ESTIMATES OF HYDROGEN PRODUCTION POTENTIAL AND COSTS FROM CALIFORNIA LANDFILL GAS

R.B. Williams§, K. Kornbluth‡, P.A. Erickson‡, B.M. Jenkins§, and M.C. Gildart§
§ Department of Biological and Agricultural Engineering
‡Department of Mechanical and Aeronautical Engineering
University of California
Davis, CA 95616 USA

ABSTRACT: Methane production from California landfills is estimated using a first order decay model and actual plus predicted waste disposal amounts from 1970 through 2025. Potential hydrogen production is estimated assuming 67% methane (landfill gas) recovery and upgrading and a 70% energy conversion efficiency of methane to hydrogen (higher heating value basis) using a steam reformer system. Statewide landfill derived methane is predicted to increase from 2.4 to 3.5 billion Nm^3 y^{-1} between 2005 and 2025. For the same period, potential landfill derived hydrogen production was estimated to range from 300 to 430 Gg y^{-1}. This hydrogen energy is equivalent to 1.3 Gl of gasoline equivalent (for 2005) or about 2% of California's gasoline usage and could fuel between 1.3 and 1.9 million fuel cell vehicles (FCV). The largest 15 landfills (in terms of current annual disposal) could potentially produce hydrogen equivalent to some 0.4 Gl of gasoline equivalent and could fuel some 500,000 FCV. The cost of landfill derived hydrogen using commercial gas upgrading and small steam methane reformer systems is estimated to be less than US\$3.50 kg^{-1} (US\$29.10 GJ^{-1}, lower heating value), not including distribution, storage, and dispensing costs.
Keywords: hydrogen, landfills, resource potential

1 INTRODUCTION

Hydrogen is an attractive alternative fuel or energy carrier especially for the transportation sector, because, as with electric vehicles, it offers an opportunity to reduce or eliminate vehicle or point-of-use pollutant emissions and improve life-cycle greenhouse gas and energy performance when compared to petroleum-sourced fuels [1].[1] However, before an extensive hydrogen transportation system is possible, significant challenges must be met, including the need to [2][2]:

- develop affordable and reliable fuel cells and hydrogen storage systems, and hydrogen distribution and fueling infrastructure,
- reduce the cost of hydrogen from renewable sources, and
- develop large scale sequestration technologies that reliably sequester CO_2 for hundreds of years or longer if hydrogen is sourced from coal.

Hydrogen is currently used in petroleum refining, chemical and fertilizer production, and the food industry. Worldwide hydrogen production is about 37 Tg y^{-1} [2]. The US hydrogen demand is about 8 Tg y^{-1} of which approximately 95% is produced from natural gas by steam methane reforming (SMR) [3].

Hydrogen can also be produced from gasification of coal and steam, electricity (via electrolysis of water), and biomass (via steam gasification, biohydrogen production, reforming of methane in biogas, and reforming of bio-alcohols). 'Renewable hydrogen' would be hydrogen derived from renewable energy; renewable electricity or biomass. The renewable hydrogen production potential from landfill gas (LFG) in California is herein estimated.

2 LANDFILL GAS ESTIMATES

2.1 Waste-in-Place

Landfill gas is produced by anaerobic decay of waste in the landfill. Therefore, current and future LFG production depends on current and future waste-in-place (WIP). Landfill gas generation in California for the period 2005 – 2025 was estimated for waste placed beginning in 1970 [4].

Solid waste landfill disposal from 1970 through 2005 is estimated to be 1000 Tg, which is the 2005 WIP amount, although actual residual mass in the landfill is less than that value due to gas production and any loss or evaporation of leachate..

Disposal for the period 1970-1990 was estimated from statewide population and per capita disposal rates. Actual disposal data were used for the period between 1990 and 2005 (555 Tg, as-received) [5]. Disposal for the period 2005-2025 is projected based on population growth projections and per-capita disposal rates. Data have also been compiled by US EPA as part of the landfill methane outreach program (LMOP). The LMOP data yield a total waste-in-place since 1922 of 850 Tg [6].[3] The earliest operating date for the landfills included is 1922 but most have opened since 1950. The California Integrated Waste Management Board estimates WIP for 364 California landfills (active and closed with WIP of 9000 Mg or greater) at 1090 Tg (which includes biodegradable alternative daily cover (ADC)) [7].

