). Finally, the data were aggregated for the life-cycle impact assessment (LCIA) phase (described in the next section). This procedure was performed several times. The iterative character of the process allowed us to determine which issues

were most significant prior to finalization of the calculations, which permitted efficient allocation of efforts to improve data quality when necessary.

The data on these units is contained in several statutory (Sydney Water 1999b) and planning documents (eg.: Sydney Water 1996, 1998a, 1998b, 1999a), supplemented when necessary with supplier data (eg.: Andritz 1999) and literature values (Kogan and Torres 1996). The data is considered prospective in nature - based on estimates of future necessary plant and equipment using contemporary operational observations. Australian inventory data for the inclusion of background systems was obtained from Grant and colleagues (1999a).

Planning data is supplied to Sydney Water by its consultants on the basis that the cost estimates are accurate to within 25% of a stated value. Given that inaccuracy can occur both in the sizing and performance of equipment, and the pricing of the equipment chosen, the sizing and performance data should be accurate to much better than 25%. Performance data from suppliers can be expected to accurately reflect optimal installation of their equipment. Life-cycle inventory and literature data is in the public domain yet possibly weaker due to its lack of specificity. Counteracting any inaccuracy in such data is its frequent occurrence as a "standard" or regular error (rather than a random error) affecting both options when a comparison is made between them. A complete discussion of errors and error propagation could go much further than this (e.g., Finnveden 2000) but is beyond the scope of this study.

Life-Cycle Impact Assessment

Selection of Impact Categories and Environmental Indicators

The environmental indicator and impact categories chosen for this study are energy consumption, global warming potential and human toxicity potential. These were chosen on the basis that they are most relevant to the particular systems undergoing comparison. Importantly, they are also three categories that have been the subject of considerable scientific debate and investigation.

Although not strictly an environmental impact category, primary energy consumption is useful as an indicator of the process intensity and the use of non-renewable resources. It can also provide useful explanatory data when examining contributions to the enhanced greenhouse effect, and is in any case a prerequisite for the evaluation of the global warming potential of process systems.

Global warming is obviously of international and local interest, given Sydney Water's status as a major consumer of electrical energy and Australia's poor per-capita performance in this area. Global warming potential (GWP) is usually evaluated on a 20, 100 or 500 year timescale. For this study, the middle of those three timescales has been selected.

Human toxicity potential (HTP) of airborne contaminants is of considerable interest in urban environments such as Sydney Water's area of operations. HTP has been studied in depth by Heijungs and colleagues (1992), Cowan and colleagues (1995), Lynch and colleagues (1995), Guinée and colleagues (1996a and 1996b), Gorree and colleagues

(1999), Jolliet (1996), Hauschild and Wenzel (1998a and 1998b), RIVM and colleagues (1998), and Huijbregts (1999).

The Australian HTP model takes into account 182 potentially toxic substances and their effects on humans (Huijbregts et al. 2001). The potential effect depends on the actual emission and the fate of the specific substances emitted to the environment. The fate of chemical substances depends on specific characteristics, such as degradation rate, bioaccumulation, evaporation and deposition. Characterization factors relative to 1,4 dichlorobenzene have been calculated on the basis of the USES LCA (Uniform System for the Evaluation of Substances in the context of LCA) model developed by Huijbregts (1999). The model has been adapted to Australian conditions.^v Human toxicity potential factors for 20 substances relevant to this study are shown in Table 1. These factors consider initial emissions to air and their direct potential impact on human health only. An infinite time horizon has been chosen.

Substance	Equivalence factors (1,4 dichlorobenzene equivalent)	Substance	Equivalence factors (1,4 dichlorobenzene equivalent)
Ammonia	1.56E-02	Mercury	1.23E+03
Arsenic	2.95E+04	Nickel	3.03E+03
Benzene	1.62E+02	NO ₂	5.47E-02
Cadmium	1.24E+04	Phenol	2.28E-02
Chromium (III)	2.97E+01	Selenium	8.12E+03
Copper	3.66E+02	SO ₂	7.95E-03
Ethylbenzene	4.66E-02	Styrene	1.67E-03
H ₂ S	1.80E-02	Toluene	1.68E-02
Hydrogen chloride	7.31E-02	Vanadium	9.42E+02
Lead	2.82E+01	Zinc	9.08E+00

