Engineered MSW landfills as a future material resource and a sink for long-term storage of organic carbon

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Abstract. A controlled, highly engineered landfill has many similarities to natural peatlands or other natural anoxic sediment deposits. In anaerobic MSW landfills, generally about 30-50 percent of the total carbon content in the waste can be converted into biogas and be collected as resource for energy or chemical industry. Remaining long-lived organic carbon, e.g. from lignin remains un-degraded, Organic carbon in fossil derived hydrocarbons, like plastics, will remain rather unaffected in the landfill. In a future with less remaining oil resources, landfill mining of these polymers can be valuable, making the landfill to a future “resource bank”. New reactor cell landfill technologies have shown that up to over 90 % of the produced biogas can be collected and used. Approximately 150-250 m³ of biogas per tonne waste can be extracted from a landfill reactor-cell over a 10-year period. Sequestration of a long-lived organic fraction in a landfill, with an annual input of 100 000 tons of waste, can compensate for annual CO₂ emissions from about 20 000 to 25 000 cars. If more than about 60 % of produced biogas can be collected from the landfill, it has positive net effects on climate change. If the waste instead would have been incinerated this would lead to major emissions of fossil CO₂, as about 30-50 % of the CO₂ in the stack gasses from a waste incinerator has fossil origin.

1 Introduction

During the last 50 years, the global CO₂ emissions have increased by 70 percent and the World's total annual emissions of greenhouse gasses are estimated to about 49 billion tonnes of carbon dioxide. Since the 1990’s the increase has been approximately 24 percent. In Sweden it is mainly domestic road transports that account for the most pronounced share of emissions, approximately 34% [1]. This is followed by emissions from industry, electricity and heat production and agriculture. Emissions from residential and commercial buildings account for 6 percent of emissions, while only 3 percent of emissions come from the waste sector. This sector reported methane emissions from uncontrolled landfills, fossil carbon dioxide and N₂O emissions from waste incineration, and nitrous oxide emissions from wastewater management. Total greenhouse gas emissions in Sweden corresponded to about

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59.8 million tons in 2009 converted to carbon dioxide units, while the Swedish emissions of the gas carbon dioxide itself were 46.6 million tonnes during the same year [1, 2]

2 The landfill as a long-term sink for organic carbon

In the 1980’s the total annual transportation of organic carbon to landfills, World-wide, was estimated to around 100 x 10^{12} g of C [3, 4]. Increased material recovery and increased incineration has probably lowered the present figures, in spite of increased waste volumes. The conditions for mineralization of organic matter in the landfill decide the accumulated fraction of organic carbon. Bogner and Spokas [5, 6] estimated that the fraction left for long-term accumulation in the World's landfills amounts to approximately 30 x 10^{12} g C per year.

Åkesson [7] has shown that approximately 150-200 m^3 of biogas, with 50-55 % methane gas concentration, can be extracted per ton treated waste with a landfill reactor cell fermentation technique. With 25 % organic carbon per ton household and light industrial waste, and with a total carbon content of 500 g C per m^3 of biogas, this would mean that around 130 x 10^3 g C per ton originally landfilled waste should remain in the landfill after approximately 15-20 years. Of this amount, lignin contributes to approximately 40 - 50 x 10^3 g C and plastics to about 20-30 x 10^3 g C. The remaining fraction, about 40 - 50 x 10^3 g could theoretically be converted to biogas after improving and optimizing the fermentation technique in e.g. landfill reactor-cells (biocells) [8]. The amount of total organic carbon discharged from landfill reactor-cells through the leachates is small in comparison to the losses through the biogas, and was estimated by Åkesson [7] to around 3-6 %. Therefore, approximately 70 - 90 x 10^3 g organic carbon per ton household waste would probably remain in the fermentation residues after an advanced fermentation in landfill bioreactors, compared to about 130 x 10^3 g C with a less optimized bioreactor cell technique for biogas production. Normally, in a well-managed landfill with biogas extraction probably around 150 x 10^3 g C is long term accumulated per ton landfilled waste. Household waste normally contains approximately 23-25 % organic carbon, while industrial waste, with lower water content and normally a higher proportion of paper, wood and plastics, contains somewhat higher proportions of organic carbon. Plastics and rubber are rather unaffected by biological degradation and are left in the landfill. Under anaerobic conditions also lignin is resistant to degradation and will remain in the fermentation residue. According to the estimates above, around 60 % of the organic carbon in the solid waste remain in the fermentation residue during normal landfilling, while about 30-50 % of the original carbon content would still remain after a better optimized landfill reactor-cell (biocell) treatment. These figures are somewhat lower compared to some earlier estimates based on landfill fermentation studies, [5, 9, 10], ranging from 60-75 % for the remaining carbon fraction.

