Smart Water Fund

Final Milestone 1 Report

Literature review of technology for the recovery of methane from wastewater

Project 10TR1 Advanced Methane Extraction

March 2013

Melbourne Water

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Background

This Smart Water Fund project is investigating methods to enhance the recovery of methane generated in anaerobic processes during wastewater treatment. Enhanced methane recovery can be captured as fuel for energy generation and minimises fugitive emissions which becomes a GHG load on the environment. The learnings and findings from this project are expected to be valuable to all water utilities that operate anaerobic processes and recover methane. This project is taking a multi-phased approach.

- Literature Review of technologies to enhanced methane recovery from wastewater
- Laboratory Scale Trials of short listed technologies
- Pilot field trials in a low and high solids environment
- Cost benefit analysis

This report represents the first phase of Literature Review.

Executive Summary

Methane is often formed when anaerobic conditions occur during the wastewater treatment process. As methane is poorly soluble in water, most of the methane escapes as easily captured, but some remains in the liquid phase as dissolved methane or small entrained bubbles. This can lead to process streams containing large amounts of methane; the ability to strip and recover this methane is environmentally desirable (as methane is a greenhouse gas) while also offering economic benefits (the captured methane may be used as a fuel, while the destruction of methane reduces any carbon price liability). The aim of this report is to provide a preliminary assessment of potential technologies for stripping and capturing methane, leading to the selection of some more promising options for laboratory trials.

Stripping methane by vacuum allows for good recovery of methane and simplifies beneficial use of the resulting gas stream. The technology is also fairly well developed, with a plant currently under construction in the Netherlands to strip methane from groundwater. However the need to operate under vacuum may increase capital expenditure, and depending on the process selected solids in the wastewater may lead to fouling.

Sparging also offers the potentially to remove almost all of the methane present in the wastewater, although increasing methane recovery will necessitate larger amounts of sparge gas leading to higher operating costs and increasing dilution of the recovered methane. This is well developed technology that has seen previous use for methane stripping, and mechanically similar to aeration equipment used at wastewater treatment.

Membrane modules, with a vacuum applied on the opposite side to the membrane, can achieve very high methane recovery. However, this technology is probably the most vulnerable to fouling, which may prevent effective implementation.

Ultrasound is sometimes used in laboratories to degas liquids, and has the potential to achieve moderately high methane recovery. However, there is little precedent to employ ultrasound for degassing on this stage, and it appears that the process would require large amounts of electricity leading to high operating costs.

Agitation or mixing may allow for partial recovery of methane from high-concentration solutions by allowing the solution to rapidly equilibrate with the gas phase; this agitation can be created by simple devices such as a weir or a (repurposed) surface aerator. Although agitation is a relatively low performance technology, it may also be relatively cheap to construct and operate.

Heating is not normally used to degas liquids, but as gas solubility decreases with temperature a head-based process is expected to drive out some dissolved methane from a solution. Because of the volume of liquid that would need to be heated, this process will require a large amount of energy to operate; it is unlikely to be suitable unless a source of waste heat is readily available.

Methane from Wastewater at Melbourne Water

Methane is a naturally occurring, lighter-than-air, flammable gas. Methane is also a potent greenhouse gas: with 21 times the global warming potential of carbon dioxide, methane is believed to play a significant role in global warming.

Natural methane production occurs in anaerobic environments, where the absence of oxygen allows methanogens to anaerobically break down carbon-containing molecules. Such anaerobic conditions are commonly encountered in wastewater treatment, meaning that wastewater treatment plants often produce significant amounts of methane. Even after capturing most methane for use in electricity generation, Melbourne Water is estimated to produce ~5000 tons of fugitive methane emissions. As a result, Melbourne Water is liable to pay approximately $2.3 million for methane emissions in 2012-13, under Australia’s carbon pricing mechanism, representing approximately half of the utility’s total liability.

At the Western Treatment Plant, most methane is produced in the anaerobic ‘pots’ (covered lagoons) of the 55E and 25W lagoon systems. Based on data for 2011-12, total production from the anaerobic pots was approximately 18,000 tonnes of methane; of this approximately 88% was captured and sent to generation or flared, while the remaining 12% escaped as dissolved or entrained methane. This methane-containing effluent stream is partially-treated wastewater, with large amounts of suspended solids (~200 mg/L).

One problem in the data reported above is the accurate determination of the amount of methane dissolved in the anaerobic pot effluent. For the 2011-12 data, a sampling program concluded that the concentration of methane in effluent was approximately 10 mg/L for 25W and 16 mg/L for 55E. However it is widely believed that errors in sampling and analysis may underestimate the amount of dissolved methane: a recent study estimated the actual methane concentration exiting the 25W anaerobic pot may be between 1.1-1.8 times saturation (~30 mg/L), and it is believed that this methane may exist as entrained bubbles as well as dissolved methane.

At the Eastern Treatment Plant, the largest source of methane are the sludge digesters, which in 2012 were estimated to produce 8,000 tonnes of methane; approximately 95% of the methane is believed to be captured and is used for generation or flared, while the remaining balance (approximately 5%) leaked from the lids of the digesters. However this data does not account for any methane that may escape in the digested sludge. The ETP digesters produce 3,000-3,500 kL/day of sludge, which exits at around ~2.5% solids concentration. The concentration of methane in this stream is not known, but as the digesters produce substantial amounts of gas it is likely that this stream will be saturated or supersaturated with methane.

Gas-Liquid Interactions

The behaviour of dilute solutions of gases dissolved in liquids is proportional to the pressure of the gas and is explained by Henry's Law: [1]

$$P_A = k_H x_A$$

where P_A is the partial pressure of the gas in contact with the solution, k_H is the Henry's Law constant, and x_A is the concentration of dissolved gas in the solution.

The solubility of gases is strongly influenced by temperature; as temperature increases the solubility of gases decreases. As a result of this, the Henry's Law constant may only be quoted for a specified temperature. Some example data for methane in water, which is the focus of this review: [2]

Table 1. Henry's Law data for methane in water

Temperature °C	k_H (atm)	Concentration at saturation (mg/L)
10	28711	31.0
20	36140	24.6
30	43573	20.4

The methane-containing mixtures that are of interest from a wastewater perspective have relatively high methane concentrations – maybe even more methane than would be present in a saturated solution. This could result from two mechanisms: supersaturation, or the presence of bubbles. Both of these are non-equilibrium states and theoretical modelling of their behaviour is poor, so experimental investigations are usually required to determine the amount of methane dissolved.

