POTENTIAL CONTRIBUTIONS OF THE WASTEWATER SECTOR TO NEW ZEALAND'S ENERGY SUPPLY

Heubeck, S., deVos, R. and Craggs, R.
National Institute of Water and Atmospheric Research Ltd. (NIWA)

ABSTRACT

Wastewater treatment can either be energy intensive, or provide an energy resource. A small shift in the selection of treatment technologies can significantly affect the energy profile of the NZ wastewater sector. Based largely on analysis undertaken by the EnergyScape programme, a model was developed to test the upper limits of the potential energy contributions of the wastewater sector from currently available technologies, such as: anaerobic digestion, fermentation and algal production. The model identified that the upper limit of technologically feasible energy resource potential from current wastewater flows was: 0.91 PJ/y (~253 million kWh/y) electricity; 1.09 PJ/y boiler fuel / heat; 1.04 PJ/y (~27 million litres diesel equivalent) gaseous transport fuel (compressed bio-methane), and 0.70 PJ/y (~32 million litres) liquid transport fuel (bio-ethanol). This study suggests that New Zealand has much to benefit from a better understanding of available wastewater treatment options – be that in the form of energy self-reliance, energy storage or economic return. Increased uptake of energy yielding wastewater treatment technologies is likely to be dependent upon either: high fossil fuel prices; sustained government incentives for the use of alternative energy; or regulatory requirements for improved control of odour, GHG emission and nutrient discharge.

KEYWORDS

Wastewater, Energy, Biogas, Ethanol, Algae, Nutrients

1 INTRODUCTION

The energy intensity of wastewater treatment processes has become an important planning parameter for designers and engineers in the wastewater industry, and many efforts to reduce energy consumption of existing installations have been undertaken over the last decades (Metcalf and Eddy, 1991). What is not generally recognised is the potential for wastewater to be an energy resource. In this paper, we use the findings of the EnergyScape programme (Scion, 2008) to describe and quantify the potential bio-energy resource of New Zealand's wastewaters. The first section of this paper reviews the technology pathways applicable to wastewater resources in New Zealand. We then consider the current contribution of wastewaters to New Zealand's energy supply. Finally, we evaluate the technical energy resource potential of wastewaters in New Zealand.

2 ENERGY RECOVERY TECHNOLOGY PATHWAYS

A wide range of wastewater treatment technologies are capable of recovering energy, whilst providing improved treatment efficiency and effectiveness. Some of the technologies considered are:

- Anaerobic digestion to biogas
- Fermentation to alcohols
- Algae production to biogas
- Algae production to liquid bio-fuels
- Microbial electrolytic cells

In reviewing these technologies, we considered technical feasibility, impact of scale, energy yield potential, as well as the potential co-benefits such as: reduction in odour, reduction in GHG emissions, and improved nutrient removal.

2.1 Anaerobic digestion to biogas

Anaerobic digestion of wastewater solids to biogas is the dominant technology for extracting energy from wastewater. Anaerobic digestion can be applied to almost all wastewaters, and is an integral part of the wastewater treatment plants serving New Zealand's larger cities. Anaerobic digestion reduces volatile solids (VS) and biochemical oxygen demand (BOD_5) of wastewaters and converts nutrients into forms suitable for tertiary treatment and / or nutrient recovery (Metcalf and Eddy, 1991; Henze et al., 1995). Primary and secondary sludge is digested in mesophilic or thermophilic heated mixed digesters, and the biogas collected and used on site. Other anaerobic digestion technologies such as UASB (Up-flow Anaerobic Sludge Blanket) and anaerobic filters are not widely used in New Zealand, but rely on the same biochemical principles and offer similar potential for the recovery and utilisation of biogas (Metcalf and Eddy, 1991).

Anaerobic digestion is also an integral process within wastewater stabilisation pond systems. Currently, much of the biogas produced by pond systems in New Zealand is vented to the atmosphere, thereby wasting a potential energy source, and contributing to odour and GHG emissions. In contrast, agricultural industries in Europe and America have been capturing this resource with covered anaerobic ponds for several decades. Recently, capture of this resource has been successfully demonstrated under New Zealand conditions, with the use of simple and reliable anaerobic pond covers on dairy farm and piggery effluent ponds (Heubeck and Craggs, 2009). This demonstrates the potential to implement anaerobic pond technology for domestic wastewater treatment in New Zealand, which previously has not been recommended due to potential odour concerns.