In Sweden, an average sized landfill bioreactor annually can be assumed to treat about 100 000 tons residual municipal waste. This amount of waste corresponds to approximately 25 000 tons organic carbon, or a fraction of approximately 15 000 x 10^6 g C each year, which will be included in a long-lived fraction. This corresponds to about 45 000 tons of carbon dioxide. The losses of organic carbon through the leachates only amount for minor fractions. The long-lived carbon fraction accumulated in the fermentation residue corresponds to the total amount of carbon emitted per year from 20 000 – 25 000 cars, running approximately 15 000 km per year and emitting approximately 130 g CO_2 per km. In addition to the accumulation of organic carbon resistant to mineralization, during landfilling or treatment in reactor cells, there is also an increasing amount of organic matter, which in spite of microbial degradation, will remain during a few years. Thus the positive effects on the carbon balance
are not only related to the most long-lived fractions with fossil origin, that finally will be
stored for a very long period of time. Bramryd and Binder [11] has, with another comparison,
calculated that the deposition of organic matter in a medium sized controlled landfill (100
000 tons per year) equals the total amount of carbon stored in approximately 65 hectares of
grown-up spruce forest, or in approximately 45 hectares of deciduous forest. It is of great
importance to establish the carbon accumulating functions in the urban society, as the CO₂
balancing processes in nature are insufficient to compensate for the increasing emissions of
carbon dioxide.

Energy forest plantations within a landfill area, irrigated with leachates, also immobilize
CO₂ in standing biomass. In such a forest plantation, supplied by liquid nutrients extracted
from the waste, organic carbon corresponding to approximately 10 metric tonnes of organic
carbon can be stored in plant biomass per hectare each time unit, in spite of a short turnover
time for the produced biomass. The content of total soil organic carbon (C) also increases,
mainly in the humus layer, after irrigation, which is an effect of a larger litter production from
a gradually increasing biomass. Even a slight increase can be measured of the carbon content
in the uppermost mineral soil layer, which depends on leaching of resistant humic substances
[12]. This means that the use of leachates as local fertilizer leads to an increased amount of
organic carbon that can be accumulated in the soil, which is positive from a carbon balance
perspective.

Other techniques for biological waste treatment, producing compost or bio-residues
relatively resistant to degradation, are also beneficial for the accumulation of soil organic
carbon. The use of compost or bio-residues in soils with high sand or clay content will
increase the humus concentration and thus the organic carbon in the soil.

3 Biogas as an energy resource and a resource in chemical industry

3.1 Biogas production from source separated food waste

EU has declared that greenhouse gas emissions shall decrease by at least 20 percent by 2020,
the share of renewable energy to meet 20 percent of all energy in the EU 2020, bio-fuels
should represent at least 10 percent of total fuel use in transport sector by 2020 and energy
use will decrease by 20 percent in 2020. The production of biogas through anaerobic
digestion offers significant advantages over other forms of bio-energy production. It has been
evaluated as one of the most energy-efficient and environmentally beneficial technologies
for bio-energy production. It can drastically reduce greenhouse gas emissions compared to
fossil fuels by utilization of locally available resources [13]. Biogas can also be used as raw
material in chemical industry, substituting oil and natural gas derived substances.
Assumptions are made that at least 60% of all food waste in Sweden can be available for
biogas production. This amount corresponds to approximately 760 GWh annually, and
represents 7% of the total biogas potential. The total biogas potential from all food waste in
Sweden amounts to 1346 GWh / year [14].