Supersaturation may occur when an initially saturated mixture is formed at conditions allowing higher methane solubility, and is then exposed to different conditions – for example water saturated with methane at a depth of 6 m (pressure of 1.6 atm) would become supersaturated at a shallower depth of 2 m (pressure of 1.2 atm). Increases in the temperature of a solution, which causes a reduction in methane solubility, may also cause a supersaturated solution to form.

Methane bubbles are expected to form in a supersaturated solution, and their buoyancy usually means that they quickly rise to the surface and burst - however under some conditions the bubbles may remain in the solution for a sustained period. Very small bubbles rise much more slowly than larger bubbles – a 1mm bubble will rise at about 0.54 m/s, whereas a 1μm bubble rises one million times slower at 0.54 μm/s (Stoke's Law states that the settling velocity of a sphere is proportional to the square of the radius). Thus micron-sized bubbles can take hours to rise just 1cm, and so are effectively stationary within the fluid for most processes.

Bubbles may also become entrained in process streams as a result of the rheological properties of the fluid. The viscosity of sewage sludge varies widely depending upon composition and shear, but even relatively dilute sludges may still be over 100 times more viscous than water. [3] Some sludges also display a yield stress, meaning that they have solid-like properties (or infinite viscosity) unless sufficient stress is applied. [4] The rate at which bubbles rise is proportional to viscosity, so sludges may be more likely to retain bubbles by slowing or preventing their rise from buoyancy.

Industrial Examples of Removing Gases from Water

There are a range of motivations and processes for removing gases from water and aqueous solutions. Usually the purpose is to produce a 'purer' liquid without problems that may be associated with dissolved gases, but there are also examples where the gas is deliberately captured for further processing.

Removal of dissolved gas from wastewater is typically a passive process – the gases produced by microbial action are allowed to diffuse into the ambient air (either at the surface of a body of water, or through the aeration process). In some instances, such as Melbourne Water's Western Treatment Plant, the gas is collected by covers for later use or treatment, but it is rare that a deliberate process to actively minimise the amount of gas present in the water. Recent reports show that Vitens and Royal Haskoning (in the Netherlands) are currently developing a process and plant to remove and recover methane from untreated groundwater, with a view to using this methane as fuel. [5] The process will use vacuum de-aeration in a vessel filled with pall rings; the design is expected to recover 90-95% of methane while operating at 5kPa. [6]

Landfill leachate may contain high concentrations of dissolved methane, which may become a fire/explosion hazard as well as a source of greenhouse gas emissions. There is relatively little information in the literature about methods for recovering this methane, however a number of companies offer systems for treating leachate and claim up to 99% methane recovery. [7] [8]

In the semiconductor industry, and for research applications, high purity water is commonly degassed. Even small amounts of dissolved oxygen can oxidise the surface of silicon wafers used in microelectronics; [9] in research dissolved gases may cause unwanted reactions or contaminate samples for analysis. These industries are typically lower volumes of water use, and place high value on the effectiveness of degassing, meaning that effective but inefficient and expensive methods may be employed. Research applications may be primarily concerned with removal of reactive species such as oxygen, in this case bubbling nitrogen or addition of reductants such as hydrazine may be sufficient (if the resulting dissolved nitrogen or chemical impurities are acceptable). Other purposes require that all non-water components are removed (as far as practicable), for this purpose membrane contactors are often used with vacuum and/or an inert sweep gas of the opposing side of the membrane. [10] [11]

Feedwater for boilers is degassed to remove carbon dioxide and oxygen dissolved in the water, in order to prevent oxidization and corrosion of the system. [12] Conventional methods make use of mechanical deaeration at high temperature or under vacuum, [13] while recent research has proposed that membrane contactors reduce operating costs while allowing more compact deaerators by increasing contact area. [14]

Many of the proposed systems for carbon capture and storage make use of an aqueous solution of monoethanolamine (or a similar amine) to capture CO_2 from combustion gases. The resulting stream is an aqueous solution rich in CO_2, which must be regenerated by separating the solution into gaseous CO_2 and a lean (low CO_2) stream of aqueous amine. This regeneration usually involves heating the CO_2-rich solution, making use of the reduction in gas solubility with temperature as well as a reversible reaction between the amine and CO_2 molecules to drive the CO_2 into the gas phase. [15]

In winemaking, high levels of dissolved oxygen introduced during processing can lead to oxidation of the wine. For this reason it is common for wines to be sparged with nitrogen, stripping most of the dissolved oxygen. [16] [17]

Preventing unwanted bubbles from blocking print heads is critical in the printing industry, requiring methods for removing small bubbles and dissolved gases from the inks. This has been achieved by vacuum degassing in tanks, [18] sometimes using ultrasound to cause cavitation and improve performance. [19] More recently, membrane contactors are being developed and promoted for debubbling of inks. [18]

Vacuum

Maturity

- Generally well developed, used with groundwater but not wastewater.

Vacuum degasification is a well-established technology, with previous application in the water and wastewater industry. A range of literature, over 50 years old, reports the use of vacuum degassing to improve sludge settling in treatment of meat processing wastes, [20] and for the removal of gases such as hydrogen sulphide from drinking water. [21]

A plant for recovering methane from supersaturated groundwater is currently under development in Spannenburg in the Netherlands. This process sprays the water into a vacuum vessel filled with pall rings, and is expected to achieve 90-95% methane recovery. [6]

Applicability to wastewater

- May be some issues with fouling, but should be workable.

With prior use in treating groundwater and activated sludge degassing, vacuum-based technology is expected to be highly applicable to removing methane from wastewater. It may be possible to use a process similar to the design for Spannenburg, although the additional solids present in wastewater may require backwashing and/or air scouring to manage clogging of media. Very large solids, such as those found in unscreened wastewater, may present a larger problem for some forms of vacuum process.

Performance

- Good, will vary with pressure of and exposure to vacuum.

The performance of a vacuum-based process will vary depending upon the design, but potentially allows for very high levels of methane recovery (e.g. 90-95% predicted for Spannenburg). The degree of recovery would depend primarily upon the degree of vacuum the wastewaters is exposed to, as well as the surface area for mass transfer and contact time available.

As well as methane, it is expected that there will be other components present in the gas stream produced by a vacuum process: for example dissolved carbon dioxide may also be stripped, as well as any volatile organic compounds present. Enhanced water evaporation is also to be expected at low pressures. These additional ‘contaminant’ gases may mean that some treatment is required for the methane-rich stream before it is fit for use as a fuel.