Captured raw biogas generally consists of 55 % to 68% methane (CH_4) and typically has an energy content of 18 to 23 MJ/m³ (NCV). In addition to carbon dioxide (CO_2), biogas often contains trace amounts of hydrogen sulphide (H_2S), ammonia (NH_3) and siloxanes (R_2SiO). Raw biogas can be used directly for low-tech applications such as boiler fuel, but the impurities can damage more complicated gas utilisation equipment such as compressors and engines. If biogas is to be used as a natural gas substitute or vehicle fuel, then intensive purification is generally required. Purification removes the majority of trace impurities as well as the majority of carbon dioxide. The upgraded high purity fuel is essentially identical to natural gas, and can be used for: electricity generation, combined heat and power (CHP) generation, vehicle fuel (in CNG vehicles), or be injected into the natural gas pipeline network (Molloy, 2008). Although the use of biogas as vehicle fuel and a renewable alternative to natural gas in pipeline networks is becoming increasingly common in Europe, there are currently no such schemes in New Zealand.

2.2 Fermentation to alcohols

Substantial reductions in VS and BOD_5 can be achieved with alcohol fermentation technologies. Application of the technology is restricted to sugar rich wastewaters as yeast cultures, other than microorganisms involved in anaerobic digestion, are unable to ferment more complex carbohydrate substrates (Metcalf and Eddy, 1991; Henze et al., 1995).

The New Zealand dairy industry produces a sugar (lactose) rich wastewater (termed 'whey') which can be fermented into ethanol by yeast cultures under anaerobic conditions. Distillation is used to recover ethanol from the whey fermentation beer, co-producing spent liquor and almost pure carbon dioxide. Most of the whey derived ethanol currently produced in New Zealand is used within the food, cosmetic and pharmaceutical industries, however limited volumes of this ethanol have been blended into petrol and retailed as E10 (10% bio-ethanol blended with 90% petrol) (Thiele and Clarke, 2007). Ethanol fermentation only destroys ~50% of the VS load of whey and whey like wastewaters - the residual VS is retained in the spent liquor. This spent liquor is a potential feedstock for anaerobic digestion, which has been used for biogas production. The combination of ethanol fermentation and anaerobic digestion of whey and whey like wastes has been practiced in New Zealand by Fonterra at Tirau for over two decades.

Sugar rich wastewaters can also be fermented by bacteria to yield a range of products that includes: bio-butanol, acetone, organic acids as well as hydrogen (H_2) and carbon dioxide. Analogous to ethanol production, bio-butanol is recovered from the fermentation beer via distillation producing spent liquor. The spent liquor from this process is also a suitable anaerobic digestion feedstock.

Bio-butanol has a higher volumetric energy density than bio-ethanol, and is easier to handle and integrate with the established petroleum infrastructure, since it can be blended into both petrol and desel. Large quantities of bio-butanol were produced commercially in many western countries prior and during the Second World War, but there has subsequently been very little work on this technology (Gapes, 2009). More research and development is required before the bio-butanol process can be considered a reliable and applicable technology for the New Zealand wastewater industry.

2.3 Algae production to biogas

Algae based wastewater treatment technologies offer an energy efficient and potentially low cost mechanism for wastewater nutrient removal. Conventional facultative and aerobic waste stabilisation ponds (WSP) fix wastewater nutrients into algal biomass with areal algal productivity of typically 1 to 5 g/m^2/d. By comparison production of algal biomass in High Rate Algae Ponds (HRAP) can achieve areal algal productivities of up to 20 g/m^2/d (Heubeck and Craggs 2007). The much higher areal algal productivity has several advantages, namely: more nutrients are fixed into algal biomass; produced algae are colonial, non-motile and therefore, easier to harvest. An alkaline pH shift induces ammonia volatilization and phosphorus precipitation (Nurdogan and Oswald, 1995; Green et al., 1996; Craggs et al 1998). These differences mean that while harvesting algae from conventional WSP is relatively difficult, harvesting of algal biomass from HRAP can effectively be achieved with relatively simple means (Craggs et al., 2009).

