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Climate impact of an optimised gas treatment on old landfills

Roland Berger[1] and Joachim Lehner[2]

Abstract

It is a well-established fact that the quality and quantity of landfill gas (LFG) start declining after a landfill is closed to further waste intake. Conventional gas treatment and utilisation systems such as flares and gas-driven engines require a certain quality of LFG: specifically, a sufficient methane concentration. Various measures are utilised to maintain the necessary quality of LFG, including a turn-down of gas extraction rates and a shutdown of low-quality gas wells, resulting in a decline of LFG production. This, however, does not have to be the case. The low calorific value (LCV) LFG capture and treatment technology developed by e-flox and referred to in this article as 'LCV LFG System' can significantly increase the collection rate and the amount of treated methane in an old landfill. This article introduces such new treatment measures, describes gas capture calculation methodologies and presents actual results based on a medium-sized landfill in Germany. The study demonstrates, among other things, that the LCV LFG system can reduce the CO_2 avoidance costs to roughly 10 €/t_{CO2eq}. We present this new technology as a quick and straightforward measure of dealing with the climate issues related to methane emissions of old landfills.

Keywords

Landfill, LFG, LCV, combustion, CO_2 mitigation, methane slip

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Introduction

This chapter gives a brief overview of landfill gas (LFG) formation and describes the examined landfill.

Formation of LFG in the landfills

An ideal landfill is a fully enclosed biogas reactor where organic matter in the waste is converted to LFG as a result of anaerobic processes. An ideal LFG contains, on a dry basis, around 55 Vol% CH_4 (Christensen et al., 1993), balanced by CO_2. In reality, methane concentration in the LFG will vary depending on the mix of organic material in the actual landfill and may range between 40 and 60 Vol%. The decomposition of organic matter over time can be modelled. Nowadays, the most common model is the first-order decay (FOD) model. Figure 1 shows the typical result of such a model.

An actual landfill does not produce ideal LFG. Reasons may include the fact that the landfill is not gas-tight or the gas well is subject to deterioration. On one hand, this may result in the LFG escaping the landfill body without being captured (methane emissions), and on the other, lead to the intrusion of air into the landfill body. This entrained air oxidises organics via aerobic processes, resulting in lower methane and higher CO_2 concentrations, substantial amounts of N_2 and (if not fully oxidised) elevated levels of O_2 in the LFG.

LFG generation in old landfills

In real life, the processes in a landfill are both anaerobic and aerobic. When part of the organic matter has decomposed, the recovery of LFG decreases. At the same time, air leaking into the landfill stays constant or even increases as a landfill matures. In other words, the decomposition processes shift gradually from anaerobic to aerobic over the lifetime of a landfill, leading to the decline of LFG quality (i.e. reduced methane concentrations). As traditional LFG treatment systems, such as flares and internal combustion engines do not work with CH_4 concentrations below 30%–40%, single gas wells or entire sections of the landfill have to be closed to maintain sufficient gas concentrations. The shut-off sections begin to emit uncaptured methane while the amount of usable LFG is reduced. This is often not seen as a quality problem of the gas collection system, but perceived instead only as a gas quantity concern. As a result, the gas treatment is ceased despite the fact that a considerable amount of methane is still formed and now emitted into the air.

[1]e-flox GmbH, Renningen, Germany
[2]Contec Ingenieurgesellschaft für Energie und Umwelttechnik mbH, Herrenberg, Germany

Corresponding author:
Roland Berger, e-flox GmbH, Dornierstr. 14, Renningen, 71272, Germany.
Email: roland.berger@e-flox.de

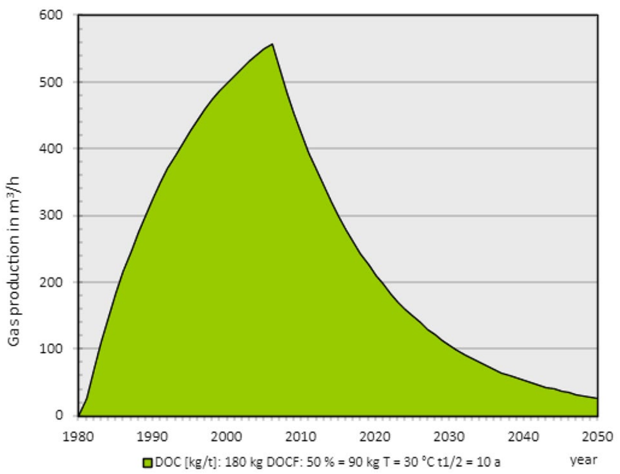

Figure 1. Typical gas recovery for a landfill, first waste in 1979, last waste in 2005.
DOC: dry organic carbon in the waste in kg*t^{-1}; DOCF: DOC available for fermentation in the landfill and t/1/2: half-life time.

