Ex-Ante Assessment of Technical Concepts for the Considered Technologies of Landfill Gas Utilization

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Low Calorific Gas for Green Power Production

LOW CALORIFIC GAS FOR GREEN POWER PRODUCTION

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by

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LoCaGas

Preface

This report presents the ex-ante assessment of technical concepts undertaken within the framework of the LoCaGas project, which focuses on innovative and decentralised pathways for the utilisation of landfill gas. The primary purpose of this document is to provide an early and structured evaluation of the technologies selected for consideration in the project, covering thermal, biological, chemical, and mechanical approaches to landfill gas upgrading and valorisation. As LoCaGas aims to identify cost-effective, low-emission, and site-adapted solutions, the assessment places emphasis on technological feasibility, integration potential, environmental performance, and the readiness of each concept for further development.

The ex-ante analysis consolidates existing scientific and technical knowledge, benchmark data, and expert insights from project partners. It serves as a foundation for upcoming research activities, including laboratory investigations, pilot-scale validation, and advanced modelling work planned in subsequent work packages. By identifying opportunities, limitations, and knowledge gaps at an early stage, the assessment contributes to the strategic orientation and prioritisation of technologies to be pursued within the project.

This report is intended for engineers, researchers, and stakeholders involved in waste management, renewable energy, and resource recovery. It also supports broader dialogue on the role of landfill gas in sustainable energy systems and the transition toward circular, low-carbon solutions.

We would like to express our appreciation to all contributors whose expertise and collaboration made this report possible.

On behalf of all LoCaGas project partners,

Robert Aranowski
Gdańsk, March 2026

Executive Summary

This report presents the current state of legislation, technologies, and operational practices related to the management and utilisation of low-calorific landfill gas (LCLFG), prepared within the framework of the LoCaGas project funded by the Interreg South Baltic Programme 2021–2027. The project addresses the growing environmental challenge associated with methane emissions from ageing landfills, which remain an important source of greenhouse gas emissions within the European Union.

The progressive reduction of biodegradable waste landfilling across Europe has resulted in decreasing methane concentrations in landfill gas streams. Consequently, conventional energy recovery systems such as gas engines and turbines often become inefficient or technically unsuitable for the utilisation of low-calorific landfill gas. This leads to increased methane emissions, underutilisation of the remaining energy potential, and growing operational difficulties for landfill operators.

To address these challenges, the LoCaGas project investigates innovative and decentralised solutions for the utilisation and treatment of LCLFG. The report focuses particularly on three technologies selected for further development and assessment within the project:

- Dual-Fuel Engines (DFE),
- Oxygen-Enriched Combustion (OEC),
- Spinning Fluids Reactors (SFR).

The report provides a comprehensive overview of the European and national regulatory frameworks governing landfill gas management in the participating countries: Germany, Poland, Sweden, and Lithuania, with Denmark participating as an associated partner. Current landfill gas extraction practices, utilisation pathways, and infrastructure availability are analysed to identify technological gaps and opportunities for implementation of advanced LCLFG treatment systems.

In addition, the report reviews and compares a broad spectrum of existing technologies applicable to low-calorific landfill gas, including thermal, biological, chemical, and physico-chemical approaches. Particular attention is given to flaring systems, microturbines, Stirling engines, catalytic oxidation systems, biofilters, and upgrading technologies such as pressure swing adsorption, membrane separation, and amine scrubbing. Their applicability to low-methane landfill gas streams, environmental performance, and energy recovery potential are critically evaluated.

A major component of the report is the preliminary ex-ante sustainability assessment of the analysed technologies, including environmental and energy-performance indicators based on Life Cycle Assessment (LCA) methodology. The assessment highlights significant trade-offs between energy efficiency, auxiliary energy demand, and greenhouse gas emissions.

The Oxygen-Enriched Combustion (OEC) concept demonstrates the highest net electrical energy output and overall efficiency among the analysed options. However, its environmental performance is partially limited by increased CO_2 emissions associated with oxygen production and electricity consumption. The Dual-Fuel Engine (DFE) concept offers operational robustness under very low methane concentrations, although its performance depends strongly on the type and share of pilot fuel required for stable combustion.

The Spinning Fluids Reactor (SFR) concept exhibits the lowest net energy output due to the auxiliary electricity demand associated with gas pretreatment and methane enrichment. Nevertheless, the reported net energy output of approximately 0.97 MJ Nm^{-3} was calculated assuming a methane concentration of only about 20% vol. in the raw landfill gas. The SFR technology significantly increases the calorific value and combustion stability of the treated gas, potentially enabling its utilisation in conventional or slightly modified gas engines. For methane concentrations of approximately 45% and higher, the expected engine efficiency may become comparable to that of conventional spark-ignition gas engines.

Consequently, the SFR concept may become environmentally and energetically attractive, particularly when low-carbon electricity is available for auxiliary processes.

The report also emphasises that the presented assessment remains subject to considerable uncertainty due to the reliance on secondary literature data, simplified system boundaries, and early-stage technological assumptions. Nevertheless, the ex-ante analysis provides a valuable basis for subsequent laboratory investigations, pilot-scale validation, modelling activities, and the development of a decision-support methodology for landfill operators.

Ultimately, this report serves as a strategic and technical foundation for the LoCaGas project, supporting the identification of cost-effective, low-emission, and site-adapted solutions for sustainable landfill gas utilisation in alignment with the EU Methane Strategy and the European Green Deal.

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Abbreviations

Abbreviation	Definition
AFR	Air–Fuel Ratio
BAT	Best Available Techniques
BGES	Biogas Energy Share
CHP	Combined Heat and Power
DEA	Diethanolamine, secondary amine solvent used for CO_2 and H_2S absorption
DFE	Dual Fuels Engine
DOC	Degradable Organic Carbon
EU	European Union
EPI	Early Pilot Injection
FFT	Fast Fourier Transform
FOD	First Order of Decay
GHG	Greenhouse Gas
GWP_{100}	Global Warming Potential over 100 years
HVO	Hydrogenated Vegetable Oil
ICE	Internal Combustion Engines
IED	Industrial Emissions Directive
IPCC	Intergovernmental Panel on Climate Change
IPP	Inner Porous Partition
LCA	Life Cycle Assessment
LCV	Low Calorific Value
LCLFG	Low Calorific Landfill Gas
LHV	Lower Heating Value
LFG	Landfill Gas
MAE, MDEA	Methyldiethanolamine, tertiary amine solvent for acid gas removal, $C_5H_{11}NO_2$
MCP	Medium Combustion Plant
MMMs	Mixed-Matrix Membranes
MOFs	Metal–Organic Frameworks
MSW	Municipal Solid Waste
NIR	National Inventory Report
NRU	Nitrogen Rejection Units
NEC	National Emission Ceilings
NMVOC	Non–Methane Volatile Organic Compounds
OEC	Oxygen-Enriched Combustion
OERs	Oxygen Enrichment Ratios
ORC	Organic Rankine Cycle
PDMS	Polydimethylsiloxane, silicone-based polymer used in gas separation membranes

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Abbreviation	Definition
PI	Post-Injection
PSA	Pressure Swing Adsorption
PTSA	Pressure-Temperature Swing Adsorption
RED II	Renewable Energy Directive UE 2018/2001
RED III	Renewable Energy Directive UE 2023/2413
RCCI	Reactivity Controlled Compression Ignition
RTD	Residence Time Distribution
RTO	Regenerative Thermal Oxidation
RME	Rape Methyl Ester
ReCiPe	Life Cycle Impact Assessment methodology used to translate life cycle inventory results into environmental impact indicators
TFS	Thin-Film Composite membrane
SFR	Spinning Fluids Reactor
SI	Spark Ignition
SOIT	Start of Injection Timing
VOC	Volatile Organic Compound
VOCs	Volatile Organic Compounds
UNFCCC	United Nations Framework Convention on Climate Change

1

Introduction

The Low Calorific Gas for Energy Production (LoCaGas) project, funded by the Interreg South Baltic Programme 2021–2027, addresses two of the pressing environmental challenges of our time: methane emissions from landfills. Methane is a potent greenhouse gas and landfills are the third-largest anthropogenic source of methane in the European Union. With many EU member states banning landfilling of organic waste, the methane concentration in landfill gas has significantly declined, making it increasingly difficult to utilize this gas for energy recovery. Conventional technologies such as spark ignited gas engines require a methane content of approximately 40%. As a result, landfills, including closed ones, continue to emit methane into the atmosphere, posing environmental risks and representing a loss of potential energy.