This technology has particular relevance for smaller municipal wastewater treatment facilities that are not land constrained (Craggs et al 1998; Craggs et al 1999). The harvest of algae removes nutrients assimilated into algal biomass from the wastewater for beneficial use. New Zealand has a large number of facultative and aerobic waste stabilisation ponds (WSP) that fix wastewater nutrients into algal biomass. Unfortunately, the vast majority of this algal biomass is not recovered – rather being released into downstream waterways, and therefore not recovering either energy or nutrients. As tightening wastewater discharge standards make it increasingly difficult for conventional WSP to remain compliant, HRAP could provide an upgrade option, resulting in an increase in the volume of algal biomass available for energetic utilisation.

Algal biomass is a unique and very versatile feedstock offering many energetic utilisation pathways (Sheehan et al., 1998). A simple and established technology for extracting energy from algal biomass is anaerobic digestion. Given that many wastewater treatment plants already incorporate anaerobic digestion facilities, the algal biomass can be directed to these facilities with minimal cost / modification.

2.4 Algae production to liquid bio-fuels

Algal biomass consists of sugars, carbohydrates, lipids and fats, which may be converted into liquid fuels via a number of pathways.

1. The sugar and simple carbohydrate components can be fermented to alcohols as described above.
2. The fat and oil components that can be extracted from algal biomass are suitable for the manufacture of biodiesel (Sheehan et al., 1998).
3. The total biomass can be converted into a bio-crude oil using super-critical water conversion.

Both the alcohol and biodiesel pathways have been (and are still) the subject of intense research efforts, particularly in the USA (Sheehan et al., 1998), however neither pathway is used at commercial scale.

The super-critical water conversion (SCWC) of algae to bio-crude process involves subjecting algal biomass with water to temperatures and pressures above the critical point of water (374 °C and 221 bar). Under these conditions the building blocks of algal biomass are broken down to short polymers, which are de-oxygenated, hydrogenated and cracked to yield a mixture of mostly aliphatic short to medium chained hydrocarbons, similar to high quality crude oil, and inorganic plant nutrients dissolved in the spent reaction water. Algal biomass is ideally suited to this process due to its low lignin content. The technology has been developed to pre commercial-scale in New Zealand (Heubeck and Craggs, 2007), and further research and development is underway to develop this technology as an energy pathway for wastewater treatment plants.

2.5 Microbial electrolytic cells

Recent laboratory studies have shown that wastewaters may be a suitable substrate for the operation of microbial electrolytic cells. In such cells, simple organic substrates such as sugars or organic acids are utilized by aerobic microbes, to generate a voltage difference between two conductor plates. With appropriate engineering techniques it may be possible to utilize the direct current (DC) generated by these cells at large scale. Besides raw wastewater, anaerobic digestion intermediates such as acetic acid may provide further potential substrates for microbial electrolytic cells. This technology is currently only operating under laboratory conditions and it is not clear if issues such as microbial cross-contamination and corrosiveness of the wastewater can ever be mitigated to a degree that would allow microbial electrolytic cells to use organic wastewaters as a feedstock at large scale.

3 CURRENT ENERGY CONTRIBUTIONS FROM WASTEWATER

In order to assess the overall current and potential future contributions of the wastewater sector to New Zealand's energy supply, a model which could match appropriate wastewater treatment pathways with resource potentials was required. When describing the current contributions, the wastewater treatment pathways are relatively well known, hence the focus is on defining the resource potential.

Several of the reports that were generated by the EnergyScape programme where used to assess the resource potential, in particular the "Energy Options for New Zealand – Situation analysis" report (Scion, 2008) and associated resource assessments by Thiele and Clarke (2007) and Heubeck and Craggs (2007). These reports considered the energy potential of (agro-) industrial effluents, farm wastewaters and manures, municipal wastewaters, as well as, the resource potential of algal biomass grown on nutrients provided by these waste streams. It should be noted, that it was sometimes difficult to differentiate between wastewater and other putrescible wastes and to distinguish between economically and technically recoverable resource potential.