In recent years, new technologies have been developed and standardised for an improved LFG collection at old landfills and a more efficient LFG treatment for gases with very low methane concentrations (VDI/DIN-Kommission Reinhaltung der Luft (KRdL), 2016, 2019).

In Germany, the implementation of these new technologies has been funded by the National Climate Protection Initiative (NKI) since 2014. This article looks at one of the first projects implemented and assesses its success in terms of

(a) Reduced climate impact;
(b) Costs for the avoidance of CO_{2eq}.

Leonberg Rübenloch landfill

Each landfill has its own characteristics. To ensure the accuracy of the assessment, it is important to understand the specific conditions of the examined landfill. The landfill in question – the Rübenloch landfill – is shown in Figure 2. It is characterised as follows:

- Total surface: 235,000 m²;
- Total volume: 4,600,000 m³;
- Volume of municipal solid waste (MSW): 2,600,000 m³ (balance construction and demolition (C&D) waste);
- Start and end of disposal: 1963–1999.

The gas system at the landfill was divided into a 'rich' and 'poor' gas sections. It allowed the landfill to keep in operation an existing gas engine system for power production, supplied mainly by high-quality wells located in the newer part of the landfill. The LCV gas treatment unit was supplied by wells in the old part and the fringe area of the landfill. The oldest part of the landfill, located on the slope of the hill, produced insufficient quality LFG due to high air entrainment in the slope, and, thus, it has never been connected to the gas treatment installation.

The new LCV LFG system implemented at the landfill in 2015 enabled the collection of previously emitted LFG, eliminating harmful methane emissions and increasing the overall quantity of recovered gas.

Review of the technologies applied

This section provides an overview of the new LCV LFG technologies for LFG collection and treatment introduced to the Rübenloch landfill in 2015.

Insipro® – Process for excessive extraction of LFG

Contec, a company specialising in landfill technologies, developed a new LFG management process that enables optimised capture of LFG as gas quality declines. This process significantly increases the amount of gas pulled out of the landfill, accepting the entrainment of larger amounts of air into the landfill body via water drains or old gas wells. This results in

(a) An increased LFG capture rate;
(b) An increase in aerobic processes.

The gas suction rate is no longer determined by the minimum methane content but, instead, by the maximum acceptable O_2 content to avoid an ignitable gas mixture (lower explosive limit (LEL)).This adjustment process requires considerable know-how related to the specific landfill and requires a periodical review. The air entrained into the landfill is oxidised in the landfill body. As a result, the CH_4/CO_2 ratio in the LFG decreases.

With the introduction of the new technology at the Rübenloch landfill, this CH_4/CO_2 ratio changed from 1.8 to 0.7. Each value below 1 shows substantial aeration of the landfill, indicating a dominating gas flow. In other words, it shows that the gas leakage into the environment (methane slip) must be lower. In turn, a CH_4/CO_2 ratio above 1 in an old landfill often indicates that gas capture is not sufficient.

There are other processes to aerate landfills and to accelerate the fermentation processes in the landfill bodies. Inspiro® does not require any air injection wells nor, typically, new LFG wells; the suction pressure is on average between 40 and 80 mbar. This means that no substantial investments are required.

E-flox LFG combustion system

The key challenge of an oxidation system for the improved gas suction method is to burn gas under 15% Vol CH_4 without supplementary fuel consumption. The main parameter is the autothermal CH_4 concentration, which is the lowest methane concentration in the LFG that can be burned without additional

Figure 2. Bird's-eye view of the landfill 'Rübenloch'.

gas. This requires pre-heating of LFG and combustion air prior to incineration by utilising the heat of flue gases of the oxidiser obtained via recuperative or regenerative heat exchangers (Berger and Lehner, 2015).

The e-flox system uses burner-integrated ceramic heat exchangers made of silicon infiltrated silicon carbide (SiSiC). These heat exchangers are robust against corrosive constituents in the LFG and can easily be cleaned from SiO_2 deposits that can form from siloxanes. Over 20 of such units are currently in operation in Germany, Switzerland, Sweden and France. These installations allow auto-thermal (unaided) combustion of LFG with as low as 6% CH_4. A further reduction to 3% can be achieved with improved heat exchangers, as the landfill aeration lowers the H_2S concentration of the LFG.

Methane emissions of the system are below 5 ppm, which means that there is virtually no methane slip. This is a significant advantage over competing systems, such as Regenerative thermal oxidiser (RTO), catalytic oxidisers or (worst case) biofilters. Furthermore, thanks to the high heat recovery of e-flox, the waste heat of the system can be used for district heating purposes via hot water heat exchangers.