Costs

- Capital cost is likely to be significant, at around $18 million; operating costs are uncertain.

Design and construction of a vacuum stripping process using 6 packed towers in the Netherlands to treat 3640 m^3/hr cost approximately €8 million for a process. [5] To treat 240 ML/day (25W at Western Treatment Plant) would require a system approximately 3 times this size – assuming capital cost scales exponentially with capacity with an index n=0.6, and converting currency at an exchange rate of €1=A$1.25, the overall cost is estimated at A$18 million.

Operating costs are likely to be dominated by the energy needed to create/maintain a vacuum in the vessels, as well as any pumping of water required. However, these costs may be partially or completely offset by energy generated using the methane and/or the avoidance of liability for emissions under Australia’s carbon pricing legislation.

Environmental and Social Aspects

- Use of vacuum technology means that any leaks in the system will tend to allow outside air in (rather than captured gases out) – this may mean the system creates relatively less odour than other options.
- Vacuum pumps may create some noise, although with suitable this is unlikely to have any impacts beyond treatment plant boundaries.

Sparging

Maturity

- Well established, commercial systems developed for stripping gas from landfill leachate.

Sparging is a widely used technique in fields ranging from water treatment to winemaking to scientific research. In research and winemaking it is common to sparge with nitrogen (or another inert gas) to displace dissolved oxygen from water, where the reactivity of oxygen is a problem.

In treating groundwater or landfill leachate, the purpose is to remove undesirable dissolved gases such as methane and ammonia from solution. For this purpose air is normally used as the stripping gas, with specialised vessels or towers to improve stripping efficiency. For example, the water treatment works at Spannenburg (being upgraded to vacuum degassing) currently use plate aeration to sparge methane-containing groundwater with air; [5] landfill leachate may be stripped of ammonia using packed bed columns. [22]

Applicability to wastewater

- Good, sparging is mechanically similar to aeration in wastewater treatment.

The technology to sparge wastewater is well developed, it is the method used for aeration in many wastewater treatment processes including Melbourne Water's Eastern Treatment Plant. This apparatus is normally used to allow oxygen to dissolve into the wastewater, but the rising air bubbles will also strip any other dissolved gases (such as methane or nitrous oxide). [23]

Performance

- Good, but dilution of the biogas (with sparge gas) may inhibit beneficial use.

Sparging with a different gas can, over time, remove almost all of a dissolved gas from solution. The current Spannenburg groundwater treatment plant strips methane from a supersaturated solution, reducing an influent concentration of 50 mg/L down to 0.3 mg/L (over 99% efficiency), [5] showing that sparging can achieve very good performance in removing dissolved methane.

The off-gas stream from a sparging process, if a significant fraction of the methane is to be recovered, will likely consist predominantly of the gas used for sparging. This may pose a problem for beneficial use of the stripped methane, unless the sparging gas can be separated and the methane enriched. The most readily available gas for stripping methane from wastewater is probably air, but this may be difficult to separate from the methane and poses risks of forming flammable/explosive gas mixtures.

A special case of sparging would be the use of captured biogas as a sparge gas. This would alleviate any problems of diluting the biogas or introducing oxygen, but with the drawback of lower methane recovery – only dissolved/entrained methane above the saturation level is likely to be recovered. In effect, this is a special form of agitation (discussed subsequently) where rising biogas bubbles provide the agitation.

Costs

- Uncertain, as design parameters not known. Expect medium CAPEX and OPEX.

Capital expenditure will depend upon the design chosen: whether towers are constructed, or a simpler aerated pond/tank is preferred. Construction of equipment for this process is likely somewhat cheaper than the cost of constructing a vacuum-based system, as the equipment need not withstand a vacuum – however more/larger equipment may be required to offset the lower efficiency of gas stripping.

Major operating costs are expected to be the energy required for pumping/blowing air, and also pumping of wastewater depending upon the design chosen.

Environmental and Social Aspects

- Any failure to capture and contain the sparged methane may allow other gases to escape, causing odour from the process.
- The blowers used to provide sparge gas are likely to be noisy (similar to other blowers at treatment plants).
- Energy used may have environmental impacts. However greenhouse gas emissions may be offset against any avoided methane emissions
- Potentially flammable/explosive gas mixtures

Membranes

Membrane degassing makes use of a microporous hydrophobic membrane to separate gas and liquid phases; the pores allow gas and vapour to escape from the liquid phase while retaining the bulk liquid. This is usually configured as a membrane contactor containing bundles of hollow membrane fibres; liquid runs through the shell side of the contactor (to minimise pressure drop) while the lumen side of the membrane contains vacuum or a sweep gas. [24]

Maturity

- Fairly mature technology, but maybe not widely used. Not previously applied to wastewater.

Membrane degassing has applications in producing ultra-high purity water for industries such as microelectronics, to reducing corrosion in boiler systems, and to remove bubbles from inks used in printing. However, it is not clear whether there are a significant number of large-scale industrial installations of membrane degassing units: manufacturers often promote trials and studies, whereas there are few reports of actual commercial installations.

Applicability to wastewater

- May not be suitable, especially for sludge or unscreened wastewater, as solids may cause fouling.

Membranes have been applied for various purposes in wastewater treatment. One major process is the membrane bioreactor, a modification of the activated sludge process where a membrane is used to retain solids while allowing treated effluent to leave the process. One of the major problems with this process is fouling, requiring frequent cleaning or replacement of the membrane; this has been alleviated by submerged membrane designs, where air bubbles (used for aeration) scour the membrane and reduce fouling. [25]

Despite this previous experience, it is unclear how much of this could translate to a membrane-based degassing process. Membranes for degassing will likely be made from different materials with different pore sizes, as they are designed to work at the gas-liquid interface rather than be surrounded by water, this may create unexpected problems. Fouling may also be a significant issue, as the air-scouring approach used in a membrane bioreactor is more difficult to employ in a degassing module; larger solids in unscreened wastewater, such as rags and hair, may become tangled around the membrane fibres and cause even greater difficulties. As a result, using membranes for degassing poorly-treated wastewater should be regarded as relatively unexplored territory.

Performance

- Potentially very good, if ideal operation is possible.

The degassing performance of membrane contactors can be extremely good – manufacturer's literature advertises that even relatively soluble CO_2 can be reduced to below 1ppm. [26] Aside from any technical issues specific to wastewater, it is likely that membrane degassing could remove essentially all dissolved methane.

Costs

- Capital cost is comparable to a simple vacuum process, with operating costs expected to be higher than a simpler process.