In order to define generic energy utilisation pathways for these resources, the EnergyScape analysis segregated the resources into three categories: Large / medium scale wastewater; small scale wastewater, and sugar rich wastewaters. For each resource, the quantity of primary resource was apportioned to several likely (or known) treatment pathways, each with recognised and described energy conversion efficiencies. The resulting overview of the current energetic utilisation of wastewater resources in New Zealand is given in Figure 1. Large scale municipal wastewater treatment facilities are currently the main producers of bio-energy from wastewater biomass (Figure 1). From the ~67,000 t/y of volatile solids (VS) treated at large scale facilities, anaerobic digestion can recover ~0.64 PJ/y as raw biogas. Since this raw biogas is almost exclusively used for on-site generation of heat and power, approximately 0.20 PJ/y (~53 million kWh/y) of electricity is generated. The waste heat is mostly used to maintain the digester temperature.

Dairy factory and meat works wastewaters contain nearly 0.28 PJ/y of primary energy, which when subject to anaerobic digestion in anaerobic ponds yields ~0.14 PJ/y or biogas. The majority of biogas produced in these facilities is currently either flared or vented to the atmosphere. Only one agro-industrial wastewater treatment facility currently recovers biogas – this facility uses the ~0.06 PJ/y of recovered biogas as boiler fuel for steam raising. Most raw dairy factory and meat works wastewaters in New Zealand are initially treated in dissolved air floatation (DAF) unit, which can remove up to 70% of the total VS contained in the wastewater stream in the form of a concentrated sludge. Currently almost all of this DAF sludge (~1.16 PJ/y) is either used as stock feed, composted or land filled. Also the majority of paunch grass recovered at meat works is currently composted or land filled and could alternatively be utilized for anaerobic digestion, preferably in combination with DAF sludge, thus increasing the total primary energy potential of wastewater solids from agro-industries which is currently land filled or composted to 1.34 PJ/y.

Little energy is currently recovered from small scale wastewater treatment operations, treating agricultural wastewaters and manures (i.e. cow shed effluent and piggery wastewater) or smaller municipal wastewater volumes. These smaller scale set-ups mainly employ conventional WSP or mechanically aerated pond technologies and / or land irrigation. A large proportion of the VS contained in these wastewater streams (representing a primary energy potential of 4.40 PJ/y) is degraded aerobically (potentially requiring energy for mechanical aeration) with the remainder being treated in conventional WSP without biogas capture.