Gas analysis

The following assessment is based on the LFG analysers installed in the LFG treatment container, which include the following:

1. *Gas analyser*. LFG is extracted, dried and filtered before it is directed to an NDIR CH_4 analyser, an NDIR CO_2 analyser and two O_2 analysers with a chemical sensor cell. The analysers are calibrated every 3 months.
2. *Flow sensor*. A calibrated turbine metre is installed on the pressure side of the LFG compressor. Pressure and temperature are measured at the same position to recalculate the flow to standard conditions (m^3 STP). The turbine metre and pressure sensor are recalibrated in intervals defined by the manufacturer. The temperature measurement is done by a PT100, which is not subject to any wear.

The results of these devices are stored every minute; the data logger prepares hourly mean values, which are then saved in a monthly summary report used for the evaluations presented in this article.

Methods for data collection and evaluation

Simple comparisons of total LFG flows and gas composition are of little value as both change considerably. As such, these parameters have to be viewed in combination with other factors. The current chapter tries to define a method that would allow a more apt comparison of different LFGs.

Extrapolation on LFG amounts required for the evaluation

This evaluation is based on the measurements of LFG treated in the years from 2015 to 2020. Historical data from the year 2012 were used as a business-as-usual reference (i.e. before the new LCV LFG system installation). A 10% per year theoretical LFG volume decrease was applied to the 2012 figures to account for the maturing of the landfill. This reduction rate is extrapolated from historical trends (when efforts were applied to maintain a constant high CH_4 concentration of the produced LFG).

After the implementation of the new technologies in March 2015, the volume of gas treated increased considerably. Based on the first 5 years of full operation between 2016 and 2020, a carbon decrease of only 4.7% per year was measured. This figure was extrapolated to derive the estimated gas volume up to the year 2025.

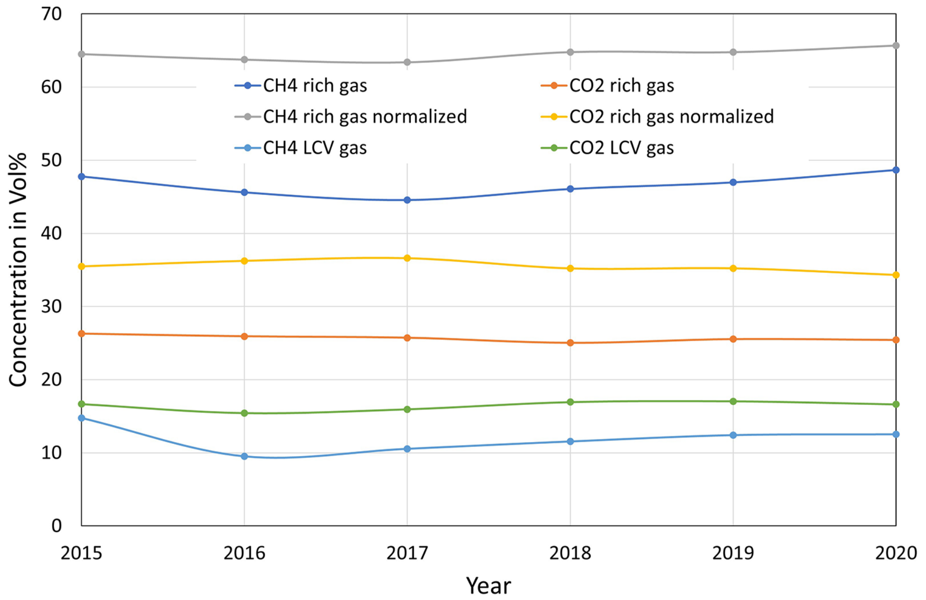

Figure 3. CH_4 and CO_2 concentrations in 'rich' and 'poor' (LCV) LFG streams and in the normalised 'rich' LFG.

Normalisation of the LFG flow

To compare LFG yields of anaerobic and aerobic sources, we normalise the volume of produced LFG by eliminating nitrogen, water and oxygen. The remaining gas only contains CH_4 and CO_2. The following formula is used

$$\dot{V}_{NLFG} = \dot{V}_{LFG} \cdot \left(x_{CH4} + x_{CO2} \right) \quad (1)$$

where x_{CH4} and x_{CO2} are the CH_4 and CO_2 concentrations, respectively, in the LFG produced.

This normalised gas stream does not distinguish between CO_2 and CH_4; in other words, it does not differentiate whether the organics are converted via anaerobic or aerobic processes in the landfill. This is essential to assess later on the climate impact of both the improved gas suction process and the gas treatment process. The normalised volume flow of LFG is the total recovered carbon as it summarises all carbon components in the LFG. Since organic carbon in the landfill body is converted to either CH_4 or CO_2, the normalisation helps determine the carbon balance of the landfill.