Data quality and sensitivity analysis

Two types of sensitivity analysis were applied to this LCA. The first type consists of testing the assumptions about the system by variation of the configuration and/or boundaries. This type of analysis has the potential to produce large variations in results. In this study, this type of sensitivity analysis is performed by including or excluding biogas from the energy accounts, and examining scenario two, both with the alternative (drying) system and with the mix of stabilization technologies used in scenario one. The results of these assessments are discussed alongside the other results in the next section.

The second type of sensitivity analysis involves varying input values for a particular system. Ideally, each data element in a life cycle inventory should be collected with an error margin reflecting the level of certainty associated with each datum. This is not appropriate to a scanning level LCA nor a prospective LCA such as this. In the absence of retrospective, measured data, it is more appropriate to apply a standard error to the output. As discussed in the context of data collection, the planning documents on which most of the inventory for this LCA rely are accurate to within 25% of the estimated dollar cost value and it is therefore considered appropriate to apply a standard 25% error tolerance to the output of the assessments.

Results and discussion

System configurations

The scenarios are compared on the bases of energy consumption, global warming potential and human toxicity potential.

Energy consumption

Figure 5: Energy consumption under different scenarios

The net energy consumption of each of the options is of the same order of magnitude ranging from 17.9 to 23.0 terajoules per annum (TJ/a - 1 TJ is 10^{12} J). Scenario one draws 18.5 TJ/a compared with 23.0 TJ/a for scenario two with drying and 17.9 TJ/a without drying. Note that in scenario one, there is no CBTF, and in scenario two, the energy required for pumping the solids from North Head to the CBTF is counted in the CBTF figure. Consequently, there is no bar in Figure 4 for the CBTF in scenario one, nor for North Head in scenario two. This pattern is repeated in Figures 6 and 7.

It should be noted that many of the burdens associated with biosolids treatment at North Head, Malabar and Bondi are merely transferred to the CBTF in scenario two. This is why the generation of electricity only appears as an energy credit at Malabar in scenario two: the main consumers of electrical power in the current Malabar biosolids processing (dewatering centrifuges) are transferred to the CBTF with the dewatering unit operation.

From an overall energy accounting perspective, the biogas produced and used within the plant does not appear in Figure 5 since it does not cross the system boundary. The volume of biogas produced from North Head biosolids is not sufficient for the drying of the biosolids from all three plants. Consequently, the additional energy drawn by

scenario two with its drying system is predominantly the result of the natural gas (methane) required.

The differences between the energy consumption of the alternatives vary in significance. With drying, scenario two uses 24% more energy than scenario one (just less than the 25% error tolerance). Scenario two without drying is not significantly more energy efficient than scenario one (using only 3% less energy). This is the consequence of the avoidance of dewatering centrifuges at Bondi in this option. Dewatering of the solids occurs instead at the CBTF, where there is sufficient capacity to dewater these solids without the installation of an additional centrifuge. The energy savings that result from centralizing the dewatering function are of the same scale as the additional energy required to pump the biosolids to the CBTF. Scenario two with drying draws 28% more energy than scenario two without drying, so we can see that the drying technology, rather than the choice of a central facility, is more influential.

The most significant contributor to the energy consumption of scenario one is the fuel for the diesel trucks transporting the biosolids and lime. Trucking represents 36% of the total energy consumed by the biosolids handling processes at these three major ocean plants. This suggests that reducing trucking distances between sewage treatment plants and biosolids users, and reducing biosolids moisture content, are relatively effective ways to improve the energy efficiency and environmental performance of biosolids handling.

Greenhouse effect

Figure 6: Global warming potential for different scenarios

Biogas is a byproduct of biosolids stabilization when digestion is used. The biogas is either flared or used productively to generate electricity, to dry and pelletize the solids, or

to heat the digesters whence it came. In any case, it is converted to carbon dioxide which has a lower global warming potential than uncombusted biogas.