In response, the *LoCaGas* project explores innovative technologies capable of utilizing low-calorific landfill gas for the generation of green electricity and heat. The project evaluates three advanced technical options for treating landfill gas with low methane content, namely Dual Fuel Engines, Spinning Fluids Reactors and Oxygen Enriched Combustion. These technologies are being developed and tested across different countries, underlining the need for international collaboration. Beyond laboratory and pilot-scale testing, *LoCaGas* integrates a sustainability assessment that includes environmental and economic criteria, and aims to develop a decision-making tool for landfill operators based on life cycle assessment. In alignment with the *EU Methane Strategy and the European Green Deal*, the project contributes to reducing greenhouse gas emissions and fostering cross-border cooperation in the Baltic region.

This report presents a comprehensive overview of the current state of legislation and technological solutions related to the treatment and utilization of landfill gas with low methane content. The primary goal is to provide background information and context on relevant national and EU-level regulatory frameworks that govern waste and landfill gas management. Each partner country of the *LoCaGas* project - Germany, Poland, Sweden and Lithuania - is examined individually, with a focus on laws, norms, and inventory reporting practices related to landfill gas emissions. The report also outlines how landfill gas is currently used in each country, including extraction rates, energy recovery practices, and available infrastructure. Denmark is an associated partner of the *LoCaGas* project which is why it is mentioned in this report as well.

Furthermore, the report introduces and compares a wide range of technologies for processing LCLFG. These include thermal, biological, and chemical-physical methods, with a special focus on flaring systems, microturbines, Stirling engines, biofilters, and upgrading techniques such as pressure swing adsorption. Each technology is assessed based on its suitability for LCLFG and its potential to support both emission reduction and energy recovery. Furthermore, the report provides specific background information on the mentioned project technologies.

By combining legal analysis and technical evaluation, this document serves as a foundation for understanding the challenges and opportunities in dealing with low-calorific landfill gas. It also supports the broader goals of the *LoCaGas* project by informing future investments and policy recommendations for sustainable landfill gas management.

2

Landfill Gas Potential and Characterization

2.1. Introduction

Landfill gas is produced through the anaerobic degradation of biodegradable waste deposited in landfills. It typically consists mainly of methane (CH_4) and carbon dioxide (CO_2), with smaller fractions of nitrogen (N_2), oxygen (O_2), and trace components such as hydrogen sulphide (H_2S), volatile organic compounds (VOCs), and siloxanes [1–3]. In the European Union, methane emissions from solid waste disposal remain a relevant component of total waste-sector CH_4 emissions; however, both landfilling activities and the associated emissions have been steadily declining over recent decades as a result of EU waste management and landfill policies [4–6].

Within the LoCaGas project, the focus is placed specifically on low-calorific landfill gas, i.e. gas streams characterised by a reduced methane content and, consequently, a substantially lower heating value. Such streams typically originate from ageing landfills, air ingress, stringent diversion of organic waste from landfilling, and partial gas capture in complex landfill geometries. At the same time, regulatory obligations to collect and treat landfill gas, together with its recognition as a renewable fuel, create a strong incentive to develop technologies capable of efficiently utilising these low-calorific gas streams [7, 8].

This chapter provides:

- a concise overview of landfill gas generation processes and its typical composition;
- a definition and categorisation of low-calorific landfill gas, including indicative lower heating value ranges;
- an overview of EU-wide trends in waste landfilling and landfill methane emissions relevant to the LoCaGas scenarios;
- country-specific characterisation of the LoCaGas partner countries (Poland, Lithuania, Sweden, Denmark, and Germany);
- a set of quantitative LCLFG scenarios for use in the ex-ante assessment of the LoCaGas technologies.

2.2. Generation and Composition of Landfill Gas

2.2.1. Introduction

Landfill gas is generated as biodegradable organic matter contained in municipal solid waste undergoes a sequence of anaerobic biochemical processes, typically described as hydrolysis, acidogenesis, acetogenesis, and methanogenesis [1]. These processes occur sequentially but may overlap spatially and temporally within the landfill body, depending on moisture availability, temperature, waste composition, and landfill operation practices.

The temporal profile of landfill gas generation is commonly characterised by an initial lag phase following waste placement, during which anaerobic conditions are established, followed by a quasi-steady plateau phase with sustained gas production, and finally a long declining tail. This decline phase may extend over several decades - often 20–40 years or more - depending on climatic conditions, the fraction of biodegradable waste, and landfill engineering measures such as compaction, cover systems, and leachate recirculation.

2.2.2. LFG Generation Models

IPCC Approach

In first-order decay models widely applied by the IPCC and in national greenhouse gas inventories, the annual methane generation rate $Q_{\mathrm{CH4}}(t)$ is approximated by Equation 2.1:

$$Q_{\mathrm{CH4}}(t) = \sum_{i} M_i \, L_{0,i} \, k_i \, e^{-k_i (t - t_i)}, \tag{2.1}$$

where M_i denotes the mass of waste disposed in year i, $L_{0,i}$ is the ultimate methane generation potential of the corresponding waste fraction, and k_i is the first-order decay rate constant [1, 9]. The parameter L_0 reflects the biodegradable organic carbon content and its conversion efficiency to methane, while k accounts for the kinetics of biodegradation, which are strongly influenced by climatic conditions and waste management practices.

Typical values of L_0 for mixed municipal solid waste are reported in the range of 80–170 $\mathrm{m}^3\,\mathrm{t}^{-1}$ of wet waste, with significantly higher values associated with readily biodegradable fractions such as food waste and other biogenic materials [7, 10]. As a result, changes in waste composition driven by waste prevention and separate collection policies directly affect both the magnitude and the temporal evolution of landfill methane generation.

Figure 2.1 schematically illustrates the temporal evolution of landfill gas production within a waste body. The figure is based on the original conceptual model proposed by Farquhar and Rovers (1973) [11], extended to include the post-closure phase (Stage V). In addition to the characteristic stages of landfill gas generation, the figure also depicts the variation in landfill gas production rates over the operational lifetime of the landfill, as well as the associated settlement behaviour.

Scholl Canyon Model

The *Scholl Canyon* model is a practical first-order kinetic approach widely used for project design and regulatory applications (especially in North America). In its common discrete form, the annual methane generation rate is computed by summing the contributions from waste accepted in prior years:

$$Q_{\mathrm{CH}_4}(t) = \sum_{i} k \, L_0 \, M_i \, e^{-k(t - t_i)}. \tag{2.2}$$

In practice, model implementations often include assumptions about the waste acceptance schedule, conversion factors between biogas and methane, and (in some guidelines) an optional lag to represent the onset of methanogenesis. The model is described in engineering guidance and has been used as a foundation for later tools such as LandGEM [12].