Reference methane concentration of generic anaerobic LFG

To evaluate the total climate impact of the implemented measures, we must compare the results with a baseline. This helps to compare LFG of different origins or in other words with different amounts of air influencing the process of LFG formation. The baseline is derived by estimating a normalised methane concentration (x_{N_CH4}) in untreated LFG produced under an entirely anaerobic process. This gas is referred to as generic LFG. For the landfill assessed in this study, we derive the generic LFG by evaluating the composition in the 'rich' gas. Figure 3 shows the CH_4 concentrations in 'rich' and 'poor' (or LCV) gases and the normalised 'rich' LFG.

The average CH_4 concentration in the normalised pure anaerobic LFG ($x_{N\_CH4} = x_{\_CH4} / (x_{\_CH4} + x_{\_CH4})$) shown in Figure 3 is 64.3 Vol%. For landfills that are entirely aerated, we suggest using a normalised methane concentration of 57%, which was determined by Gregory et al. (2014).

Climate impact calculation method

To assess the climate impact of the new LCV LFG system, we assume the reference methane concentrations as described above. With the new technologies, the capture rate of LFG is increased significantly and the LFG is oxidised regardless of its concentration. As the methane emissions of the LFG treatment are in the single-digit ppm region, we assume that all CH_4 in the gas stream is fully oxidised.

The Intergovernmental Panel on Climate Change (IPCC) provides technical information that can be used to estimate greenhouse emissions and removals, which includes a global warming potential (GWP) factor. To calculate the climate impact of the new technologies, we apply the IPCC emission factor for CH_4, which is 84 for a 20-year period (GWP20) and 28 for a 100-year period (GWP100). As all climate impact reduction targets under the Paris Treaty focus on the next 30 years, we believe GWP20 to be the more relevant factor. However, since many evaluations of climate change are based on the GWP100 factor of 28, we will consider both scenarios.

Landfill gas flows are measured in volume; therefore, the following conversion has to be applied to calculate the climate impact in units of t_{CO2eq}

$$\dot{m}_{CO_2eq}\left[t_{CO_2eq}\right] = GWP\,\dot{m}_{CH_4} = GWP\,\dot{m}_{CH_4} \cdot \rho_{CH_4}$$

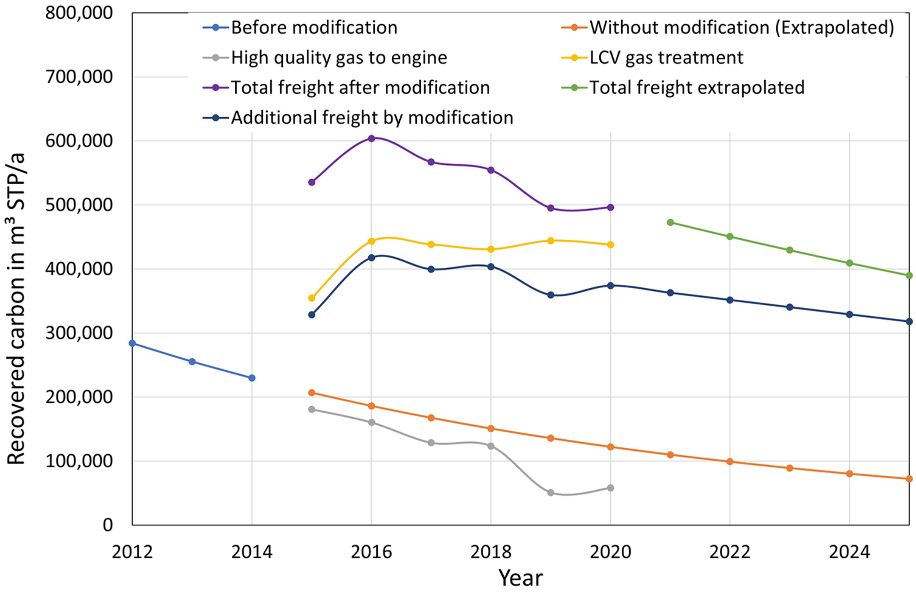

Figure 4. Normalised LFG flow or recovered carbon per year.

where $\dot{V}_{CH_4}$ is the volume flow of avoided CH_4, (i.e. CH_4 that would have been generated if the captured LFGs were entirely of anaerobic nature). This calculation gives the mass stream of CO_2 equivalent avoided by the LFG treatment.

Results

This chapter describes the impact of the modification on the landfill, and the application of the LCV LFG technology in terms of

(a) The amount of LFG treated;
(b) Climate impact of the modification.

Impact on the quantity of treated LFG

The normalised LFG flows, shown in Figure 4, were calculated using the measured LFG flows and the CO_2 and CH_4 concentrations before and after the landfill system modification. This normalised LFG flow represents all carbon leaving the landfill via the recovered LFG. We call it ‘recovered carbon’.