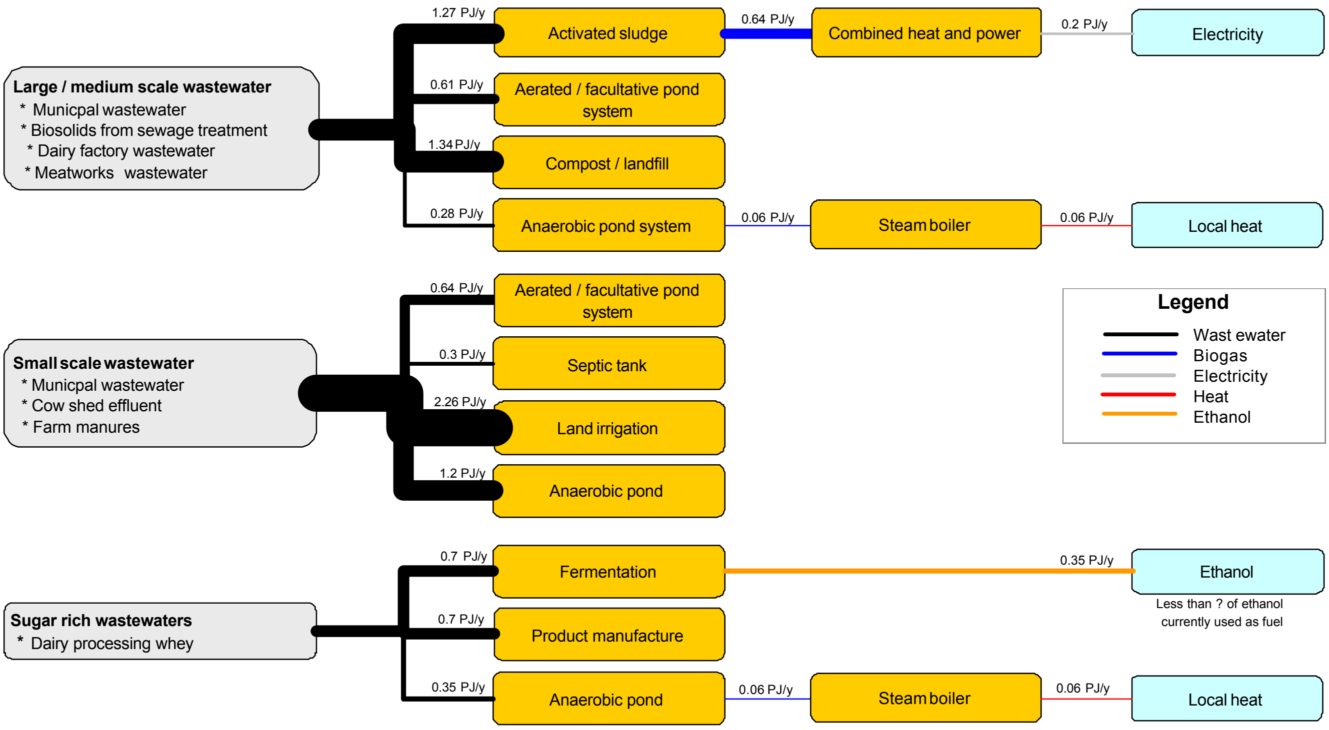

Figure 1: Current energy contributions from wastewater resources in New Zealand

Whey and whey like wastewaters produced by New Zealand's large dairy processing industry deserve special attention due to the unique energy products that can be extracted from this resource. Thiele and Crosbie (2005) considered the bio-ethanol production from whey at three New Zealand dairy factories (Reporoa, Edgecumbe and Tirau). These sites produced roughly 0.35 PJ/y (~16 million litres/y) of bio-ethanol from approximately ~0.7 PJ/y of feedstock. It was estimated that a similar amount of whey was used for the extraction of specialist food and feed ingredients (i.e. sugars, protein) at other dairy processing sites. Less than ⅓ of the ethanol output is currently used as transport fuel – the majority is sold to the beverage industry.

Bio-ethanol fermentation of whey and whey like wastes is only a partial wastewater treatment process, as the spent liquor produced as a by-product still contains substantial amounts of VS (~ 2%) and BOD_5. Only one whey base ethanol manufacturing facility in New Zealand currently uses the spent liquor energetically via anaerobic digestion to biogas. It is estimated that up to 0.06 PJ/y of biogas from the spent liquor resource are produced at the site, which is used in a boiler for steam raising. The spent liquor from other ethanol production facilities is treated aerobically and / or irrigated to land.

4 FUTURE POTENTIAL ENERGY CONTRIBUTION OF THE WASTEWATER SECTOR

A model was developed to test the upper limits of the potential energy contributions of the wastewater sector. The model only considered currently available technologies, and a market situation that favors the utilisation of bio-energy. This scenario could result from the introduction of either a hefty carbon tax and / or a physical shortage of natural gas and petroleum. The utilisation pathways were selected separately for each wastewater resource based on techno-economic feasibility.

4.1 Large / medium scale wastewater systems

Our model assumed that a large contribution to New Zealand's energy supply could be made by the dairy and meat processing industries. Virtually all of the DAF sludge and paunch grass that is currently composted or land filled could be used for anaerobic digestion in heated mixed digesters or covered anaerobic ponds. In addition, biogas that is currently flared or vented from anaerobic ponds would be captured and used either to produce combined heat and power, or combusted as boiler fuel.

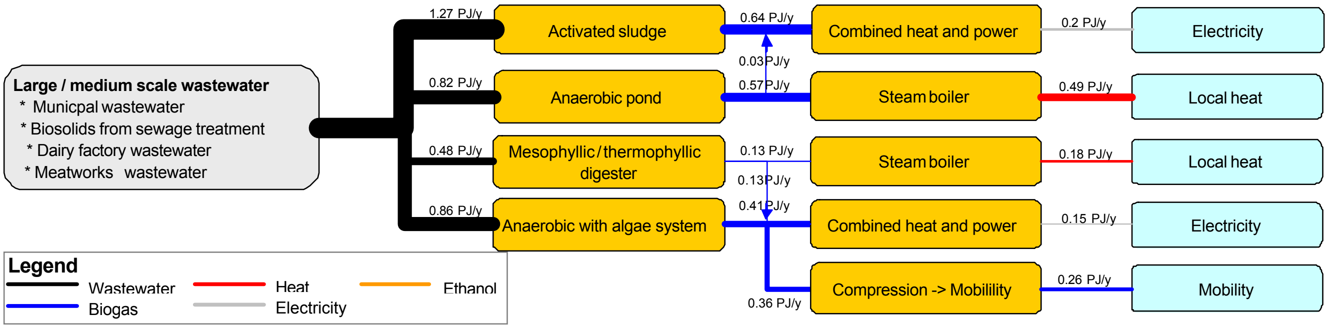

Figure 2: Potential future energy supply from large / medium scale wastewater treatment operations