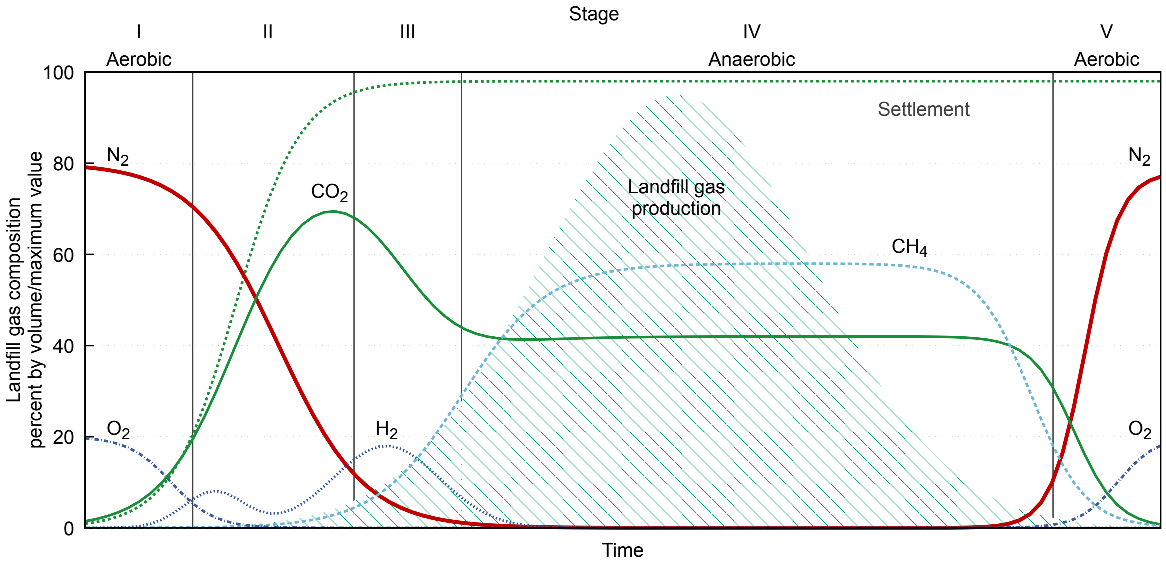

Figure 2.1: Changes in the production and composition of landfill gas over time (Based On Farquhar And Rovers).

US EPA LandGEM Model

LandGEM is a widely adopted implementation of a first-order landfill gas model used for screening-level estimates and project planning. Conceptually it remains first-order, but it standardizes inputs and default parameters (notably k and L_0) and provides a consistent computational framework for estimating total LFG or methane generation over time [13, 14]. LandGEM is often applied with site-specific calibration where measurements are available, because default parameters can under- or over-estimate for specific climates, waste compositions, and operational practices.

GasSim/GasSim2 Model

GasSim (and its later developments such as *GasSim2*) were developed for UK regulatory/risk-assessment practice and incorporate a multiphase representation of waste degradability, commonly decomposing waste into pools with different decay rates (fast/medium/slow) based on biodegradable fractions [15–17]. In addition to generation, GasSim frameworks typically connect generation to emissions via modules for collection efficiency, oxidation, lateral migration, and uncertainty treatment (often via probabilistic/Monte Carlo approaches), making them more comprehensive than a pure generation-only equation.

Dutch TNO First-Order Model and Afvalzorg Multiphase Model

In the Netherlands, a number of national and project-level tools have been used historically, including the *TNO* first-order model and the *Afvalzorg* multiphase model. The TNO approach is generally first-order, while the Afvalzorg approach is commonly presented as a multiphase model where separate degradable pools (or waste fractions) decay independently with different rate constants [17–19]. Such multiphase structures can improve fit to observed LFG time profiles, particularly where readily degradable organics produce an early peak and slowly degradable fractions sustain long tails.

EPER/E-PRTR Model

Several European inventory-oriented methods have been used under EPER/E-PRTR reporting contexts. These approaches differ in kinetics complexity and how they treat recovery, oxidation, and what portion of historical waste acceptance is considered. Comparative studies document that, depending on the national approach, models may range from simplified first-order formulations to even more aggregated (e.g., effectively “zero-order” or limited time-window) representations [1, 17, 20]. These models are generally aimed at consistent national reporting rather than detailed site engineering forecasts.

Sigmoidal Empirical Models

When sufficient field data exist (e.g., measured gas extraction rates), *sigmoidal* models can be used to represent the cumulative methane production curve. A commonly used example is the *Modified Gompertz* model for cumulative methane yield:

$$G(t) = G_{\max} \exp\left\{-\exp\left[\frac{R_{\max}e}{G_{\max}}(\lambda - t) + 1\right]\right\}, \tag{2.3}$$

where $G_{\max}$ is the ultimate methane potential, $R_{\max}$ is the maximum production rate, and λ is a lag parameter. Logistic variants are also used. These models are often chosen for curve-fitting and forecasting from observed trends rather than mechanistic interpretation, and have been compared against first-order approaches in the literature [21, 22].

Data-Driven and Hybrid Approaches

A growing set of studies combine classic kinetic structures (first-order or multiphase) with parameter estimation, optimization, and uncertainty analysis. Examples include calibrating k and L_0 to site data, using genetic algorithms to fit fraction-specific parameters, or applying machine learning to estimate empirical-model parameters (e.g., Gompertz) [22–24]. These approaches can improve predictive performance where monitoring data exist, but require careful validation to avoid overfitting and to preserve physical plausibility.

Typical Composition of Landfill Gas

Under well-established anaerobic conditions and in the absence of significant air ingress, landfill gas composition is relatively stable and dominated by methane (CH_4) and carbon dioxide (CO_2), typically present in approximately equimolar proportions. Numerous reviews and field measurement campaigns report methane concentrations in the range of 45–60 vol.% for *conventional* landfill gas, accompanied by carbon dioxide contents of 35–50 vol.%. The remaining fraction consists primarily of nitrogen (N_2), oxygen (O_2), and a wide range of trace components [1, 2, 7, 25, 26].

These trace components include reduced sulphur compounds, notably hydrogen sulphide (H_2S), as well as volatile organic compounds (VOCs) and siloxanes. Although present at ppm or sub-ppm levels, such constituents are of particular relevance for gas utilisation systems, as they contribute to corrosion, catalyst poisoning, and engine fouling, and may significantly influence emission performance and maintenance requirements.

Table 2.1 summarises indicative composition ranges for landfill gas in a European context, based on recent literature sources and monitoring data from operating landfill sites.

Field measurements at European landfill sites confirm that, although methane concentrations of 45–60 vol.% are commonly reported as typical, substantial spatial and temporal variability occurs within individual landfills. Variations arise due to heterogeneous waste composition, uneven settlement, localised air ingress, and differences in gas collection efficiency. For example, a recent study conducted at a Polish municipal landfill reported methane concentrations ranging from 30 to 63 vol.% and carbon dioxide contents between 18 and 42 vol.%, with oxygen levels locally reaching up to 9.8 vol.% in certain sectors of the site [25]. Comparable levels of variability have been documented for landfill sites in the Czech Republic and Romania, highlighting the inherently heterogeneous nature of landfill gas systems [26, 27].

2.3. Definition and Relevance of Low-Calorific Landfill Gas

2.3.1. Concept and Thresholds

For the purposes of the LoCaGas project, we use the term *low-calorific landfill gas* (LCLFG) to describe LFG streams with significantly reduced methane content and thus lower energy density, typically due to:

- advanced landfill age and depletion of readily degradable organics;
- partial mixing with air through defects in the cover system or poorly sealed gas wells;

Table 2.1: Indicative composition ranges of landfill gas in typical EU landfills (volume percent, dry basis) [1, 2, 7, 25].