3. 2 Landfill gas

The production of landfill gas is related to anaerobic landfills, where the supply of oxygen is
insufficient for a full compost process, i.e. when the waste layers exceeds about 1-2 meters.
Landfill gas has for a long time been collected from landfills in western Europe and the US.
From the beginning, the main purpose was to reduce the methane gas emissions and decrease
the risk of spontaneous fires, and often the gas was just flared off. However when energy
prices started to increase globally, landfill gas started to be regarded as an energy resource. In Sweden the first landfill gas extraction unit was built in Malmö in 1984, followed by a facility in Helsingborg the next-coming year. The Swedish State Department of Energy invested heavily in research and development to improve the landfill gas technique, resulting in the creation of the bioreactor cell technique, with optimal and controlled fermentation to be installed at landfills. In the bio-reactor cells a total biogas extraction rate of about 120 m$^3$ of biogas per metric ton of waste over the period of 10 years was found and about 12 m$^3$ of biogas per metric ton of waste per year. In the experiments at the SYSAV plant in Malmö about 90–95% of the produced biogas could be extracted and recovered from the bioreactor cells [7]. The effective collection of landfill gas combats climate change and the gas can be used as a renewable fuel, leaving a long-lived organic fraction for carbon sequestration in the landfill. On the other hand, if less than about 60% of the produced biogas is collected the negative effects of methane as a greenhouse gas prevail. Most controlled landfills in developed countries nowadays collect at least over 75%, sometimes up to over 90 %, of the produced landfill gas. Gas leakage can also be prevented using a top-cover layer of biologically active sewage sludge, where methane-oxidizing bacteria are working [1]. Through mechanical pre-treatment and improved mixing of the waste, the biogas production can be improved and concentrated in time, making the gas quality higher, and the volume reduction of the waste is considerable, due to the optimized degradation processes [1, 8, 15].

One advantage of the use of biogas extracted from landfills and reactor cells as a fuel is that it helps to solve a waste problem. In Sweden today landfill gas is extracted from 47 of the landfills in operation. This generated over 370 GWh of which 24 GWh in the form of electricity. In addition to this, about 65 GWh is flared away. Provided that a reliable and efficient biogas collection system is installed, a strictly controlled landfill can represent a technology to combat global warming. New reactor landfill technologies, in e.g. Sweden, have shown promising results collecting up to about 95 % of the produced biogas in the landfill cell [1, 7].

In some areas in Sweden, e.g. Northwest Scania, significant investments in biogas production are made through efficient digestion of waste in various forms of biological treatment processes (reactor fermentation, landfill reactor cell fermentation and from the original landfill). The production of landfill gas at the Northwest Scania Recycling Company in Helsingborg is enough to warm up about 3500 homes, which means 70 000 MWh of landfill gas [16]. Due to a rapidly increasing demand for renewable motor gas, landfill gas is also refined to motor fuel. A similar trend is seen in many countries. At the same time as the residual waste is used to produce an environmentally friendly motor fuel, this also creates economy for a reliable collection of produced gas in the landfill, and thus eliminates diffuse gas emissions to the atmosphere. At the same time, nutrients can be extracted through the leachates to be used in e.g. energy crop production. Mainly because of lack of available technologies for landfill gas upgrading and high assessed upgrading costs, landfill gas has so far mostly been used for heating and cogenerations plants (CHP). In recent years, interest has been brought to upgrade landfill gas, and thus it is possible to use landfill gas as fuel for vehicles [17]. In Stockholm region in Sweden there was approximately 32 million Nm$^3$ of biogas produced in 2008. This means that over 7000 cars and 250 buses can run on biogas from landfills and waste treatment facilities in this region [18]. With the right conditions, according to Benjaminsson et al [17] it is possible to achieve a cost-effective landfill gas upgrading. In order to prevent the release of the methane from landfills, many countries, like e.g. the US, are introducing a system for trading with carbon emission units related to landfill gas. This stimulates the construction of reliable biogas collection systems in landfills, both for operating landfills and closed ones.
3.3 Other forms of waste-to-energy techniques

Incineration is often mentioned as an alternative to landfilling and biogas production. In Sweden however, the main focus today is on the emissions of fossil CO₂ from incinerators and how these can be reduced through the reduction of plastics and other synthetic material in the waste. During incineration, MSW is regarded as partly a “fossil fuel”, and a new facility is built in Stockholm with the aim to separate plastics from the waste before burning the residues in an incinerator. Around 30-50% of the carbon dioxide in the stack gasses from an MSW incinerator is of fossil origin, and Sweden thus has an intention to reduce waste with fossil origin. To work in this direction, a new tax of 3 SEK (0,30 €) is laid on all one-way plastic bags in shops, in order to reduce the annual consumption to only 40 bags per person and year. Moreover, the emissions of N₂O, a strong greenhouse gas in the stack gasses from incinerators, resulting from NOx reducing techniques, also are of recent focus concerning climate change.