2.2 Landfill gas model

The model used for LFG production is essentially the LandGEM model developed by USEPA [8]. The model assumes a first order decay of waste beginning the first year after placement. The gas generation rate, g_n (m^3 y^{-1}), as a function of time for waste placed in the landfill in any year n is

[1] Life-cycle GHG emissions and energy system efficiency improvements depend on hydrogen source and vehicle drive type (natural gas and some renewable hydrogen pathways combined with a fuel-cell vehicle outperform petroleum fuels in both GHG emissions and overall energy system efficiency)

[2] A transition period of 50 years is considered in the National Academies 2004 report

[3] For 217 landfills with existing or potential landfill gas to energy recovery.

$$g_n = W_n L e^{-kt} \quad (1)$$

W_n = quantity of waste placed in year n (wet Mg)
L = methane generation potential factor (m^3 Mg^{-1} y^{-1})
k = rate constant (y^{-1})
t = time from base year (y)

Total gas generation, g_t (m^3 y^{-1}), is the sum over all years up to the current year as shown by equation (2).

$$g_t = \sum_n g_n = L \sum_n W_n e^{-kt} \quad (2)$$

For conventional landfill, the model estimates were based on USEPA AP-42 [9] parameters with $k = 0.04$ y^{-1} and $L = 4.0$ m^3 Mg^{-1} y^{-1} yielding an ultimate methane generation potential of about 100 m^3 Mg^{-1} for disposal post-1970 (Figure 1 displays model output for one tonne of waste landfilled in year 0).

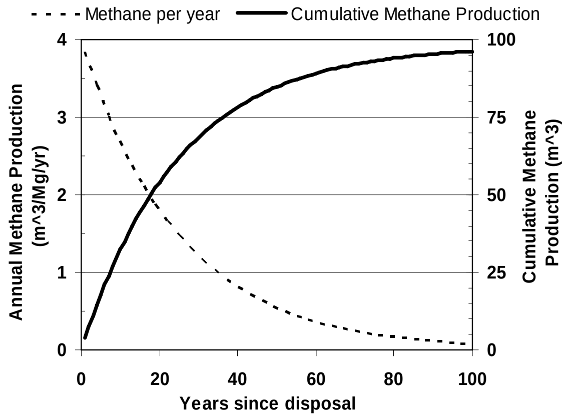

Figure 1: Landfill methane model output for 1 Mg of disposed waste.

2.3 Landfill gas production

For 2005, the model estimates California LFG methane production is about 2.4 billion Nm^3 y^{-1} (GNm^3 y^{-1}). Total LFG volume (including the CO_2) is about 4.8 GNm^3 y^{-1}. Landfill methane generation is projected to grow to about 3.5 GNm^3 y^{-1} by 2025. Recoverable methane (67% of generated) is projected to grow from 1.6 to 2.3 GNm^3 y^{-1} over the same period [Figure 2]. Disposal post-1990 contributes most of the landfill gas by 2025 [4]. The methane production from California landfills is about 4% of current natural gas consumption (62 GNm^3 y^{-1}) [10].

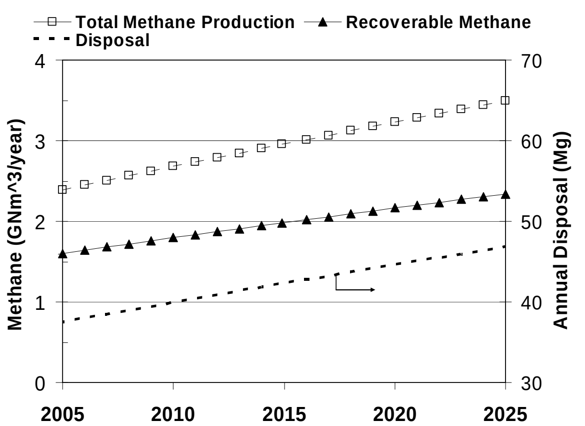

Figure 2: Projected gross and recoverable landfill methane and annual disposal for California.