Component	Typical range [vol.%]	Comments
CH_4	45–60	Primary energy carrier; declines with air ingress and landfill ageing
CO_2	35–50	Product of biological degradation; partly dissolves in leachate
N_2	0–15	Indicative of air intrusion; leaks in cover systems and gas wells
O_2	0–5	Marker of significant air ingress; may locally reach $\sim$10%
H_2S	0–1 000 ppm	Strongly dependent on waste composition (e.g. gypsum, sulphur-containing waste)
Others (VOCs, siloxanes, etc.)	trace (hundreds ppm)	Relevant for engine fouling, corrosion, and emissions

- strong diversion of organic waste from landfill, leading to lower average methane potential for the remaining waste;
- intermittent or low-pressure gas extraction regimes.

Table 2.2 proposes a practical classification of LFG quality classes, including indicative lower heating values assuming a linear relation with CH_4 fraction and a methane LHV of 35.8 MJ Nm^{-3}.

Table 2.2: Proposed landfill gas quality classes and indicative lower heating values.

Class	Description	CH_4 [vol.%]	Typical use	Indicative LHV [MJ Nm^{-3}]
C1	Conventional LFG	45–60	Standard CHP engines, boilers	16–21
C2	Moderately diluted LFG	30–45	Robust engines, microturbines, SFR	11–16
C3	Low-calorific LFG	15–30	Dual-fuel engines, SFR, specialised burners	5–11
C4	Very low-calorific LFG	5–15	Thermal/catalytic oxidation, niche power	2–5

The applicability of conventional LFG utilisation technologies, such as flaring and gas engine-based CHP units, is strongly dependent on the calorific value of the gas, typically expressed as the LHV. From a fundamental perspective, the absolute lower limit for methane combustion is defined by its flammability threshold in air (approximately 5% vol. CH_4), corresponding to an LHV of about 1.8–2.0 MJ/Nm^3. However, this value only represents the ignition limit and does not ensure stable or efficient operation of combustion systems.

In practical applications, significantly higher calorific values are required. For landfill gas flaring systems, the minimum LHV for stable and continuous combustion typically ranges from 5 to 10 MJ/Nm^3, depending on flare design, the presence of pilot burners, and combustion air control systems. Below this range, flame instability, incomplete combustion, and increased emissions of carbon monoxide and volatile organic compounds may occur.

Gas engine-based CHP units impose more stringent requirements due to the need for stable in-cylinder combustion and reliable ignition. In most commercial systems, a minimum LHV of approximately 12–15 MJ/Nm^3 (corresponding to roughly 35–40% vol. CH_4) is required to ensure proper operation, acceptable efficiency, and to avoid misfiring or engine damage. Although some modern engines are capable of operating at lower methane concentrations, this typically requires advanced control systems or gas conditioning.

Consequently, landfill gas streams with calorific values below approximately 5 MJ/Nm^3 are generally unsuitable for utilisation technologies and may require upgrading, enrichment, or alternative conversion pathways, like flaring.

From an energy systems perspective, classes *C3–C4* are the most challenging, as many conventional utilisation technologies can no longer operate with acceptable stability and efficiency. However, regulatory pressure to control methane emissions–including from residual and closed landfills–makes these streams highly relevant for future mitigation strategies [4, 7].

2.3.2. Effect of Methane Content on Energy Density

The lower heating value (LHV) of landfill gas is primarily determined by its methane content, as methane is the main combustible component of the gas mixture. For pure methane, the LHV is commonly reported to be approximately 35.8 MJ Nm^{-3} [28, 29].

Assuming that the remaining components of landfill gas, such as carbon dioxide and nitrogen, are inert with respect to combustion, the LHV of landfill gas can be approximated as scaling linearly with the volumetric fraction of methane. This simplified relationship is frequently used for indicative analyses and preliminary assessments of low-calorific gases [30, 31].

Based on this assumption, the indicative relationship between methane content and LHV presented in this report was derived by linear interpolation between zero calorific value at 0 vol.% CH_4 and the reference LHV of pure methane. While this approach neglects minor effects related to gas impurities and non-ideal behaviour, it provides a transparent and sufficiently accurate representation for comparative and conceptual analyses within the scope of the LoCaGas project.

Figure 2.2 illustrates the approximate relationship between methane content and LHV for an idealised LFG mixture composed of CH_4, CO_2 and inert gases (N_2/O_2). The curve highlights the rapid loss of energy density when CH_4 falls below about 30 vol.%; this defines the critical region for LCLFG technologies such as those investigated in LoCaGas project.

Limitations of LHV and Alternative Indicators of Energy Usability

While the lower heating value (LHV) provides a convenient measure of the chemical energy content of landfill gas, it does not fully reflect its practical usability in combustion systems. In particular, the presence of non-combustible components such as carbon dioxide (CO_2) and nitrogen (N_2) introduces a significant inert ballast, which must be heated during combustion and thus reduces the achievable flame temperature and overall process efficiency.

As a result, two gas mixtures with identical LHV values but different compositions may exhibit substantially different combustion behaviour, including flame stability, ignition limits, and pollutant formation. This effect becomes particularly pronounced for low-calorific landfill gas, where high fractions of inert components strongly dilute the combustible fraction.

To better characterise the practical energy performance of such gas mixtures, additional indicators are commonly used:

- **Wobbe Index (WI)** – defined as the ratio of the heating value to the square root of the relative gas density:

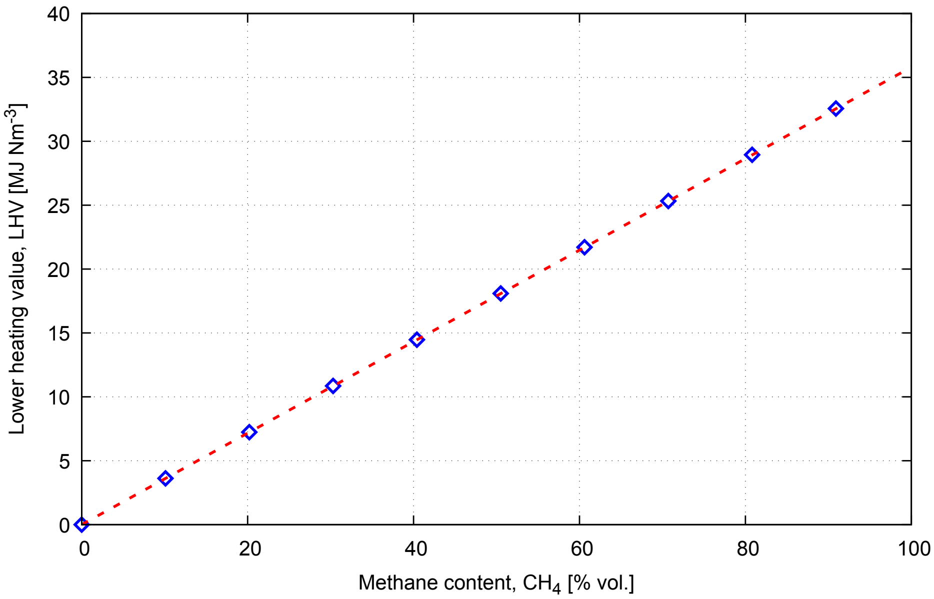

Figure 2.2: Indicative relation between methane content and lower heating value (LHV) of landfill gas. Values assume a methane LHV of 35.8 MJ Nm^{-3} and linear scaling with CH_4 volume fraction.

$$WI = \frac{LHV_{\mathrm{mix}}}{\sqrt{d}}, \tag{2.4}$$

where d is the gas density relative to air. The Wobbe Index is widely used in gas engineering because it directly relates to the energy input through a burner or engine under constant pressure conditions. It implicitly accounts for both the energy content and the effect of inert dilution on volumetric flow rates.