The cost of a Liqui-Cel 14x28 membrane contactor was quoted at US$20,000 in January 2013 with an additional US$300 for a mounting kit; this contactor is capable of liquid flow rates up to 90.8 m^3/hr. Adding an estimate of $500 for shipping, and converting currency at 1 AUD=1.05 USD, this unit would cost A$19,810. Thus, to treat 240ML/day at WTP would require 110 units, at an approximate cost of $2.2 million.[1]

The other major capital item will be vacuum pumps: assuming total recovery, 240 ML/day of liquid containing 30 mg/L methane will result in the production and pumping of 7200kg/day of methane. If the overall biogas is 70% methane, this requires pumps capable of handling approximately 11 m^3/min (2900 gallons/min). Cost curves show that a single stage, 500 gallon/min pump cost US$25,000 in 1998, so 6 pumps handling 11 m^3/min would cost US$150,000 in 1998. [27] Using the Marshall and Swift Cost index until 2000, followed by the Intratec Chemical Plant Construction Index until 2012, then converting to Australian dollars, present day cost is estimated at A$232,000.

The overall cost of the major equipment is thus $2.4 million, and applying a Lang Factor of 4.7 for a fluids processing plant, [28] the overall capital cost is estimated at $11 million.[2]

Operating costs are difficult to determine, as the behaviour of the membranes (and cost of replacement) is not known. However, the costs are likely to be higher than the cost of operating the conventional vacuum process: both processes require energy to create a vacuum, but maintaining and replacing membranes is likely to be more expensive than caring for relatively cheap packing media.

Environmental and Social Aspects

- If the process is developed to minimise the volume of air handled, this technology may be a quieter option than sparging or vacuum alternatives.
- Odour may again be an issue, depending on management of gas leaks.
- Energy used may have environmental impacts. However greenhouse gas emissions may be offset against any avoided methane emissions.

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[1] No scaling discount was applied: this system may require frequent scouring or backwashing, so a number of smaller units are likely to be preferable.

[2] This assumes no other major equipment is required.

Ultrasonication

Ultrasound (sound with frequency above 20kHz, inaudible to humans) may be used to assist in degassing of liquids. In a liquid ultrasound causes cycles of high and low pressure, and the low pressure part of the cycle causes the nucleation of bubbles. Once formed, these bubbles attract other dissolved gas molecules and as they grow they rise in the liquid and leave the solution.

With suitable design, ultrasound can be used to degas a liquid far below the equilibrium dissolved gas concentration. [29] This makes use of the fact that ultrasound is constantly promoting bubble formation (and degassing) throughout the liquid, while dissolution of the gas phase (which would re-establish equilibrium) may be slower if there is a limited contact area.

Maturity

- Limited maturity, especially for industrial scale degassing.

Ultrasound is widely used on a laboratory scale for basic processes such as cleaning and degassing. More advanced applications, where ultrasonication is used to improve reaction kinetics or extraction of bioactive compounds, are at an intermediate stage of development – there has been extensive research, as well as some pilot trialling, but there is little evidence of full-scale industry adoption. [30] One of the more advanced applications is in the use of ultrasound for the manufacture of biodiesel, with reports of facilities producing up to 6 million gallons per year using ultrasound to dramatically improve the speed of reaction. [31]

Applicability to wastewater

- Good, previously used in treating wastewater sludge prior to digestion.

Ultrasound has been used to process a variety of fluids, including water, fruit juice, sewage sludge, and biodiesel. [32] Use with sludge has ranged from laboratory-scale studies through to full-scale trials treating up to 190 m^3/day. [33] Thus, the treatment of wastewater by ultrasound appears to be technically feasible.

Performance

- Moderate to good – ultrasound can strip some but not all dissolved gases.

Ultrasound may achieve final concentrations below saturation, but will not remove all gas from a solution. Based on figures in literature and on manufacturer's websites, it appears that concentrations around 20% of saturation may be achieved. [29] [34] This suggests that a methane solution at 20°C, in contact with biogas (80% methane) at 1 atm pressure, could achieve an effluent methane concentration of 3.8 mg/L. If the feedwater initially contained 30mg/L, this is means the potential recovery is 88%.

Costs

- OPEX very high due to energy requirements, CAPEX also very high - but limited data is available to produce cost estimates.

The energy requirements for ultrasonic degassing of wastewater are uncertain, but may be estimated by several routes. According to an equipment manufacturer, a 10kW ultrasound device may be used to treat up to 10 m^3/hr of liquid. [35] For the flowrates handled in the 25W process at WTP (240ML/day, or 10,000m^3/hr), this suggests that 10MW of ultrasonic power would be required. Assuming an electricity price of $100/MWh (typical for electricity imported to WTP), this amount of electricity would cost approximately $9 million – the real figure may well be higher if the power quoted is actual sonic power and ultrasound generation is not 100% efficient.

An alternate estimate may be based around data from the ultrasonic treatment of wastewater sludge prior to digestion. This work used 5×3 kW ultrasound units to treat up to 190 m^3/day of sludge. [33] Scaling to 240 ML/day would thus require 19 MW of ultrasonic power, at an annual electricity cost of

$17 million. However the power requirements for degassing may be lower than the requirements for cell disruption, so it is possible that lower power may be effective.

Both of the above calculations were for general applications of ultrasound, rather than specific data about degassing. An alternative estimate may then be made by extrapolating laboratory degassing research to a larger scale. This research shows that 200 mL of solution may be significantly degassed by applying 16 W of ultrasonic power for 10 minutes (although higher power was required to achieve the best degassing performance). [29] The flow in 25W at WTP in 10 minutes is ~1.7 ML (~8 million times the volume used in the laboratory study) so scaling the specific power input (and allowing for 85% electroacoustic efficiency) leads to an electricity requirement of around 157 MW to operate the ultrasound system.

Capital cost estimates are difficult, as there is no precedent for the manufacture or purchase of a system with this power. The largest systems encountered during the literature review are 16kW units, and a quotation of €1.5 million was obtained for 10 of these units (which included a volume discount). However even the smallest estimate of a 10 MW system will require 625 units, leading to a cost estimate of €94 million, or A$119 million for the ultrasound units alone.

Environmental and Social Aspects

- Ultrasonic noise may have undesirable health effects at high volumes, requiring that any process be designed to manage or attenuate the noise.
- The very large amount of energy used may have environmental impacts.
- This process is likely to use more energy than can be generated from the methane captured. Thus it is likely to increase overall electricity demand for the site.
- Only likely to achieve partial methane recovery, the remaining gas is likely to be emitted to the atmosphere.