The recovered carbon before the modification was relatively low, and the extrapolated recovered carbon continued to decrease significantly. The 2015 modification of the system resulted in a considerable increase in recovered carbon. In April 2015, the system was restarted resulting in lower average gas rates for this year. For the 5 years between 2016 and 2020, the results on carbon freights are more significant as they represent a continuous operation for the whole period. While collected ‘rich’ gas remained nearly constant, the LCV LFG collection and treatment resulted in triple the amount of total carbon extracted from the landfill. In 2019, the ‘rich’ gas collection decreased due to problems related to the gas engine, which caused a decrease in total recovered carbon. We expect a shutdown of the engine in the near future, and a switchover of the entire system to the LCV gas treatment. This switch is expected to lead to a further increase of the total carbon treated in the system. The extrapolated total recovered carbon for years 2021 and beyond is based on the average decrease in 2016–2020, which equals a 4.71% reduction per year.

CO_2 avoidance costs of the LCV LFG treatment

The calculated recovered carbon combined with the derived stream of treated methane allows us to calculate the CO_2 avoidance volumes as shown in Figure 5. See the ‘Climate impact calculation method’ section for methodology. This chart demonstrates that substantial amounts of CO_2 equivalents can be avoided with the LCV LFG system.

Based on the avoided CO_2, the costs for this avoidance can be calculated as follows:

- *CAPEX*. We assume a 250,000 Euro cost for an LFG treatment system with a design flow rate of LFG of up to 250 m^3 STP h^{-1} and up to 500 kW peak load. This includes a plant container, a new LFG compressor, a new LFG analyser and piping work. If compressors and analysers are available, costs could be decreased to 120–150 k€.
- *OPEX*. Ten percent of CAPEX with a 3% annual increase (worst case, typical: 5% CAPEX and 2.5% annual increase).
- Financing costs are not considered.

The above costs are a conservative (worst case) assumption as gas treatment is in most cases mandatory and additional costs for the LCV LFG technologies are, therefore, lower. These cost assumptions combined with the annual volume of avoided CO_2 were taken as a basis to calculate the CO_2 avoidance costs for the Rübenloch landfill plant. They are presented in Figure 6 for both GPW20 and GWP100 factors. For GWP20, the costs decline to below 5 € t^{-1}. For GWP100, costs of almost 10 € t^{-1} are feasible. This is especially true considering that the present conservative

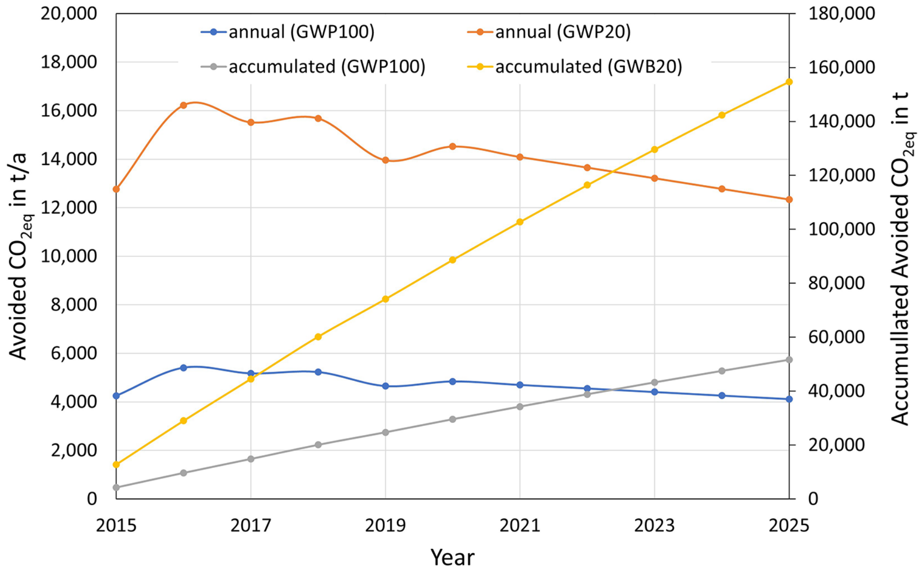

Figure 5. CO_2 avoidance annually and accumulated for 10 years after start.