- **Adiabatic flame temperature** – a fundamental thermodynamic parameter describing the maximum achievable temperature during ideal combustion. The presence of CO_2 and other inert gases reduces this temperature due to their heat capacity, thereby weakening flame intensity and potentially limiting stable combustion.
- **Combustion stability limits** – including minimum methane concentration and flammability limits. Even if the LHV remains non-zero, highly diluted mixtures may fall below practical thresholds required for stable operation in engines or burners.
- **Useful energy output** – defined as the product of the fuel LHV and the conversion efficiency of a given technology:

$$E_{\mathrm{useful}} = LHV_{\mathrm{mix}} \cdot \eta, \tag{2.5}$$

where η is not constant but typically decreases with increasing dilution by inert gases.

Among these indicators, the Wobbe Index and the adiabatic flame temperature are particularly relevant for comparing low-calorific gas streams, as they explicitly account for the diluting effect of non-combustible components. Therefore, in the context of LCLFG utilisation, LHV should be interpreted together with these complementary parameters to obtain a more realistic assessment of energy usability.

It can be observed that the decrease in the Wobbe Index is more pronounced than the reduction in LHV, reflecting the combined effect of reduced methane content and increasing gas density due to CO_2 dilution.

Figure 2.3 presents the corresponding relationship between methane content and the Wobbe Index. In contrast to LHV, the Wobbe Index decreases more rapidly at low methane concentrations, reflecting not

Table 2.3: Comparison of LHV and Wobbe Index for representative CH_4–CO_2 landfill gas mixtures.

Class	CH_4 [vol.%]	LHV [MJ Nm^{-3}]	Relative density d [-]	Wobbe Index [MJ Nm^{-3}]
C1	50	17.9	1.04	17.5
C2	37.5	13.4	1.18	12.3
C3	22.5	8.1	1.30	7.1
C4	10	3.6	1.42	3.0

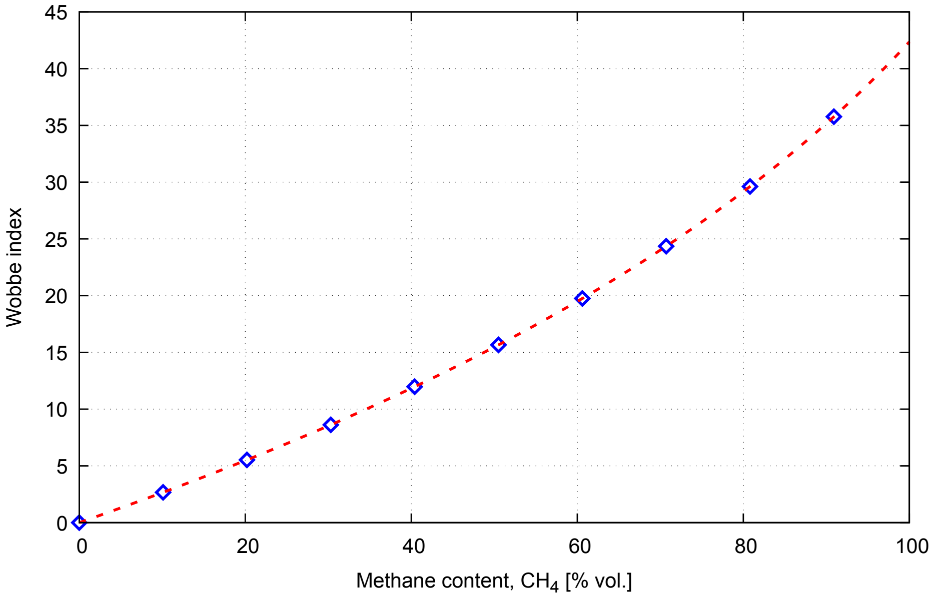

Figure 2.3: Indicative relation between methane content and Wobbe Index for landfill gas. Values assume a CH_4–CO_2 mixture and account for changes in gas density due to CO_2 dilution.

only the reduction in chemical energy content but also the increasing density of the gas mixture due to CO_2 dilution. This behaviour is particularly relevant for assessing the operability of low-calorific landfill gas in combustion systems.

2.4. EU-Wide Trends Relevant for LFG and LCLFG

2.4.1. Waste Landfilling and Methane Emissions

Across the EU-27, waste management policies have substantially reduced the proportion of waste sent to landfill. Eurostat and EEA data show that the total amount of waste (excluding major mineral wastes) entering landfills decreased from around 173 Mt in 2010 to 137 Mt in 2022 (a reduction from 23% to 17% of domestically generated waste) [5, 6]. For municipal waste, landfilling fell by about 58% between 1995 and 2023, from roughly 121 Mt to 51 Mt [32].

In parallel, methane emissions from the waste sector have declined by roughly one third since 1990, with solid waste disposal on land accounting for about 80% of waste-sector CH_4 emissions [4]. Recent modelling for the EU suggests that average LFG methane content at many sites still lies in the 45–60% range, but the volume of gas generated, and the fraction occurring as higher-dilution residual streams, is evolving towards lower and more variable values [7].

Table 2.4 summarises indicative trends relevant for LoCaGas project scenario building.

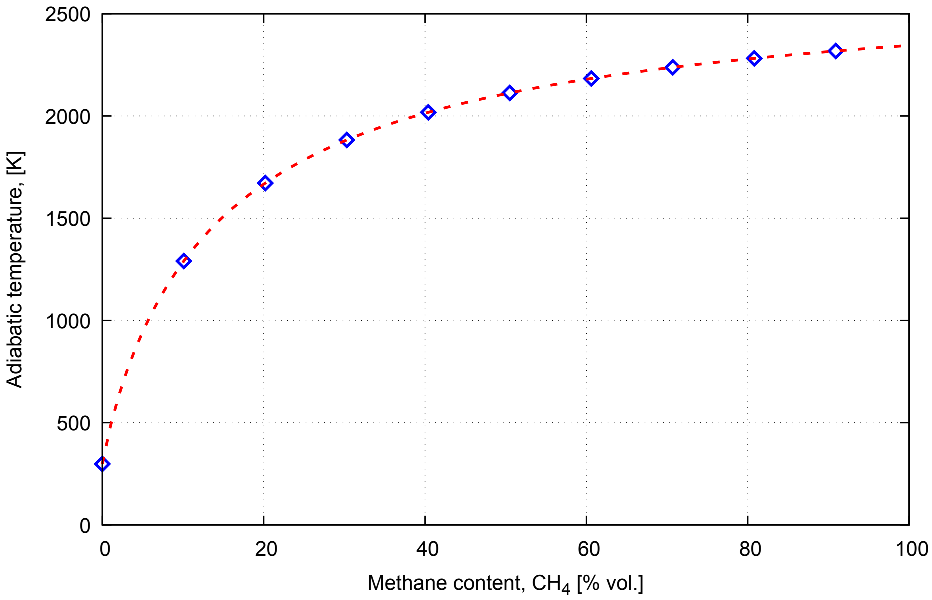

Figure 2.4: Indicative relation between methane content and Wobbe Index for landfill gas. Values assume a CH_4–CO_2 mixture and account for changes in gas density due to CO_2 dilution.

Table 2.4: Indicative EU-27 trends relevant for landfill gas (approximate values based on [4, 5, 7, 32]).

Indicator	1995	2010	2022/2023
Municipal waste landfilled [Mt/a]	∼121	∼88	∼51
Total waste to landfill (excl. minerals) [Mt/a]	n.a.	173	137
Share of total waste landfilled [%]	n.a.	23	17
Waste-sector CH_4 emissions [Mt CO_2 /a]	∼150	∼115	∼100
Share of CH_4 from solid waste disposal [%]	∼80	∼80	∼80

Figure 2.5 shows a normalised index of municipal waste landfilled in the EU-27, highlighting the downward trend and forming the basis for simplified LFG volume scenarios.