If CO₂ emissions from biogas combustion are excluded in accordance with the methodological choices discussed earlier, the results of the assessment are as follows: scenario one makes a contribution to the enhanced greenhouse effect of 17.6x10⁶ kg carbon dioxide equivalents, compared with 18.3x10⁶ kg carbon dioxide equivalents for scenario two with drying. This is an insignificant increase of 4% over scenario one. Scenario two without drying results in the emission of 17.1x10⁶ kg carbon dioxide equivalents (Figure 6).

The results with regard to global warming alter if CO₂ emissions that leave the system boundary are counted in the life cycle inventory. If CO₂ from drying at the CBTF is included, the choice of scenario two would cause an 82% increase in the contribution to the enhanced greenhouse effect to 78.9x10⁶ kg carbon dioxide equivalents from the scenario one value of 40.6x10⁶ kg carbon dioxide equivalents.

Human toxicity potential

In both scenarios, most of the toxic substances emitted to the environment are airborne contaminants released as a result of the high energy intensity of the processes. Therefore, the emphasis of the human toxicity potential assessment is on all substances released to air (as listed in Table 1).

Figure 7: Human toxicity potential under different scenarios

The combined potential for human toxicity via airborne contaminants is lowest for scenario two without drying (4.14x10⁴ kg (1,4 dichlorobenzene equivalent)/year) and insignificantly higher for the other two options (4.31x10⁴ and 4.50x10⁴ kg (1,4

dichlorobenzene equivalent)/year for scenario one and scenario two with drying, respectively). The results are influenced by several factors:

- At Malabar, credits occur due to electricity generation. Australian electricity production usually contributes significantly to heavy metal emissions via the smokestacks of coal-fired power generators. At Malabar STP, electricity is generated and exported from the boundary of the biosolids handling system to other parts of the STP. This represents avoided electrical generation in other parts of New South Wales, Australia.
- Trucking is the major contributor to human toxicity potential of the North Head (lime) and CBTF (without drying) systems. In these cases, approximately two-thirds of the toxic emissions are caused by transportation.
- In scenario two with the drying process at the CBTF, the major contributions to toxic emissions come from drying process (33%), dewatering (29%) and trucking (about 16%).
- The result is predicated on the absence of heavy metals in biogas and natural gas, and the heavy-metal contaminated fuel used in the majority of NSW's electrical generation. Approximately 5% of NSW's electricity is of hydroelectric origin with the remainder predominantly coal-sourced (Bush et al. 1999).

Lime amendment versus thermal drying and pelletization technologies

The technology comparison of lime amendment versus thermal drying is made on the basis of the same key indicators used in the comparison of system scenarios.

Energy consumption

The following discussion considers the total annual energy demand for lime amendment and thermal drying. The values calculated for energy consumption of the lime and drying systems for North Head biosolids treatment are 133 and 42.1 TJ/a, as shown in Figure 8. (The results are shown in MJ/a - megajoules per year.)

Figure 8: Energy consumption: drying versus lime at North Head

The comments made in connection with the impact of trucking on the overall energy consumption of the different system scenarios are supported dramatically in this figure. The energy consumed by trucking greater masses of biosolids generated by lime amendment, and the lime required for the process, result in the total energy consumption of the drying option being only 32% of the amount required for lime amendment. Because transportation of limestone to the plant represents only 8% of the trucked material by mass, the most significant issues are the distance the biosolids are trucked and their mass. The pelletized and the lime-amended biosolids are transported to the same sites in this comparative study, so the key difference is the moisture content of the biosolid product. Pelletized biosolids can be assumed to reach 92% solid material by mass, while lime-amended biosolids are typically only 34% solids.

Note that, consistent with Figure 5, Figure 8 does not include endogenous biogas used beneficially as energy consumed, as it is generated within the system boundary. If it were included, it would increase the energy consumption of the North Head drying option from 42.1 TJ/a to 283 TJ/a in this case.

Greenhouse effect

All greenhouse gas emissions of the two types of technology are included here.