2.4 Recovery of landfill gas

For landfills with gas collection and recovery systems, collection efficiency (the fraction of LFG generated that is recovered for use or flaring) "typically ranges from 60 to 85 percent with an average of 75 percent most commonly assumed" [9]. From an intensive field measurement and modeling campaign, CH_4 mass balances have been recently determined at three landfills with gas recovery systems in France [11]. Recovery efficiencies ranged from 41 to 98 percent depending on landfill cover material and time of year. Landfills with final cover made of compact clay had highest gas recovery rates. For this analysis, LFG methane available for reforming to hydrogen is assumed to be 67 percent of the amount generated statewide (this includes LFG collection efficiency of 75 percent and upgrading to high purity methane with net efficiency of 90 percent).

3 HYDROGEN ESTIMATES

3.1 Reforming to Hydrogen

Approximately 95% of hydrogen production in the US is from natural gas using SMR (worldwide share is about 80%) [2, 3]. Scale ranges from 250 Mg d^{-1} H_2 production at large oil refineries to as small as 250 kg d^{-1} needed for onsite reforming at vehicle fueling stations [12].

The net reaction for hydrogen production from methane via SMR is:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (3)$$

Net energy efficiency of practical reformer systems ranges from 80% (feedstock energy to hydrogen energy, higher heating value or HHV basis) for large systems to about 64% for small distributed systems (range is 72-60% on lower heating value or LHV basis) [2, 13-15].

3.2 Landfill gas to Hydrogen estimate

Hydrogen production estimates in this analysis assume steam methane reforming (SMR) technology with a 70% net energy efficiency of conversion (HHV basis; feedstock energy to hydrogen energy).

Based on the recoverable methane estimated in Figure 2, about 300 Gg y^{-1} of renewable hydrogen could be produced from California LFG, increasing to about 430 Gg y^{-1} by 2025 (Figure 3).

Current LFG to energy generation capacity in California is about 285 MWe plus direct use applications. However, for reasons of low gas quality or variable supply, actual generation from landfill gas, though less than the installed capacity, is unknown at this time. Assuming LFG-to-electricity production of 300 MW over the analysis period, the remaining recoverable LFG could produce from 160 to 300 Gg y^{-1} of hydrogen (Figure 3).

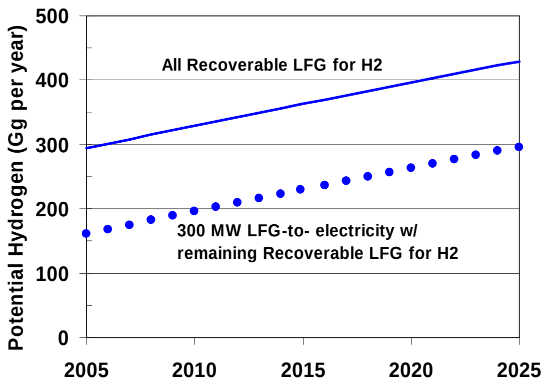

Figure 3: Potential hydrogen production from California LFG

3.3 Vehicles fueled by landfill hydrogen

One metric ton (1 Mg) of hydrogen is equivalent to about 4000 l (1050 gallons) of gasoline on a HHV basis, so the ultimate LFG hydrogen potential from California landfills is equivalent to about 1.29 Gl (340 million gallons) of gasoline. This is about 2% of California's current gasoline usage [16].[4]

Assuming (1) an average passenger vehicle in California has gasoline fuel economy of 7.8 l per 100km (30 miles per gallon), (2) an average vehicle is driven 24,100 km y^{-1} (15,000 miles/yr), and (3) a fuel cell vehicle might be twice as efficient as a gasoline vehicle, then the LFG hydrogen estimate for 2005 could have fueled 1.3 million fuel cell vehicles. Up to 1.9 million vehicles could be fueled by renewable LFG hydrogen in 2025, all else being equal (Figure 4).