2.4.2. Implications for LCLFG

The combination of:

- decreasing waste inputs to landfill,
- progressive ageing of existing sites,
- stricter cover systems and gas capture,

implies that the average landfill in many EU countries is moving from a regime dominated by high-calorific, high-flow LFG towards a regime characterised by lower flows and lower CH_4 concentrations—ultimately increasing the relative importance of LCLFG streams for both mitigation and energy utilisation.

For LoCaGas project, this trend underlines the relevance of technologies that can:

- operate at lower methane contents and more variable gas quality,

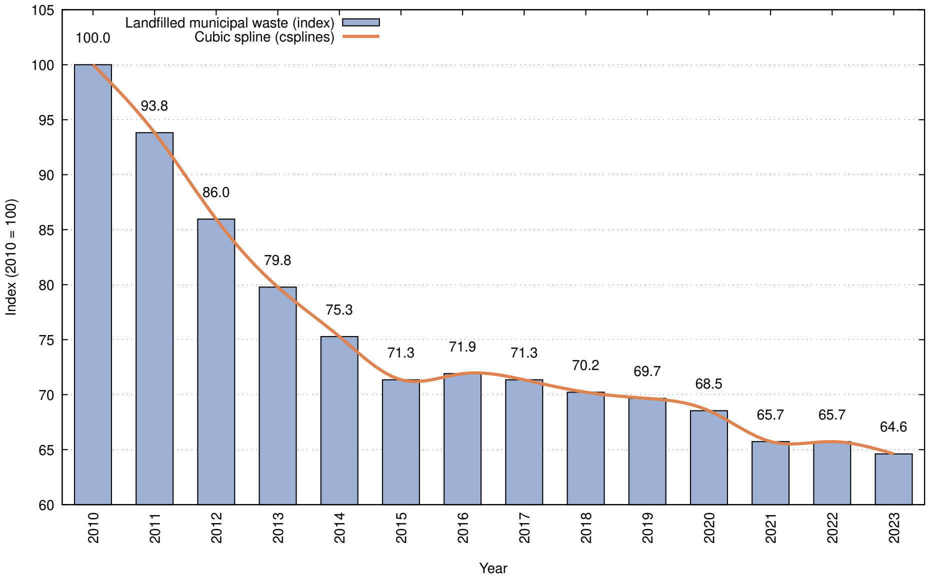

Figure 2.5: Indicative trend of municipal waste landfilled in the EU-27 (index 2010 = 100), based on Eurostat and EEA data [5, 32]. Values are approximate and intended for scenario building.

- remain economically viable at smaller scales and reduced flow rates,
- maintain high methane destruction efficiency even when energy recovery is modest.

2.5. Landfill Gas Characteristics Across LoCaGas Partner Countries

2.5.1. Overview

The LoCaGas partnership covers Poland, Lithuania, Sweden, Denmark and Germany, representing a spectrum from still relatively landfill-dependent systems (with significant LFG potential) to countries where landfilling of organic waste has been largely phased out and LFG is increasingly a residual, declining resource [33, 34]. Table 2.5 summarises selected indicators relevant for LFG and LCLFG.

Table 2.5: Indicative landfill gas context in LoCaGas partner countries (approximate, based on [4, 8, 32, 33]).

Country	LFG situation	Typical CH_4 range	LFG utilisation	LCLFG relevance
Poland	Many active/closed sites; still sizeable landfilling	30–60%	CHP engines on major sites	Emerging on older/smaller sites
Lithuania	Limited number of regional landfills; high utilisation rate	40–55%	Several CHP units at regional landfills	Increasing as sites age
Sweden	Landfill ban on organics since 2005; declining LFG	25–50%	Mainly heat; some CHP; Stirling/microturbines	High at many sites (age + diversion)
Denmark	Very low landfilling; strong WtE and recycling	10–40%	Selected dual-fuel engines; some flaring	Very high; focus on low-CH_4 streams
Germany	Advanced diversion from landfill; many sites in aftercare	30–55%	CHP and flaring at legacy sites	High for old landfills and aftercare gas

In the following subsections, short profiles are given for each partner country. For detailed historical data on Lithuania, Poland and Sweden, the LFG Baltic report provides an extensive compilation of extraction and utilisation experiences [33].

2.5.2. Poland

Poland has historically relied strongly on landfilling for municipal waste, although the share of landfilled municipal waste has been decreasing under EU and national waste legislation. According to the National Waste Management Plan and subsequent updates, hundreds of landfills for non-hazardous waste operated in the early 2000s, with 301 active landfills receiving municipal waste still recorded in 2017. A large subset of these sites is equipped with degassing systems, and around 90–100 LFG-based power plants with a total electrical capacity of about 60 MW have been reported in recent years [3, 33, 35].

Measured gas compositions at Polish landfills show CH_4 contents between 30 and 60% val., CO_2 between 18 and 42% vol. and O_2 between 0.3 and 9.8% vol., with substantial variations between sectors and over time [3, 25]. This indicates that, alongside conventional LFG streams, significant volumes of moderately diluted gas (class *C2*) and locally LCLFG (class *C3*) already occur.

For LoCaGas, Poland represents:

- a country with substantial remaining LFG potential and a mix of engine-based CHP and flaring;
- a context where advanced utilisation of *C2–C3* quality gas can extend energy recovery and improve methane mitigation at both large and medium-sized landfills.

2.5.3. Lithuania

Lithuania has undergone a rapid modernisation of its waste management system following EU accession. Around 14 modern regional landfills have been established, with 11 of them equipped for LFG extraction and utilisation. In addition, several closed landfills have implemented LFG-based electricity or CHP plants, with total installed electric capacity on the order of 6 MW and corresponding heat recovery in some cases [33].

The reported tariffs for electricity generated from LFG (around 8.6–11.1 euro cent/kWh depending on plant size) have historically provided favourable conditions for investment in LFG-to-power projects, making Lithuania one of the countries in the Baltic Sea region with relatively high LFG-based power production per capita [33]. Most systems operate on *C1–C2* quality gas, but ageing of sites and further diversion of organics are expected to increase the share of LCLFG over time.

For LoCaGas, Lithuania provides:

- examples of regional landfills with established gas collection and CHP;
- a policy environment supportive of LFG utilisation, useful for testing technologies that can maintain performance as CH_4 content declines from *C1* to *C2*/*C3*.

2.5.4. Sweden

In Sweden, a ban on landfilling of organic waste introduced in 2005 led to a strong shift towards waste-to-energy (incineration) and biological treatment. The number of active landfills has decreased, and LFG generation is dominated by older waste deposits. According to the Swedish Energy Agency and national waste statistics, LFG is currently extracted at roughly 50 landfills, with total production around 104 GWh in 2024, mainly used for heat and to a lesser extent for electricity [5, 33].

The declining methane content at many sites has prompted demonstration of alternative technologies such as externally fired Stirling engines and micro gas turbines, capable of operating at CH_4 contents down to 15–20 vol.% [33]. This makes Sweden a natural test bed for LCLFG solutions and directly relevant for LoCaGas.

2.5.5. Denmark

Denmark has one of the lowest municipal waste landfill shares in the EU, thanks to long-standing policies favouring recycling and waste-to-energy. As a result, LFG generation is relatively modest and concentrated at a limited number of sites. However, Danish companies have developed specific technologies to utilise LCLFG, notably dual-fuel engines where low-calorific landfill gas (down to $\sim$15 vol.% CH_4) is co-combusted with diesel in modified compression-ignition engines [33].

For LoCaGas, the Danish context is important because:

- it represents a ”future state” for many EU countries where only residual LFG remains;
- Existing dual-fuel concepts provide a benchmark for the project’s own dual-fuel and other technologies being developed within the LoCaGas project for *C3*-class gas.