Figure 9: Global warming potential: drying versus lime at North Head

In keeping with our approach to the assessment of the impact of configurations on the overall global warming potential of the biosolids handling, Figure 9 shows the results of the assessment of greenhouse gas emissions at North Head, excluding biogas combustion from the calculations. The contribution to the enhanced greenhouse effect of the drying option is 45% better than the lime-amendment option: 8.75×10^6 and 1.59×10^7 kg CO₂ equivalents, respectively. This is a significant difference, although relatively small compared to the difference in energy consumption. This is a consequence of the difference in greenhouse intensity of fuel consumption by diesel motors and coal-fired power generators. It is significant that the fuel sources of the dryer are the digesters within the system boundary. If natural gas were used to fire the dryer, an additional 9.28×10^6 kg CO₂ equivalents would be emitted, making the lime amendment option clearly preferable in terms of its contribution to the enhanced greenhouse effect.

Human toxicity potential

Human toxicity potential includes relevant substances released to the atmosphere (as listed in Table 1).

Figure 10: Human toxicity potential: drying versus lime at North Head

Consistent with the overall analysis of human toxicity potential in the examination of different configurations, Figure 10 shows that the human toxicity potential of the lime amendment process does not differ significantly from that of the thermal drying process. The most important contribution to human toxicity is made by trucking operations, primarily as a consequence of the large quantities of benzene emitted to the atmosphere.

The toxicity associated with drying is a consequence of the electrical consumption of the pumps involved in maintaining the mixed state of the digester, and decanting it. Drying also involves electrical power (estimated at 240 kW) to rotate the drier drum and provide other ancillary services.

Additional comparisons drawn

Resource consumption – North Head (drying)

Figure 11: Resource depletion at North Head (drying): operation v construction

Data exists on the quantity of non-renewable fuels used in the processes of generating electricity, building and driving trucks. This is presented raw (on a non-normalized basis) in Figure 10 along with the materials used during construction. This indicates that the operation of the North Head drying option uses far more resources than the construction of the plant to do it. The figure is based on one year of operation. Averaging the quantity of materials over the 20 years of their operational life reduces the total annual consumption of construction materials to 5% of the materials used in the operation of the plant. Digestion is the most material-intensive part of the plant as a consequence of the scale of the units, representing approximately 90% of the total construction material budget.^{vi}

In interpreting this data, it is worth bearing in mind that this study examines the incremental additions to the infrastructure required to operate the systems at full primary level. The majority of the biosolids plant required for this has already been constructed in order to treat the solids removed under the current system of less than primary treatment.

Energy consumed by transportation

Figure 12: Energy consumption by transportation in different scenarios

The energy required for pumping thickened biosolids at Malabar and Bondi in scenario two is accounted for in the total figures for these plants. Figure 12 indicates the relative significance of these amounts in the overall energy budgets. Using thermal drying processes decreases the transport energy budget significantly whether it is used to treat the biosolids from the three major ocean plants, or merely North Head. The energy involved in transportation of dewatered or limed biosolids is a major component of the energy budget of the associated biosolids treatment processes.

Conclusions

General conclusions

The environmental impacts explored by this LCA represent only some of the factors that Sydney Water must consider as it plans to upgrade biosolids facilities. In terms of regional and global issues, this LCA indicates that whether Sydney Water makes a choice to centralize or not will not effect the environmental outcomes as much as the technology choices. It also suggests that the choice of treatment technologies other than biogas-fuelled thermal drying would result in additional environmental impact.

The life cycle resource consumption of the drying option is dominated by the operation of the system, rather than its construction. The resources are predominantly consumed by energy production for the plant. As previously stated, the choice of biosolids processing technology is more significant than the choice of system configuration scenarios.

The largest proportion of the energy required by transportation activities is consumed in trucking. The drying options (whether installed centrally or merely at North Head STP) require the least energy for transportation.

A key issue in improving the environmental profile of biosolids handling is the avoidance of coal-sourced electrical energy. Selection of renewable energy sources such as biogas, and cleaner energy sources, such as natural gas, will improve the environmental performance of biosolids operations both by reducing the carbon-intensity of energy use, and the toxicity of emission byproducts. This has been shown for both the decision between drying and lime amendment, and also the choice of whether or not to install biogas-fuelled cogeneration equipment at North Head or the CBTF.