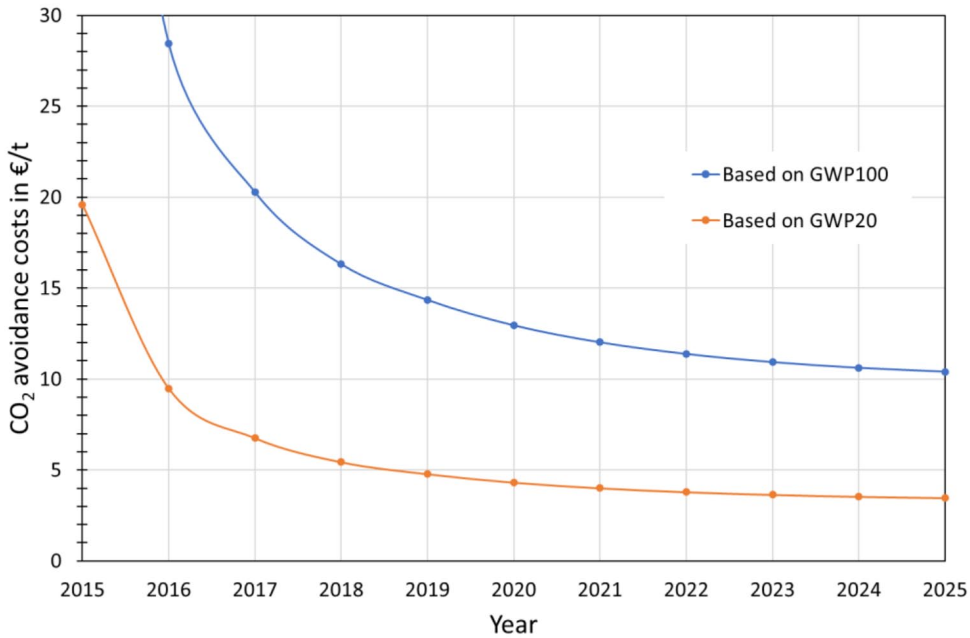

Figure 6. Decrease of CO_2 avoidance costs for the LCV LFG treatment system shown against years of operation.

figures are based on a 10-year operating time of the plant, whereas a typical calculation should assume a 20-year lifespan.

The comparison of CO_2 avoidance costs of other technologies is presented in Table 1. It demonstrates clearly that the LCV LFG technology offers a highly cost-efficient CO_2 reduction solution. Moreover, since the LFG requires treatment in any case and no new location has to be established, the introduction of this technology is very easy.

Impact on methane leakage

The above sections show that much more LFG was treated after introducing the new LCV LFG technology. Higher volumes of treated LFG mean significantly lower leakage of methane into the atmosphere. While there are no economically affordable methods yet to precisely quantify methane leakage, there are techniques to make informed estimates. The Rübenloch landfill is inspected yearly, whereby measurements on the landfill surface are taken with a flame ionisation detector (FID). The following images show the results of such measurements before and after the modification. It should be pointed out that these are only snapshots of methane concentrations taken over 1 or 2 days, and do not represent a quantitative result.

Green areas show negligible methane concentrations, while yellow, orange and red indicate increasingly higher concentrations. Although these measurements only show qualitative changes, the results are apparent. Measurements taken during the operation of the old system (Figure 7) show high methane concentrations

Table 1. Comparison of CO_2 avoidance costs of advanced LFG treatment versus renewable power technologies (FEE Kurzbericht 2005; Gillingham and Stock, 2018; Kbakhtyar et al., 2014) when comparing against conventional power generation in 2010.

Technology	Comparison	Cost in € t_{CO2eq}^{-1}
Solar technology	Existing electrical power plants	140–850
Biodiesel	Fossil diesel	150–420
Wind energy (on- and offshore)	Existing electrical power plants	20–260
Innovative LFG treatment	CH_4 emissions (GWP)	5–20

LFG: landfill gas; GWP: global warming potential.