2.5.6. Germany

Germany has strongly reduced landfilling of biodegradable municipal waste through a combination of regulatory bans, high landfill standards and extensive waste incineration capacity. Many landfills are now in aftercare, yet they still emit substantial methane. UNFCCC inventory data indicate that landfills in Germany emit on the order of a few hundred kilotonnes of CH_4 per year, similar in magnitude to Sweden and Lithuania when expressed per capita in some datasets [4, 8].

In Germany, landfill gas (LFG) has historically been used mainly for on-site electricity and heat generation in CHP units or flares, rather than for upgrading to grid-quality biomethane. This is partly a consequence of German waste policy: landfilling of untreated municipal solid waste has been banned since June 2005, which has strongly reduced new methane formation in landfills and has made many LFG streams smaller, older and more variable in composition [36]. In 2020, Germany still reported about 280 landfill gas-based electricity plants, but the biomethane sector was dominated by biogas from agricultural, manure and biowaste substrates; about 232 plants upgraded biogas to biomethane [37].

A recent exception is the landfill-gas-to-biomethane project of Berliner Stadtreinigung (BSR), awarded to ETW Energietechnik in 2026. The plant is designed to process up to 700 $Nm^3\ h^{-1}$ of landfill gas into biomethane suitable for gas-grid injection. The process includes a landfill-gas-specific upgrading system with downstream nitrogen reduction, intended to cope with high nitrogen contents, fluctuating methane concentration, oxygen ingress and trace contaminants such as VOCs and siloxanes [38, 39]. The project illustrates that LFG upgrading is technically feasible in Germany, but remains a niche application compared with conventional biogas upgrading.

Other German landfill sites more commonly demonstrate hybrid energy-site concepts rather than direct LFG upgrading. For example, at the Coesfeld-Hoeven landfill and energy site, declining landfill gas with about 30 vol.% methane has been supplemented by natural gas for engine operation, while a separate biowaste digestion and upgrading line produces approximately 250 $Nm^3\ h^{-1}$ of biomethane for grid injection [40]. Similarly, AGR reports active capture and use of landfill methane from former municipal landfills mainly in CHP units [41]. Overall, the German case shows a mature landfill-gas collection and utilisation sector, but only limited deployment of LFG-to-biomethane upgrading.

Table 2.6: Selected German examples related to landfill gas utilisation and upgrading.

Site/operator	Status	Relevance
Berliner Stadtreinigung (BSR), Berlin	Planned/awarded in 2026	Dedicated LFG-to-biomethane project; up to 700 $Nm^3\ h^{-1}$ LFG; grid-quality biomethane; nitrogen reduction and trace-contaminant handling.
Coesfeld-Hoeven landfill and energy site	Operating energy-site concept	Declining LFG used in engine operation; separate biowaste digestion and upgrading produces about 250 $Nm^3\ h^{-1}$ biomethane for grid injection.
AGR former municipal landfills	Operating LFG utilisation	Active LFG collection and use mainly in CHP units; representative of the dominant German approach to LFG management.

2.6. LCLFG Scenarios for the Ex-ante Assessment

2.6.1. Gas Quality Acenarios

For the ex-ante assessment of the LoCaGas technologies, we propose a set of standardised LFG composition scenarios representing different stages of landfill evolution and degrees of dilution. These scenarios are summarised in Table 2.7.

Table 2.7: Proposed LFG composition scenarios for LoCaGas ex-ante assessment (volume percent, dry basis; balance to 100% is N_2/O_2).

Scenario	Description	CH_4	CO_2	N_2+O_2
S1	Conventional LFG (young/mid-age landfill)	50	45	5
S2	Moderately diluted LFG (partial air ingress)	35	50	15
S3	Low-calorific LFG (advanced age / high dilution)	22	55	23
S4	Very low-calorific LFG (aftercare / edge zones)	12	55	33

Approximate LHVs associated with these scenarios are:

- *S1*: $\sim$18 MJ Nm^{-3}, representative for standard LFG engines/CHP;
- *S2*: $\sim$12.5 MJ Nm^{-3}, still usable in robust engines, microturbines and SFR;
- *S3*: $\sim$7.9 MJ Nm^{-3}, in the core operating region for LoCaGas technologies;
- *S4*: $\sim$4.3 MJ Nm^{-3}, mainly relevant for dual-fuel concepts and thermal/catalytic oxidation with limited power recovery.

These scenarios should be applied consistently across:

- thermodynamic and combustion modelling of SFR, dual-fuel and oxygen-enriched SI engines;
- emission modelling (e.g., NOx, CO, unburned CH_4);
- techno-economic assessments, including sensitivity to gas quality.

In the case of the SFR technology, the use of commercially available standard CHP units means that detailed emission analyses of NOx, CO, and unburned CH_4 will not be performed within the project scope.

Due to the high complexity of analyses involving multiple landfill gas quality classes, the experimental investigations will focus on the *S3*-class gas scenario, corresponding approximately to an LFG composition with 20% CH_4. The remaining LFG classes will be assessed primarily using literature data, thermodynamic calculations, and mathematical modelling approaches.

2.6.2. Flow-rate and Time-Evolution Scenarios

In addition to gas quality, the ex-ante analysis should consider different flow-rate regimes and their time evolution. A simplified but consistent approach is to define three representative scales:

- F1–Small landfill/closed cell: 50–150 Nm^{-3} h^{-1} LFG at peak, with exponential decline (decay constant $k \approx$ 0.05–0.07 a^{-1}).
- F2–Medium regional landfill: 150–500 Nm^{-3} h^{-1} at peak, $k \approx$ 0.05 a^{-1}.
- F3–Large urban landfill: 500–1 500 Nm^{-3} h^{-1} at peak, $k \approx$ 0.04 a^{-1}.

Figure 2.6 illustrates normalised flow-rate scenarios for these three scales, assuming a common reference time t_0 corresponding to the onset of active gas extraction.

Combining quality scenarios (*S1*–*S4*) with flow-rate scenarios (F1–F3) yields a matrix of operating conditions for the LoCaGas technologies, e.g.:

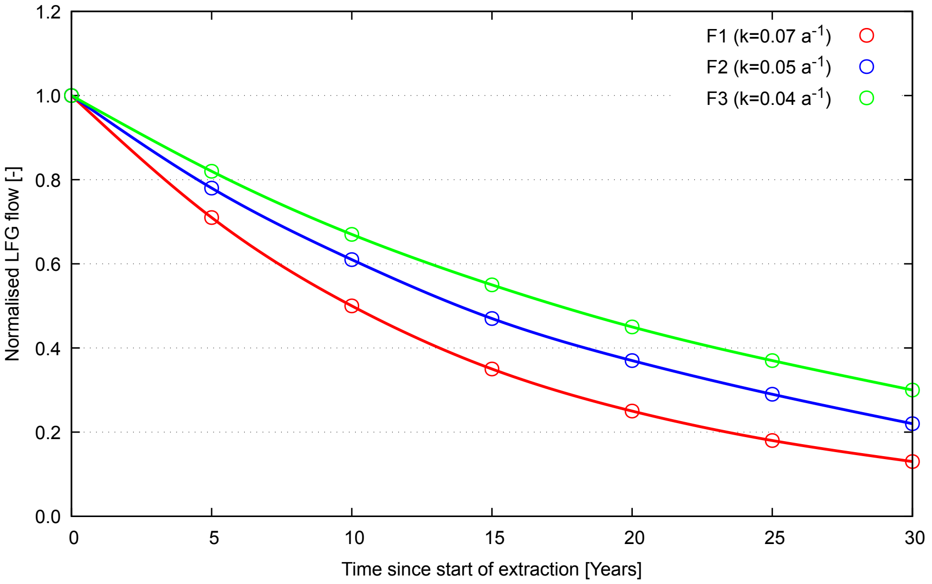

Figure 2.6: Indicative normalised flow-rate scenarios for small (F1), medium (F2) and large (F3) landfills, assuming exponential decline with decay constants $k = 0.07$, 0.05 and 0.04 a^{-1}).