Alternative system scenarios

Scenario two would not use significantly more energy than scenario one. Additional energy is required for pumping the settled biosolids and the operation of the dryer, but this is partially offset by the reduction in energy for transportation of treated biosolids and quicklime. This outcome is not controlled by the fact of centralization, but has to do with the choice of drying and pelletizing technology for all the biosolids instead of lime amendment at North Head and dewatering at Bondi and Malabar.

The combustion of biogas was not included in calculations of global warming potential for the reasons outlined in the initial discussion of methodological choices. Taking this into account, the contribution to the enhanced greenhouse effect of the different options does not vary significantly.

The human toxicity potential of scenario two without drying is marginally lower than that of the other systems, that is, 4% less than scenario one and 8% less than scenario two with drying. This is a consequence of the choice of drying technology, which allows a proportion of the trucking activities to be avoided.

Lime amendment versus thermal drying and pelletization technologies

The energy consumption of the North Head biosolids processing system with thermal drying is only 68% less than the lime amendment option.

The drying option is approximately 45% better than the lime amendment option in terms of its contribution to the enhanced greenhouse effect.

Selection of the drying option would result in a 21% improvement in human toxicity potential compared with the lime amendment option at North Head STP.

LCA as a decision making support tool

While it is not the role of this report to determine developments in Sydney Water's decision-making processes, this prospective LCA study allows the authors to assess the potential value of LCA in supporting planning activities in the future.

LCA can provide unique contributions to strategic planning for Sydney Water because it considers diverse environmental impacts related to waste water treatment systems and processes. Environmental impacts are taken into account whether they occur on or off site. Hence, the holistic approach allows a comprehensive environmental assessment that prevents against ‘problem shifting’, that is, the transfer of environmental problems from one part of the technical system or the environment to another.

The available process data, impact models and software used are adequate to this kind of study. Specialized LCA software (e.g., GaBi3) is valuable, particularly at the inventory and impact stage. It allows easy access to large quantities of data about important background systems that would otherwise have to be collected for each study.

The results of this study supply new insights into the environmental impact of the processes studied. The recognition of the significance of trucking in energy consumption, global warming and human toxicity potential issues, for example, is ensured by the LCA methodology. Further studies might consider more environmental indicators and impact categories. Each LCA is specific to the cases under analysis, so it may be expected that future LCAs in other parts of the business will offer other new insights. LCA can be used to improve “life cycle thinking” in Sydney Water’s planning activities, taking into account the entire lifespan of a plant, and the other processes in its supply chain. This is essential in order to properly assess the ecological sustainability of developments.

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ⁱ Tons denotes metric tons. 1 ton = 1 megagram = 1.12 (US) short tons

ⁱⁱ ‘Foreground systems’ refers to the alternative systems under examination in this study, as shown in Figures 2 to 4. The ‘background’ system “comprises all other processes which interact directly with the foreground system, usually supplying material or energy to the foreground or receiving material or energy from it” (Clift 1999) and are not the domain of the alternatives being examined.

ⁱⁱⁱ This is generally justified on the basis that: 1) for most supply chains, the proportion of the output of the chain which would be directed to the foreground system is minimal; and 2) the impact of plant construction activities is generally much less than the impacts of their operations.

^{iv} This has been qualitatively confirmed by Otoma and colleagues (1997).

^v The Australian Human Toxicity model is based on the USES LCA model (Huijbregts 1999). This model has been adapted to Australian conditions by integrating Australian environmental parameters, human characteristics (eg. daily intake of food), input parameters for fate analysis and human exposure assessment and weighting factors for aggregation of the Risk Characterization Ratio (Huijbregts et al. 2001).

^{vi} The construction, operation and demolition of small-scale sewage-treatment processes have been analysed in Emmerson and colleagues (1995) and Lundin and colleagues (2000): The energy consumption of construction is significant impact on the overall environmental profile in both studies. In Emmerson and colleagues (1995) the energy consumption ranges from 5 – 50% for the construction of the plants, while the contribution to climate change is significantly lower (less than 15%). However, resource consumption has not been considered in any of these studies.