Agitation

Although not conventionally used as a degassing technique, agitation through mixing, spraying or flowing over a weir may allow a substantial reduction in the amount of methane present in wastewater. Agitation increases the movement of any bubbles present in the wastewater, increasing the rate at which the bubbles coalesce; as they grow, larger bubbles will rise to the surface of the liquid.

Agitation will also increase the area contact area between the liquid and the gas phase, allowing the system to reach equilibrium more rapidly. This means that an initially supersaturated solution will lose dissolved gas until it achieves a balance with the gas phases as dictated by Henry's Law.

Maturity

- Untested, but expected to be easy to develop and implement.

This method has not had any previous application to wastewater or similar systems. However the basic ideas are well known: shaking a bottle of soft drink (supersaturated with carbon dioxide) will cause it to fizz violently as the gas exits the liquid, while stirring sugar or salt causes it to dissolve more rapidly. Although there is no precedent, this would not be a complicated or highly technical solution.

Applicability to wastewater

- Easily applied to wastewater, thicker sludges may be more challenging.

These methods can easily be applied to wastewater. Surface aerators are an example of agitation (although normally applied to increase the amount of dissolved gas); other forms of mixing may also be adopted. Construction of a weir is a well-established process, seen in in many rivers, although adapting an existing process to allow for the requisite drop in water levels may be challenging.

Performance

- Moderate-Low, only applicable to streams with very high methane content.

Methane recovery will be limited; agitation is only likely to remove bubbles and the supersaturated portion of the dissolved methane. For wastewater at 20°C, in contact with biogas (80% methane) at 1 atm pressure, the equilibrium amount of dissolved methane is approximately 18.9 mg/L. If the feedwater contained 30mg/L, the potential recovery would be 37%. This is relatively low recovery compared to many of the other processes considered, however it is also likely to require much less energy to operate (potentially no energy, in the case of a weir).

It may be possible to combine agitation with another method, such as vacuum technology. The use of a vacuum will allow much more methane to be recovered (as the equilibrium favours less dissolved methane) while the improved mass transfer of a spray or a falling film allows for a reduction in the size of the equipment needed.

Costs

- Moderate-Low, will depend on method chosen and integration with process.

A weir is the simplest form of agitation, and would be dominated by the cost of constructing the weir with negligible operating costs. An indication of cost may be drawn from a 2011 study by Aurecon Australia into developing weirs on the Torrens River. [36] The study estimated that the construction of 16 weirs along the river, each 4m high, would cost approximately $8.4 million. These weirs are estimated to average ~15m in width (satellite images suggest the river is approximately 10-20m wide in the relevant area), compared to the ~150m width of the covered section of the 25W anaerobic pot. Using the difference in width, and the number of weirs, to scale the costs leads to an estimated cost of $5.3 million to construct a weir 150m wide and 4m high. However, actual costs may be significantly higher - working in a sewage treatment environment is likely to introduce additional complication over construction on a river.

Alternately, vigorous mixing and good gas transfer may be achieved with a surface aerator or similar device. Depending upon the results of a suitable trial, the flows may be passed through a covered pond containing the aerator. Taking the example of flow from the 25W anaerobic pot passing through a 2m deep pond with a surface area of 400 m^2, this would provide for an average hydraulic residence time of ~6 min. Total capital costs are estimated at approximately $430,000: $110,000 to construct the pond[3], $200,000 to put in place covers and associated infrastructure[4], and $120,000 for a 110kW surface aerator[5]. Operating costs will be predominantly the electricity required to run the aerator: a 110kW unit operating continuously for one year would require 964 MWh of electricity, at $100/MWh this means annual operating costs would be around $100,000.

Environmental and Social Aspects

- If gas is not captured effectively, agitation may cause odour problems.
- Depending on source, energy used may have environmental implications.
- Only likely to achieve partial methane recovery, the remaining gas is likely to be emitted to the atmosphere.

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[3] Flinders University budgeted $55,000 to construct 2 shallow algal ponds, each 500m^2. The proposed pond, although a smaller area than either algal ponds, is deeper – this depth will make construction more difficult, so the budget was doubled.

[4] This is 0.5% of the budget assigned to the 55E cover replacement (WP2 budgeted $16.2 million, then WP3 noted an additional $24.8 million), reflecting that a 20×20m pond is approximately 0.5% of the area covered on 55E (roughly 200m×400m).

[5] Cost of the 110kW aerators recently purchased by Melbourne Water, provided by Nick Skinner.

Heading

It is unlikely that heating will be a suitable method for methane recovery from wastewater. The brief analysis below suggests this method would incur very high operating costs with relatively poor methane recovery, so no further assessment was undertaken.

Performance

- Moderate, best suited to streams with high methane content

The performance of a heat-based approach is poor, unless extremely high temperatures are employed (above the boiling point of water). Data shows that the solubility of methane in water at 20°C is 24.6mg/L, and even after heating this solution to 85°C (the limit of the data set used) the solubility of methane at saturation is 13.0 mg/L [2] – meaning that over half of the methane could remain in solution.

Costs

- OPEX will be extremely high, due to energy required for heating.

Even assuming the use of high effectiveness (ε=0.9) heat exchangers to recover thermal energy in the process, [37] the energy demand of a temperature-based methane recovery process is enormous. To treat 1ML of wastewater by heating from 20°C to 85°C requires 272GJ of energy, with 90% heat recovery this becomes 27.2GJ. Large scale implementation becomes prohibitive: treating 480 ML/day (the flow to Western Treatment Plant) would require 13041GJ/day, or a constant energy supply of 151MW. If this energy was supplied as natural gas at a price of $9/GJ, the annual cost of energy alone would be approximately $43 million. As a result, this process is unlikely to be suitable for implementation unless a source of waste heat (for which there is no other more beneficial use) is readily available.

No detailed capital cost estimate was developed for a heating process, as the extremely high operating costs are likely to dominate any economic assessment. However, the process operates at atmospheric pressure with moderately complex equipment – so it is likely to be less expensive to construct than e.g. a vacuum process.

Evaluation of Options

The preceding review has considered 6 possible technologies for removing methane from wastewater. Treatments based on ultrasonication or heating of the wastewater seem to be unsuitable, as both have extremely high energy requirements that will make operation very expensive. This leaves 4 potential technologies: vacuum, sparging, membranes, and agitation. These can then be assessed for their suitability to treat the two main types of methane-containing stream at Melbourne Water: partially treated wastewater leaving the anaerobic pots at WTP (low solids), and the digested sludge produced at ETP (high solids).