In order to decrease the volume of incinerated waste, and especially the amounts of imported waste for incineration, the Swedish Government has introduced a tax of 70 SEK (about 7 €) per metric ton on all waste that is incinerated. This tax will in the coming years increase to 200 SEK (20 €) per metric ton. The goal is that no new incinerators will have to be built in the future due to the enforcement of a better circularity. Through the development of a stricter source separation procedure already in the households, in combination with better information and education, the amounts of waste for incineration in Europe is expected to decrease significantly.

4. Material recycling and strategies for a circular economy

The trend among all governmental authorities, politicians, cities and planners is to invest heavily in a circular economy. The aim is to achieve a “zero residual waste” strategy strongly reducing future use of incineration or final landfilling. More or less everything that is found in the residual waste today, in the future is supposed to be brought to a second or third life. This includes new recycling systems for textiles, synthetic fibers, different types of plastics and other package materials.

In a project financed by the Swedish State Department of Energy wood waste, old furniture, a.s.o. are used as raw material for production of particle-board in several cycles. After final use of the wood products in building material, they can be used as a filter for eutrophicated water, and finally composted to produce soil improvement. Tannins as a non-allergic alternative for formalin, is also extracted from wood waste to be used as glue for the particle-board [19, 20]. New more effective sorting facilities for mixed plastics are also built in Värnamo and Lanna in south Sweden, which will increase the material recovery of plastics.

5 Landfill mining and the landfill as a future resource bank

Landfills can in many respects be referred to as “resource banks” for future material recovery, especially for material that cannot be used today, but might be a valuable resource in the future. Landfill mining is a technique developed in many European countries [21–24]. In Sweden, however, this technique is not economically realistic today. One reason for this is, that the non-recoverable residues from landfill mining have to be landfilled or incinerated, and then these amounts are subjected to disposal fees and taxes. Thus, landfill mining is only used in situations where the area has to be sanitized or when the area has a high market price for new housing developments. Normally restored landfill areas are instead used for parks, golf courses or as recreational areas. Old landfills are often relatively centrally situated in cities, and converting old landfills to green space and recreational areas is welcome. This
gives the landfill space an additional value as an Ecosystem Service. However, in the far future, when, e.g., metal resources or plastic polymers will become scarcer, landfill mining with new techniques can be an important way of mining material resources. Thus, landfills can be regarded as future resource banks, with a high value in the far future. The landfill mining technique is today not fully developed when it comes to a high grade of utilization of the excavated material, and much is burned. This is especially the case with polymers like plastics, synthetic textile, synthetic rubber, a.s.o. Thus burning this is a massive waste of future resources, when better refinery techniques probably will be available, and these resources thus should be re-landfilled or stay in the landfill without excavation. In the future, polymers with fossil origin, with new technical and chemical solutions, might be a valuable resource when the supply of oil has decreased.

Much of our present knowledge about ancient cultures are revealed through excavation of old rubbish dumps [25,26]. Increased interest has also been devoted to more recent excavation projects where landfills around 100 years old have been excavated to give information about the way of living and cultural and economic standards. Especially in the US and the UK such archaeological investigations of landfills are relatively usual [27,28]. Thus our present landfills can be expected to be valuable sites for archaeological investigations and historical information in the far future.

6 Conclusions

- Landfills can be regarded as future “resource banks” from where material in the far future can be excavated and used as a raw material when e.g. petroleum resources are scarce. Landfills also have a value for future archaeological and culture historical investigations.
- Landfill reactor cells act as a carbon sink for long-term sequestration. Provided produced methane is effectively collected well-controlled landfills can counteract global warming. Organic matter in the landfill also stabilizes biochemical processes and is important to minimize leaching of heavy metals.
- With modern landfill techniques, using improved landfill reactor cells, over 90 % of the produced biogas can be collected and used.
- A middle-sized landfill system, receiving approximately 100 000 tons of waste per year, and with leachate irrigation in a forest plantation, can compensate for the annual CO₂ emissions from around 20-25 000 cars.
- To minimize diffuse biogas emissions, limits should be introduced based on the actual methane emissions, rather than introducing bans on landfilling of organic matter.

7 References

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