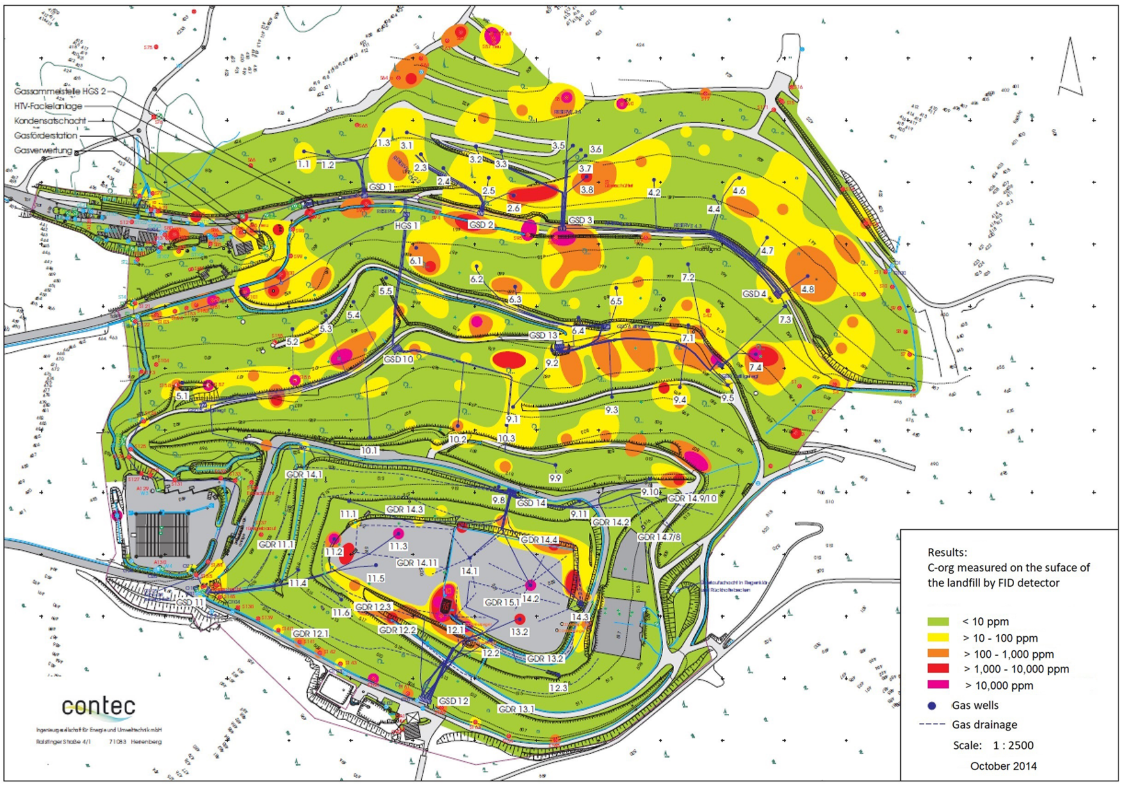

Figure 7. Results of C-org measurement on the landfill surface prior to the implementation of the new system (October 2014).

– yellow to red areas – across the entire landfill, whereas with the introduction of the new LCV LFG technology, large areas of the landfill had turned green, indicating a considerable reduction in methane leaks. Figure 8 compares measurements taken almost 4 years apart – in October 2015, shortly after implementing the new system, and again in April 2019; and it demonstrates that the positive effects of the LCV LFG system represent a long-term improvement.

Considering the significant increase in the volume of gas treated as exhibited in the preceding chapter, this result is not surprising. The measurements act as a confirmation of the efficiency of the LCV LFG system and demonstrate the improved gas treatment quality of the examined landfill.

Discussion of the results

The results described in the preceding chapters are based on measurements taken on an actual landfill, and extrapolation of such measurements. The following considerations need to be taken into account in assessing the general validity of the results:

- Are the carbon streams from LFG in line with gas prediction models?
- Does the optimised gas collection and gas treatment process generate more carbon conversion?

LFG prediction to validate the results

IPCC (2000; Pipatti and Svardal, 2006) define a modelling algorithm for assessing the LFG generation based on different types of organics in the waste and the mean time required to decompose these organics via digestion processes. This model was used to predict the LFG generation at the Rübenloch landfill examined in this article. The model requires highly accurate input data. As the required level of accuracy is impossible to obtain for an old landfill, the model results may vary in precision. However, it is

Figure 8. Results of C-org measurement on the landfill surface after the implementation of the new system (October 2015 and April 2019).

the best available method to predict the formation of LFG over time.

Figure 9 gives an overview of the normalised annual LFG recovery as calculated per the IPCC model (prognosis) and compares it with

- The normalised gas amounts calculated based on the measurement of collected LFG;
- The normalised gas amount extrapolated from the old measurement data (before the implementation of the new technique).

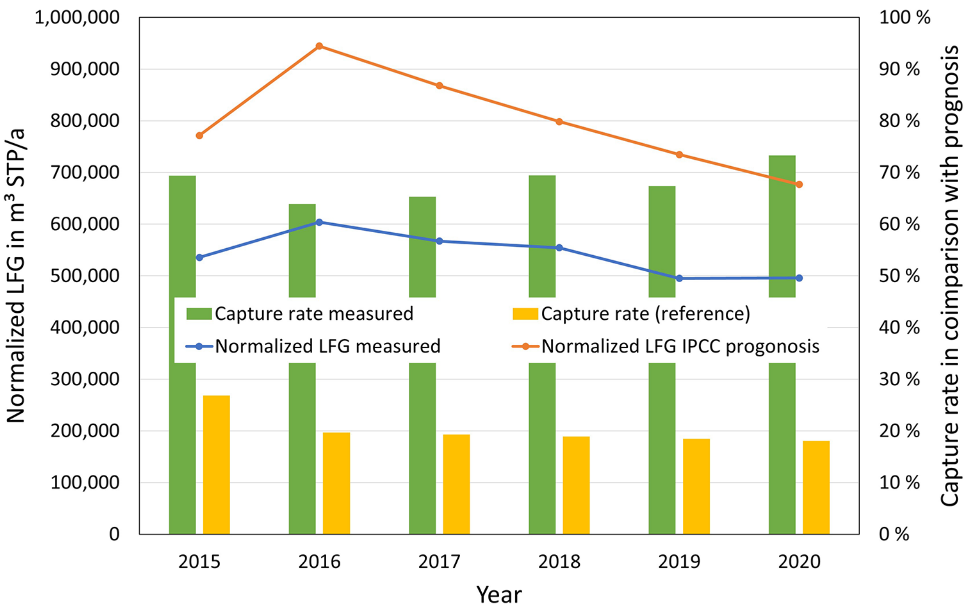

Figure 9. Carbon yield calculated with IPCC model in comparison with treated carbon.