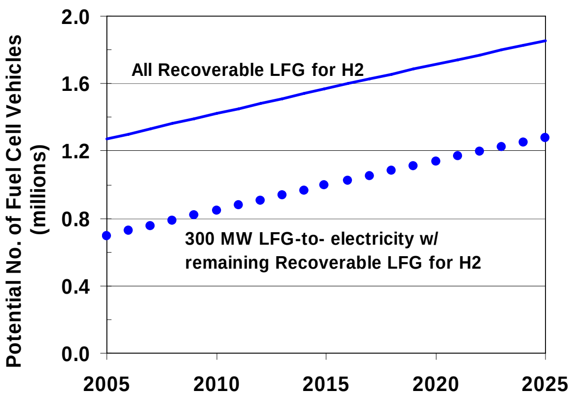

Figure 4: Number of fuel-cell vehicles that could be fueled by California LFG

Similar modeling was done for each of the 15 most active landfills in California (i.e., those 15 with the highest annual disposal amounts). Eleven of the fifteen are in Southern California and the remainder are distributed in the Central Valley and the East Bay Area. These 15 landfills combined accept nearly 60% of California waste disposal and contain approximately 35% of WIP. The hydrogen from LFG produced in the 15 most active landfills would be equivalent to 0.4 Gl of gasoline and could fuel approximately 500,000 fuel cell vehicles.

[4] Current annual usage is about 60 Gl (16 billion gallons) of gasoline.

4 HYDROGEN PRODUCTION COSTS

Hydrogen production costs from natural gas using SMR range from about US$1.50 kg^{-1} at large scale facilities (1.2 Gg d^{-1}) to about US$3.75 kg^{-1} at a 500 kg d^{-1} facility (assumes US$7 GJ^{-1} natural gas price) [2].

The cost to upgrade LFG suitable for use as vehicle fuel (i.e., compressed natural gas) or for injection into natural gas pipeline systems is estimated to be about US$2.50 GJ^{-1} for larger systems (~ 3000 Nm^3 hr^{-1}) and around US$6 GJ^{-1} for small systems (~ 250 Nm^3 hr^{-1}) [17-20] (Figure 5). These costs do not include the gas collection system costs as gas collection is required at most operating landfills in California for emissions control.

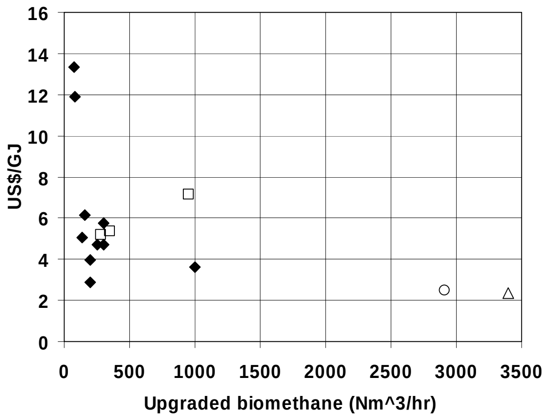

Figure 5: Biogas upgrading costs [17-20]

The hydrogen production cost from natural gas via SMR varies from about US$1.25 kg^{-1} for large systems (1,200 Mg d-1) to about US$ 3.50 kg^{-1} for small systems (500 kg d^{-1}) with a natural gas price of US$6 GJ^{-1} [2].

Based on estimated LFG upgrade costs of US$6 GJ^{-1} or lower, costs for hydrogen from LFG are expected to be less than US$3.50 kg^{-1} (US$29.10 GJ^{-1}, LHV). These costs do not including distribution, storage, and dispensing. Delivered cost is site and mode specific and can add another US$1-2 kg^{-1} (US$8-17 GJ^{-1}) [13].