Since dairy and meat processing sites often have large heat demands, the use as boiler fuel appears to be the most practical pathway for utilisation of biogas derived from DAF sludge and paunch grass. These resources have the potential to provide up to 0.67PJ/y local heat, while smaller fractions of this biogas may be directed to CHP applications.

There appears to be little potential to increase the energy contributions from large scale municipal sewage treatment systems which employ the activated sludge process, however, a large number of large / medium scale municipal and industrial wastewater systems which currently use aerated or facultative ponds could employ covered anaerobic pond technology to recover biogas from ~0.86 PJ/y of primary energy. For systems that will not meet future nutrient discharge criteria, the incorporation of algal technologies in the wastewater treatment process may be a viable option. Given the current state of technology, the wastewater grown algal biomass would most likely be used for production of additional biogas via anaerobic digestion. Most of the biogas derived from covered anaerobic pond systems and algal biomass associated with industrial effluents would most likely be used for on-site CHP.

Biogas purification and compression to gaseous transport fuel is an option for many pond based municipal wastewater treatment plants, where anaerobic pretreatment has reduced aerator electricity demands substantially. Biogas to transport fuel schemes can provide more usable consumer energy than CHP plants for a given amount of raw biogas. It may be possible to derive up to 0.26PJ/y (~ 6.7 million litres diesel equivalent) of gaseous transport fuel from covered anaerobic ponds and algae production facilities annually.

4.2 Small scale wastewater systems

While this sector does not currently contribute to New Zealand's energy supply, there is great potential to do so in the future. The treatment of dairy farm effluent and piggery wastewaters which currently, are mostly irrigated directly onto agricultural land, offer the greatest potential. By utilizing these wastewater resources for anaerobic digestion up to 2.07 PJ/y of biogas could be recovered. The biogas produced in these facilities was assumed to be used mainly for CHP (1.29PJ/y), providing 0.44 PJ/y (122 million kWh/y) electricity, and for upgrading to gaseous transport fuel (0.77PJ/y / ~ 19 million litres diesel equivalent per year).

Small scale biogas recovery systems, such as farm scale mesophilic digesters (Hulls, 2008) and covered anaerobic ponds (Heubeck and Craggs, 2009) have recently been demonstrated successfully at field scale in New Zealand. Such systems can easily be integrated into existing wastewater management systems or even retrofit existing infrastructure, and would therefore allow for a large proportion of this currently under-utilised potential to contribute to New Zealand's energy supply. Regional Council requirements to provide deferred effluent irrigation storage capacity, and reduce odour emissions, may spur a rapid adoption of covered anaerobic pond technology in the near future.

The potential of future anaerobic wastewater treatment systems incorporating algal technologies would be restricted to municipal wastewater treatment plants which are required to have lower effluent nutrient concentrations. These facilities could potentially yield 0.14 PJ/y of biogas for mobility applications and 0.08 PJ/y (~22 million kWh/y) electricity from combined heat and power plants.