The gas amounts are given in capture rate % as compared with the forecast data.

Note that the normalised LFG quantity forecast for the year 2015 is smaller as the count starts from April.

The chart shows that much more carbon is treated in the LFG collection system after the introduction of LCV LFG system. However, there is still a considerable gap between the calculated volumes of the Rübenloch landfill and a theoretical carbon stream. The following considerations may explain this gap:

- Inaccuracies of the input data of the model, such as tonnage and waste composition;
- The waste degradation rates are incorrect;
- The landfill surface does not yet have a sealing layer to avoid direct leakage;
- A part of the gas is still not treated due to old and/or damaged gas wells;
- Part of the gas is still not treated due to gas losses in the ‘rich’ gas area of the landfill;
- Part of the landfill body is flooded with water, this influences the digestion process.

The typical capture rates at landfills with similar treatment systems are between 60% and 110% of the calculated stream. Capture rates above 100% reflect the inaccuracy of the applied prediction calculation. Furthermore, the gap between modelled and measured recovered carbon is closing over the years (indicated by the increasing green columns in years 2016–2020 in Figure 9). The most probable reason for this is that the forecast model does not predict long-term emissions correctly. Carbon sources in the landfill with a longer half-life times seem to be more dominating in this phase. In other words, the forecast model may need to be adjusted with new data from the actual landfill.

Influence of the new gas treatment system on carbon conversion in the landfill

The new gas treatment system accepts that air is entrained into the landfill body, allowing aerobic microbes to grow. While the following effects are being discussed, they are not fully understood and are difficult to quantify

1. Air in the landfill might induce decomposition of woody biomass, which would react much slower under entirely anaerobic conditions.
2. CO_2 dissolves in water. Therefore, a higher CO_2 concentration due to the new gas treatment will result in an increased CO_2 concentration in the water. This amount of carbon is not taken into account in our balance, resulting in an underestimation of the amount of captured LFG.
3. Aerobic processes increase the temperature of the landfill. Thus, both aerobic and anaerobic processes are accelerated, yielding an increased LFG recovery.

These phenomena influence the digestion processes in the landfill and increase the gas recovery while applying the LCV LFG process. For the operator of the landfill, this is not necessarily a disadvantage. The idea is to accelerate the biomass conversion and cease active gas treatment (ideally) within 20 years after implementing the new process, which can be seen as a valuable benefit. However, gas capture rates identified in the preceding chapter show no substantial increase in digestion rates when comparing to the existing models.

Nevertheless, this potential accelerated biomass conversion and gas recovery might yield more carbon converted than under normal conditions, which is not an advantage in terms of carbon capture. We think that this effect is marginal compared to the considerable improvement of methane treatment. Further research is required to understand the extent to which it contributes to the overall LFG recovery.

Conclusion

The results of a 5-year experience with the new LCV LFG treatment technology show that this technology can dramatically increase the quantity of carbon treatment, thus reducing the climate impact of an old landfill by oxidising methane to CO_2. Even when calculating this reduction with only the GWP100 factor, which does not reflect the large medium-term impact of the measure, the system provides for a relatively small landfill an average reduction of about 4000 t CO_2 per year. For Germany, this corresponds with a specific CO_2 emission in the power sector for 2019 of 401 g CO_2 kWh_{el}^{-1} (Icha, 2020) with 9.975 MWh_{el} or a continuous regenerative load of 1.14 MW_{el} (for 8750 h a^{-1}). When compared with wind power with a maximum value of 2000 full-load hours per year (only valid for good wind locations) and a specific CO_2 emission of 7–(11)–56 g kWh_{el}^{-1} (Schlömer et al., 2014), this corresponds to a wind power plant of about 5 MW_{el}. In other words, the CO_2 reduction achieved with the Rübenloch project is comparable to a 5 MW_{el} wind turbine. Furthermore, if we were to consider a 20-year time frame – the expected lifetime of a wind turbine – using the GWP20 instead of the GWP100 factor, the effect is comparable to about 15 MW_{el} of wind power generation.

In comparing the costs for such CO_2 reduction, it is evident that national and international policies should ensure that old landfills are accounted for in national CO_2 budgets and measures for emission reduction. Old landfills should get the highest priority in climate protection legislation. They offer an affordable and straightforward method for CO_2 mitigation.

This article focussed on the effect of LCV treatment technology on old landfills. However, landfills in operation might suffer from such low LFG recovery as well as the high air leakage of the open landfill results in low-quality LFG as well and LFG quantities are much higher in this phase of the landfills life. This should be subject to further investigations.

Declaration of conflicting interests

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