It is important to note that any recovery solution is located as near as possible to the end of the anaerobic treatment process, with minimal contact between the untreated effluent and the atmosphere. Too much handling or processing before the methane is extracted may mean some methane is displaced from solution and emitted/lost, while it is preferable that the treated effluent (low in methane) is not returned into an anaerobic environment where further methane will be produced.

Vacuum degassing is a well-established technology that has been applied across a range of industries. There is also precedent for use in removing methane from water (although not wastewater) with the facility currently under construction at Spannenburg in the Netherlands. Using this technology should result in the recovery of most of the dissolved/entrained methane, in a stream with a relatively high methane content that can easily be used as fuel. This process may be more difficult to apply to sludge than to watery streams, as it may be difficult to achieve a suitably large area for mass transfer (sludge may block packed beds or spray towers).

Sparging is also a well-established technology in the wastewater industry, where it is typically used to aerate wastewater. The technology has seen previous use for removing dissolved gases from water: it is the ‘old’ technology used to remove methane at the Spannenburg treatment facility, and sparging is also used to remove ammonia and methane from landfill leachate. Sparging can be easily applied to low solids streams, and should also work for high solids streams unless the sludge is so viscous or solid-like that bubbles no longer effectively rise to the surface. One drawback of this technique is that methane is likely to be only a minor constituent of the gas stream produced, which will be dominated by the gas used for sparging; this may inhibit the use of the methane as a fuel, unless additional processing is used to concentrate/enrich the recovered gas.

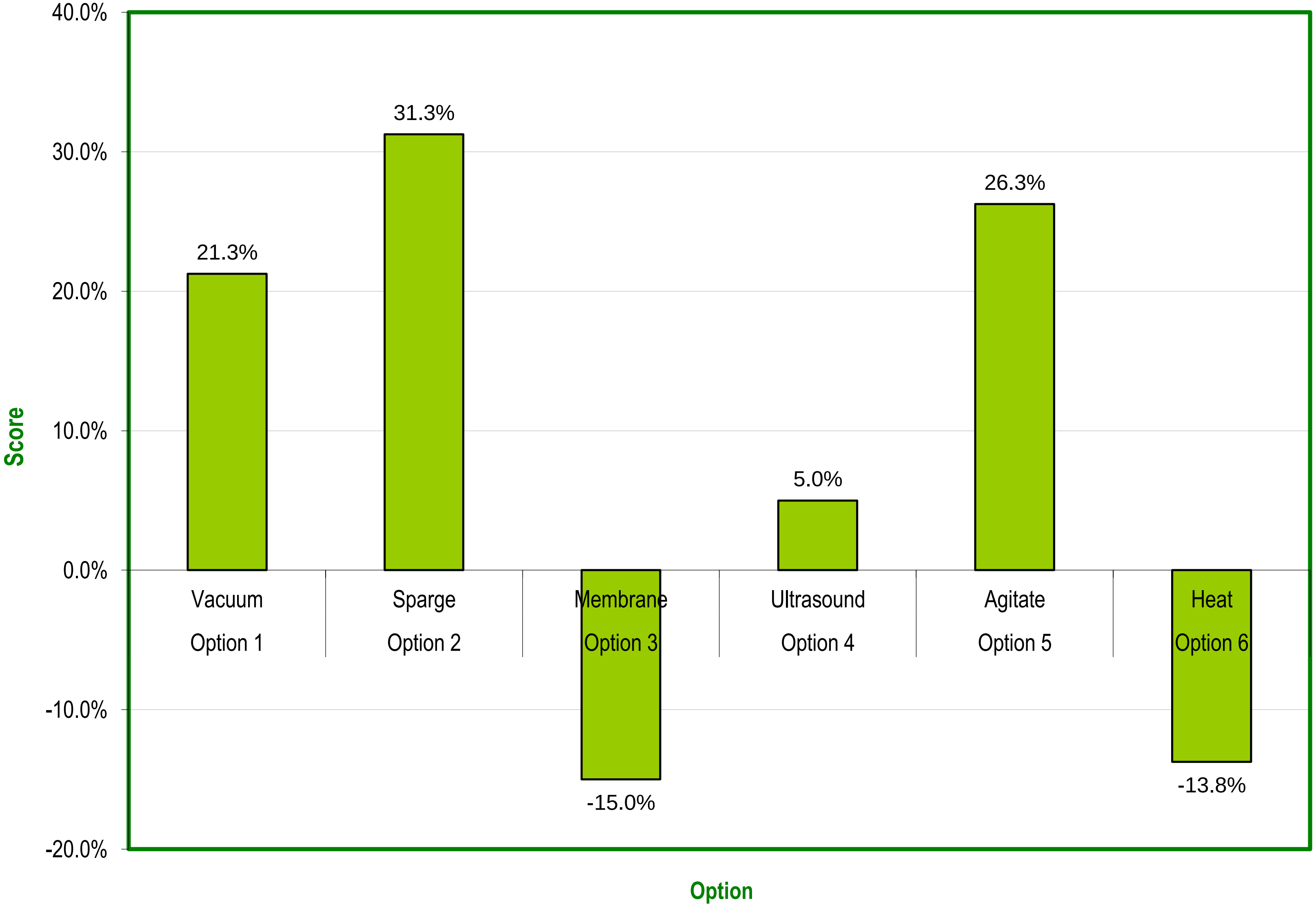
Agitation is a relatively simple process, and should be applicable to both water and sludge – although achieving sufficient agitation of sludge may be more difficult. This method may be able to be employed at relatively low cost, and the gas stream collected would be high in methane and easily utilised. However, only limited recovery of methane could be expected: the component of dissolved or entrained methane above the saturation point.