5 SUMMARY CONCLUSIONS

- LFG is a potential source of renewable hydrogen with sizeable potential for production in California.
- There are some 1000 Tg of waste-in-place since 1970 in California landfills.
- LFG methane generation is estimated to be about 2.4 GNm^3 y^{-1}. and is projected to grow to some 3.5 GNm^3 y^{-1} by 2025.
- Based on the recoverable LFG methane, about 300 Gg y^{-1} of renewable hydrogen could be produced from California LFG, increasing to about 430 Gg y^{-1} by 2025.
- Estimated LFG hydrogen for 2005 could have fueled 1.3 million fuel cell vehicles. Up to 1.9 million vehicles could be fueled by renewable LFG hydrogen in 2025.
- The largest 15 landfills (in terms of current annual disposal) could potentially produce hydrogen equivalent to some 0.4 Gl of gasoline equivalent and could fuel some 500,000 FCV.
- Based on estimated LFG upgrade costs of US$6 GJ^{-1}

or lower, costs of hydrogen from LFG are expected to be less than US$3.50 kg^{-1} (US$29.10 GJ^{-1}, LHV).

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REFERENCES

[1] Edwards, R. and J. Larive. (2006).*Well to wheels analysis of future automotive fuels and powertrains in the European context - Well to Tank Report*. European Commission Joint Research Centre. Available at: http://ies.jrc.cec.eu.int/wtw.html.

[2] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. National Research Council and National Academy of Engineering. 2004: National Academies Press.

[3] *Today's Hydrogen Production Industry*. U.S. Department of Energy 2006 [cited 2007; Available from: http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.html.

[4] Gildart, M., et al. (2005).*An Assessment of Biomass Resources in California*. California Biomass Collaborative.

[5] *California Integrated Waste Management Board*. [cited; Available from: http://www.ciwmb.ca.gov/LGCentral/Rates/Graphs/RateTable.htm.

[6] USEPA. *Landfill Methane Outreach Program*. [cited 2005; Available from: http://www.epa.gov/lmop/proj/index.htm.

[7] Walker, S., *Compilation of landfill wast-in-place (WIP) and landfill gas-to-energy information.* November 30 Memorandum to Howard Levenson, 2005.

[8] Pelt, R., et al. (1998).*User's Manual Landfill Gas Emissions Model, Version 2.0.* , in *Prepared for Control Technology Center, EPA and EPA Office of Research and Development.* Prepared for Control Technology Center, EPA and EPA Office of Research and Development.

[9] *USEPA AP 42, Fifth Edition, Volume 1 Chapter2: Solid Waste Disposal*. Section 2.4 MSW Landfills 1998 [cited; Available from: http://www.epa.gov/ttn/chief/ap42/ch02/index.html].

[10] *California Energy Commission*. 2006 [cited; Available from: http://www.energy.ca.gov/naturalgas/statistics/gas_supply_by_source.html.

[11] Spokas, K., et al., *Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?* Waste Management, 2006. **26**(5): p. 516-525.

[12] Ogden, J.M. (2002).*Review of small stationary reformers for hydrogen production*. IEA Hydrogen Task 16.

[13] Ogden, J.M., *Prospects for building a hydrogen energy infrastructure.* Annual Review of Energy and the Environment, 1999. **24**: p. 227-279.

[14] Spath, P.L. and M.K. Mann. (2001).*Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming*. NREL: Golden, CO.

[15] Wang, W., et al., *Thermodynamic analysis of autothermal reforming of light hydrocarbons for hydrogen*, in *229th ACS National Meeting*. 2005, American Chemical Society, Washington, D. C: March 13-17, San Diego, CA USA.

[16] *California Board of Equalization*. 2005 [cited; Available from: http://www.boe.ca.gov/sptaxprog/reports/imvf10ynet.pdf.

[17] (2004).*Conventional and emerging technology applicatioins for utilizing landfill gas*. US EPA Landfill Methane Outreach Program.

[18] Krich, K., et al. (2005).*Biomethane from Dairy Waste- A sourcebook for the production and use of renewable natural gas in California*. USDA Rural Development and Western United Dairymen.

[19] Persson, M. (2003).*Evaluation of upgrading techniques for biogas*, in *School of Environmental Engineering*. Lund University: Lund, Sweden.

[20] Pomerantz, M. and L. Turcotte. (2004).*Production of pipeline gas from landfill gas in Canada*. SWANA.