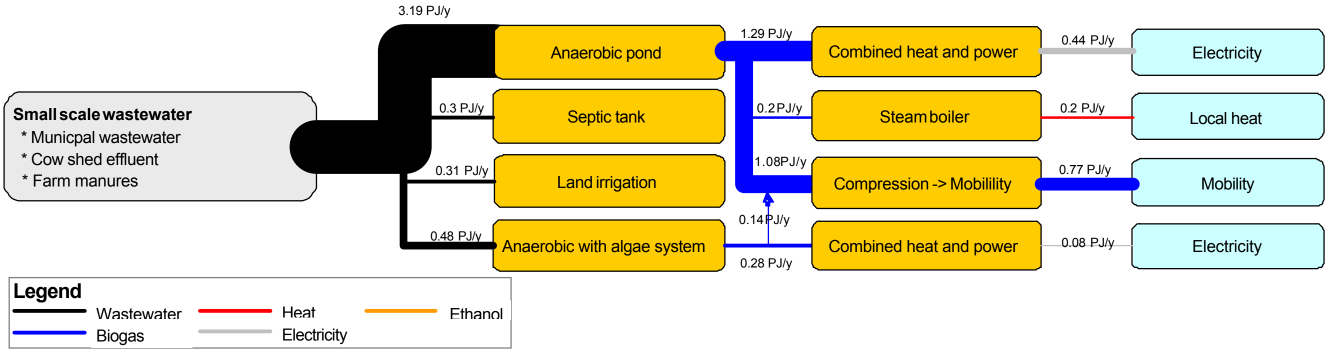

Figure 3: Potential future energy supply from small scale wastewater treatment operations

4.3 Sugar rich wastewaters

In an environment where fossil fuels are scarce or expensive to use, economic fundamentals may support the maximum utilisation of whey and whey like wastewaters for the manufacture of bio-ethanol transport fuel. It would also be expected that the operators of the ethanol plants would seek to extract the maximum energy benefit from the associated spent liquor resource. Our model therefore assumed that all whey would be fermented to bio-ethanol, and all spent liquor digested anaerobically to biogas. This would yield 0.7 PJ/y (~32 million litres/y) of bio-ethanol and 0.35 PJ/y of raw biogas for on-site steam raising (see Figure 4).

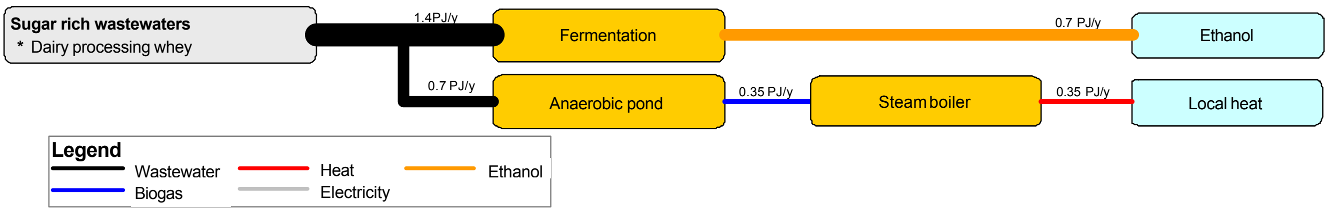

Figure 4: Potential future energy supply from New Zealand's sugar rich wastewater resources

5 CONCLUSIONS

This paper estimates the future potential contributions of the wastewater sector to New Zealand's energy supply. Based substantially on data developed by the EnergyScape programme, the upper limit of technologically feasible energy resource potential was assessed to be:

- 0.91 PJ/y (~253 million kWh/y) electricity,
- 1.09 PJ/y boiler fuel / heat,
- 1.04 PJ/y (~27 million litres diesel equivalent) gaseous transport fuel (compressed bio-methane), and
- 0.7 PJ/y (~32 million litres) liquid transport fuel (bio-ethanol).

Building the infrastructure to capture these resources would take over a decade, and can only be accomplished if fossil fuel prices continue to remain high, and initiatives to reduce our dependence on these fuels are supported by comprehensive and long-term government legislation and regulation (e.g. tax breaks, feed-in tariffs or a carbon tax). Creating and maintaining a work force with the skills to construct and operate wastewater energy utilisation technology will be a particular challenge.

It is likely that other regulatory requirements, such as minimisation of odour, or tightening wastewater nutrient discharge standards, will spur implementation of technologies such as covered anaerobic ponds, mesophilic farm waste digesters or algae based wastewater treatment technologies, with the associated energy benefit realised as an add-on rather than being the prime driver.

The study suggests that New Zealand has much to benefit from better understanding available wastewater resources and treatment options – be that in form of energy self-reliance, energy storage or economic return.