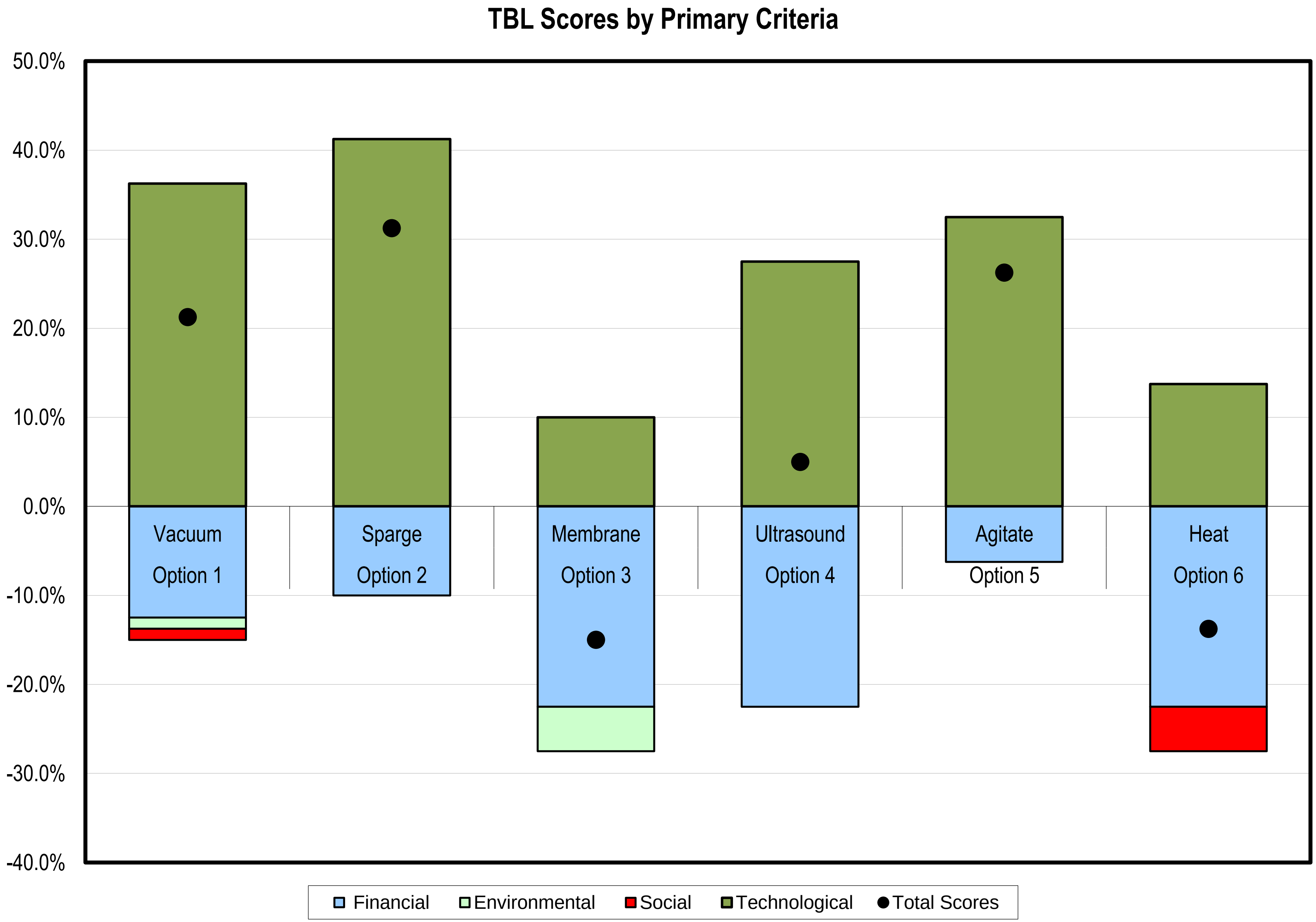
Membrane-based degassing can achieve very good performance, however it is a relatively new technology with no closely related applications in the wastewater industry. As a result, this is the most speculative of the possible technologies reviewed. The major concern with the use of membranes will be fouling: the high solids content means that it is unlikely that membranes will be suited to recovering methane from sludge, and even more watery streams may still cause too much fouling for an effective recovery system.

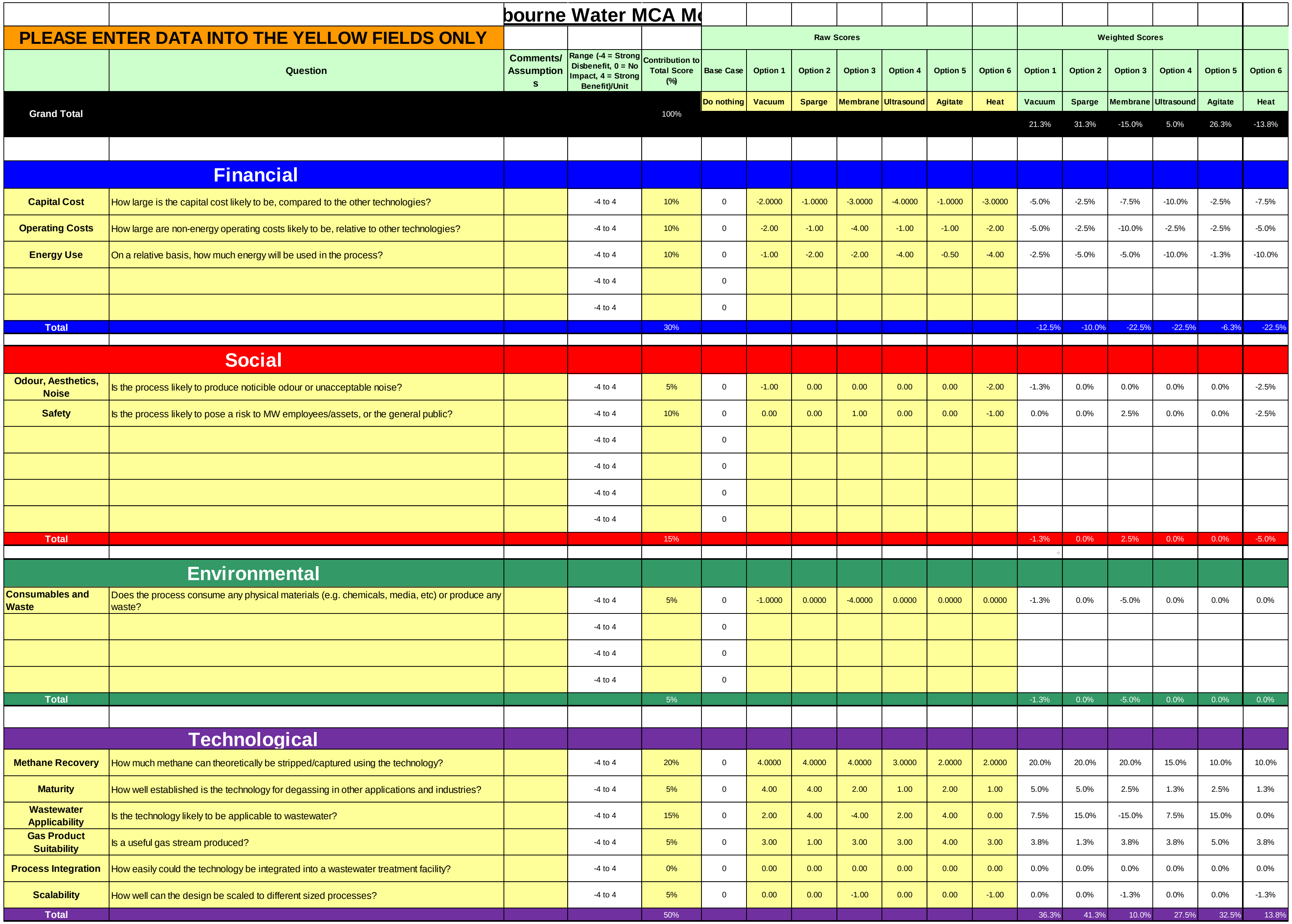
Table 2. Summary of key data for different methane-recovery technologies

	CAPEX ($m)	OPEX (Excluding Energy)	Energy Use	Maximum CH4 Recovery (from 30mg/L)	Process Notes	Other Notes
Vacuum	High (~$18 million)	Medium (packing may need replacement)	Medium	95%	Fouling may be an issue, need to backwash/scour packing.	
Sparging	Medium-High (less than vacuum?)	Low	Medium-High	99%		Gas stream will be diluted by sparge gas
Membrane	Medium-High ($11 million)	High (need to maintain/ replace membrane)	Medium	100%	Fouling likely to be an issue, may be severe with higher solids.	
Ultrasonic	V. High ($119 million)	Low	V. High (Electricity for ultrasound)	88%		
Agitation	Low-Medium ($0.5-5 million)	Low	Low-Medium	<50%		
Heat	Medium-High (Not costed)	Low	V. High (Gas for heating)	50%		

Total TBL Scores




TBL Scores by Primary Criteria
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
-10.0%
-20.0%
-30.0%
-40.0%
Vacuum
Option 1
Sparge
Option 2
Membrane
Option 3
Ultrasound
Option 4
Agitate
Option 5
Heat
Option 6
Financial
Environmental
Social
Technological
Total Scores



		bourne Water MCA M															
PLEASE ENTER DATA INTO THE YELLOW FIELDS ONLY					Raw Scores							Weighted Scores					
	Question	Comments/ Assumptions	Range (-4 = Strong Disbenefit, 0 = No Impact, 4 = Strong Benefit)/Unit	Contribution to Total Score (%)	Base Case	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Grand Total				100%	Do nothing	Vacuum	Sparge	Membrane	Ultrasound	Agitate	Heat	Vacuum	Sparge	Membrane	Ultrasound	Agitate	Heat
												21.3%	31.3%	-15.0%	5.0%	26.3%	-13.8%
Financial																	
Capital Cost	How large is the capital cost likely to be, compared to the other technologies?		-4 to 4	10%	0	-2.0000	-1.0000	-3.0000	-4.0000	-1.0000	-3.0000	-5.0%	-2.5%	-7.5%	-10.0%	-2.5%	-7.5%
Operating Costs	How large are non-energy operating costs likely to be, relative to other technologies?		-4 to 4	10%	0	-2.00	-1.00	-4.00	-1.00	-1.00	-2.00	-5.0%	-2.5%	-10.0%	-2.5%	-2.5%	-5.0%
Energy Use	On a relative basis, how much energy will be used in the process?		-4 to 4	10%	0	-1.00	-2.00	-2.00	-4.00	-0.50	-4.00	-2.5%	-5.0%	-5.0%	-10.0%	-1.3%	-10.0%
			-4 to 4		0												
			-4 to 4		0												
Total				30%								-12.5%	-10.0%	-22.5%	-22.5%	-6.3%	-22.5%
Social																	
Odour, Aesthetics, Noise	Is the process likely to produce noticible odour or unacceptable noise?		-4 to 4	5%	0	-1.00	0.00	0.00	0.00	0.00	-2.00	-1.3%	0.0%	0.0%	0.0%	0.0%	-2.5%
Safety	Is the process likely to pose a risk to MW employees/assets, or the general public?		-4 to 4	10%	0	0.00	0.00	1.00	0.00	0.00	-1.00	0.0%	0.0%	2.5%	0.0%	0.0%	-2.5%
			-4 to 4		0												
			-4 to 4		0												
			-4 to 4		0												
			-4 to 4		0												
Total				15%								-1.3%	0.0%	2.5%	0.0%	0.0%	-5.0%
Environmental																	
Consumables and Waste	Does the process consume any physical materials (e.g. chemicals, media, etc) or produce any waste?		-4 to 4	5%	0	-1.0000	0.0000	-4.0000	0.0000	0.0000	0.0000	-1.3%	0.0%	-5.0%	0.0%	0.0%	0.0%
			-4 to 4		0												
			-4 to 4		0												
			-4 to 4		0												
Total				5%								-1.3%	0.0%	-5.0%	0.0%	0.0%	0.0%
Technological																	
Methane Recovery	How much methane can theoretically be stripped/captured using the technology?		-4 to 4	20%	0	4.0000	4.0000	4.0000	3.0000	2.0000	2.0000	20.0%	20.0%	20.0%	15.0%	10.0%	10.0%
Maturity	How well established is the technology for degassing in other applications and industries?		-4 to 4	5%	0	4.00	4.00	2.00	1.00	2.00	1.00	5.0%	5.0%	2.5%	1.3%	2.5%	1.3%
Wastewater Applicability	Is the technology likely to be applicable to wastewater?		-4 to 4	15%	0	2.00	4.00	-4.00	2.00	4.00	0.00	7.5%	15.0%	-15.0%	7.5%	15.0%	0.0%
Gas Product Suitability	Is a useful gas stream produced?		-4 to 4	5%	0	3.00	1.00	3.00	3.00	4.00	3.00	3.8%	1.3%	3.8%	3.8%	5.0%	3.8%
Process Integration	How easily could the technology be integrated into a wastewater treatment facility?		-4 to 4	0%	0	0.00	0.00	0.00	0.00	0.00	0.00	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Scalability	How well can the design be scaled to different sized processes?		-4 to 4	5%	0	0.00	0.00	-1.00	0.00	0.00	-1.00	0.0%	0.0%	-1.3%	0.0%	0.0%	-1.3%
Total				50%								36.3%	41.3%	10.0%	27.5%	32.5%	13.8%

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