NOMENCLATURE

AD	Anaerobic Digestion
BOD_5	Biochemical Oxygen Demand
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
DAF	Dissolved Air Floatation
E10	A retail blend of 10% bio-ethanol with 90% petrol
GHG	Green House Gas
GJ	Gigajoule
HRAP	High Rate Algae Pond
kWh	Kilo Watt Hour (electrical unit)
NZ	New Zealand
PJ	Petajoule
R&D	Research and Development
RD&D	Research, Development & Demonstration
TS	Total solids
UASB	Up-flow Anaerobic Sludge Blanket (digester)
VS	Volatile solids
WSP	(conventional) Waste Stabilisation Pond

REFERENCES

Craggs, R. J., Green, F. B. and Oswald, W. J. (1998) "Advanced Integrated Wastewater Pond Systems (AIWPS): potential application in New Zealand". *Proceedings of the NZWWA annual conference* pp 56-62

Craggs, R. J., Green, F. B. and Oswald, W. J. (1999) "Economic and Energy Requirements of Advanced Integrated Wastewater Pond Systems (AIWPS)". *Proceedings of the NZWWA annual conference*: 1-7.

Craggs, R.; Heubeck S.; Lundquist, T.; and Benemann, J. (2009) "Algae biofuel from wastewater treatment high rate algae ponds". This issue.

Gapes, R. (2009) "Biobutanol – Second Generation Biofuels" *Oral presentation at the BANZ Liquid Biofuels Conference 2009*, 25th March 2009, Wellington, New Zealand.

Green, F. B., L. Bernstone, T. J. Lundquist, J. Muir, R. B. Tresan and W. J. Oswald (1995) "Methane fermentation, submerged gas collection and the fate of carbon in advanced integrated wastewater pond systems." *Water Science and Technology,* 31, 12, 55-65.

Green, F. B., L. Bernstone, T. J. Lundquist and W. J. Oswald (1996) "Advanced Integrated Wastewater Pond Systems for Nitrogen Removal." *Water Science and Technology,* 33, 7, 207-217.

Henze, M. (1995) Basic Biological Processes, Wastewater Treatment - Biological and Chemical Processes. M. Henze, P. Harremoes, E. Arvin and J. Jansen. Berlin, Springer - Verlag: 55 - 111.

Heubeck, S. and Craggs, R. (2007) "Resource Assessment of Algae Biomass for Potential Bio-Energy Production in New Zealand" Technical report prepared for the New Zealand Forest Research Institute (Scion) as part of the EnergyScape project, October 2007, Hamilton, New Zealand.

Heubeck, S. and Craggs, R. (2009) "Biogas recovery from a temperate climate covered anaerobic pond." *Water Science & Technology,* In print.

Hulls, K. (2008) „Biogencool Biogas Energy System for Dairy Farms" *Oral presentation at the New Zealand Biogas 2008 conference*, 10th of July 2008, Hamilton, New Zealand.

Mara, D. (1997) Design manual for waste stabilisation ponds in India. Leeds, Lagoon Technology International Ltd.

Metcalf and Eddy, Ed. (1991) Wastewater Engineering: Treatment, disposal and reuse. New York, McGraw Hill Inc.

Molloy, S. (2008) „Upgraded Biogas for Vehicle Fuel" *Oral presentation at the New Zealand Biogas 2008 conference*, 10th of July 2008, Hamilton, New Zealand.

Nurdogan, Y. and Oswald, W.(1995) "Enhanced nutrient removal in High Rate Ponds." *Water Science and Technology* 31, 12, 33-43.

Scion (2008) "Bioenergy Options for New Zealand II – Situation Analysis, Biomass Resources and Conversion Technologies", Summary report, compiled by the New Zealand Forest Research Institute (Scion) 2008, Rotorua, New Zealand.

Sheehan, J., Dunahay, T., Benemann, J. and Roessler, P. (1998) "A look back at the U.S. Department's of Energy aquatic species programme - Biodiesel from algae" Close-out report prepared for the National Renewable Energy Laboratory, Golden, Colorado, USA.

Thiele, J. and Crosbie, R. (2005) "Estimate of the Energy Potential for Fuel Ethanol from Putrescible Waste in New Zealand" Technical report prepared for the Energy Efficiency and Conservation Authority, June 2005, Dunedin, New Zealand.

Thiele, J. and Clarke, N. (2007) "Bioeenrgy Resource Assessment Municipal Biosolids and Effluents and Dairy Factory, Meat Processing and Wool Processing Waste" Technical report prepared for the New Zealand Forest Research Institute (Scion) as part of the EnergyScape project, October 2007, Dunedin, New Zealand.