- *S1*–F3: conventional LFG utilisation on large sites (reference for current practice);
- *S2*–F2: moderately diluted gas at regional landfills;
- *S3*–F1: LCLFG at small/closed landfills (core LoCaGas use case);
- *S4*–F1/F2: very low-calorific gas in aftercare or highly diluted zones.

2.7. Implications for LoCaGas Technologies

From the above characterisation and scenarios, the following implications for the LoCaGas technologies can be drawn:

1. Staged fuel reforming should focus on *S2*–*S3* quality gas, where reforming can stabilise combustion and extend the usable range of CH_4 content. The scenarios provide boundary conditions for reformer design (residence time, temperature, equivalence ratio).
2. Dual-fuel engine concepts are particularly relevant for *S3*–*S4* scenarios in F1–F2 flow regimes, where pure-gas engines cannot operate reliably. Polish, Swedish and Danish experiences with dual-fuel operation on LCLFG provide calibration points for expected diesel (or renewable pilot fuel) substitution rates [33].
3. Oxygen-enriched spark-ignition engines can potentially extend stable operation towards *S2*/*S3* gas while improving combustion stability and reducing methane slip, with careful optimisation to respect NOx emission limits under the MCP Directive.
4. Country-specific application windows emerge from the scenarios: *S2*–F3 in Poland and Lithuania; *S2*–*S3*–F1/F2 in Sweden and Germany; *S3*–*S4*–F1 in Denmark. These can guide the selection of representative case studies and pilot sites in the LoCaGas project.

Overall, the shift in EU waste management towards lower landfill dependence does not remove the need for LFG utilisation technologies; rather, it changes their design space towards flexible, low-calorific and often smaller-scale applications, exactly in the domain addressed by LoCaGas.

3

Regulatory Framework for Landfill Gas Utilisation in the EU and LoCaGas Partner Countries

3.1. Introduction

The utilisation of landfill gas (LFG), including low-calorific landfill gas (LCLFG), is strongly shaped by the European Union (EU) legal framework and its transposition into national legislation. For the LoCaGas project, which investigates advanced technologies such as staged fuel reforming (SFR), dual-fuel engines and oxygen-enriched spark-ignition engines for landfill gas utilisation, the regulatory context is a key driver and boundary condition.

On the one hand, EU waste and landfill legislation progressively restricts landfilling of biodegradable waste and requires the collection and treatment of LFG. On the other hand, air quality and industrial emissions directives impose limits on pollutants from combustion plants. In parallel, the Renewable Energy Directive (RED) recognises landfill gas as a renewable fuel and provides incentives for its utilisation. Together, these instruments create both obligations and opportunities for the deployment of innovative LFG-based energy technologies in the LoCaGas partner countries.

This chapter summarises the most relevant elements of the EU-level framework (Section 3.2) and the national implementation in Germany, Sweden, Poland, Lithuania and Denmark (Section 3.3), focusing on aspects that directly affect LFG collection, treatment and energetic use. The implications for the LoCaGas technologies are highlighted throughout the chapter.

3.2. EU-level Framework

3.2.1. Landfill Directive 1999/31/EC and Amendment (EU) 2018/850

The Landfill Directive 1999/31/EC establishes minimum requirements for the design, operation and aftercare of landfills in the EU. It defines three basic landfill categories:

1. landfills for hazardous waste,
2. landfills for non-hazardous waste,
3. landfills for inert waste.

A core objective of the directive is to prevent or reduce negative impacts of landfilling on surface water, groundwater, soil, air and human health. To this end, the directive requires:

- significant reduction of biodegradable municipal waste sent to landfill, with stepwise targets (25%, 50%, 75% reductions compared to 1995 levels at 5, 8 and 15 years after implementation),
- the exclusion of specific waste fractions from landfill (e.g. liquid waste, explosive and infectious healthcare waste, whole tyres),
- stringent conditions for permitting and operation of landfills, including hydrogeological assessment, pollution prevention plans and aftercare provisions,
- comprehensive monitoring of leachate, groundwater and landfill gas during operation, closure and post-closure phases.

The 2018 amendment (Directive (EU) 2018/850) strengthens these requirements in line with circular economy objectives. It expands the list of waste streams that must not be landfilled, particularly separately collected waste suitable for recycling or recovery, and introduces a binding target that by 2035 a maximum of 10% of municipal waste may be landfilled. The amendment further clarifies reporting obligations and methods for characterising waste and landfill performance.

For LFG utilisation, the Landfill Directive and its amendment are crucial because they:

- require the collection and treatment of landfill gas at sites receiving biodegradable waste, with a clear preference for energy recovery where feasible,
- define LFG management as an integral part of the landfill design, operation and aftercare concept,
- provide the legal basis for national obligations on LFG capture, flaring and utilisation.

These provisions create a structural demand for reliable and efficient LFG utilisation technologies, including options capable of handling low-calorific or variable gas compositions, as targeted in LoCaGas.

3.2.2. Waste Framework Directive 2008/98/EC and amendment (EU) 2018/851

The Waste Framework Directive 2008/98/EC establishes the overarching legal framework for waste management in the EU. It introduces the well-known waste hierarchy:

1. prevention,
2. preparation for reuse,
3. recycling,
4. other recovery (e.g. energy recovery),
5. disposal.

The directive defines key concepts such as waste, recovery, recycling and extended producer responsibility. It sets binding targets for recycling rates and requires Member States to implement waste management plans and waste prevention programmes.

The 2018 amendment (Directive (EU) 2018/851) reinforces circular economy principles by:

- increasing minimum recycling targets for municipal waste,
- introducing more detailed rules for separate collection, including bio-waste,
- strengthening extended producer responsibility schemes.

Although the Waste Framework Directive does not regulate LFG directly, it has two important implications:

- it reduces the future generation of LFG by diverting biodegradable waste away from landfills,
- it indirectly raises the importance of safe and efficient management of existing landfills, where LFG generation will continue for decades.

For LoCaGas, this means that while the overall LFG potential may decline in the long term, there is a strong policy pressure to optimally utilise LFG from existing and legacy sites.

3.2.3. Industrial Emissions Directive and Medium Combustion Plants Directive

Directive 2010/75/EU on industrial emissions (IED) consolidates and updates EU legislation on integrated pollution prevention and control. It covers a wide range of industrial activities and sets requirements for the use of best available techniques (BAT), emission limit values and permitting. Large combustion plants are subject to specific emission standards and monitoring obligations under the IED; however, these detailed rules apply only to plants with a rated thermal input of at least 50 MW.

For smaller facilities, Directive (EU) 2015/2193 on the limitation of emissions of certain pollutants from medium combustion plants (MCP Directive) fills the gap. It applies to combustion plants with a rated thermal input between 1 and 50 MW and sets emission limit values for sulphur dioxide (SO_2), nitrogen oxides (NOx) and particulate matter, differentiated by plant size, age and fuel type.

Many LFG-based energy plants fall within the range of medium combustion plants, including typical engine-based and boiler-based installations considered in the LoCaGas context. The MCP Directive therefore:

- defines emission performance requirements for LFG combustion,
- imposes monitoring and reporting obligations on plant operators,
- influences the choice and configuration of combustion technologies and emission control systems.

For the LoCaGas technologies, the MCP framework is particularly relevant when assessing compliance with NOx, SO_2 and dust emission limits for engines operating on LFG or LCLFG, including dual-fuel and oxygen-enriched concepts.

3.2.4. National Emissions Reduction Commitments Directive 2016/2284/EU

Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants (NEC Directive) establishes binding national emission reduction commitments for five pollutants: sulphur dioxide (SO_2), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC), ammonia (NH_3) and fine particulate matter ($PM_{2.5}$). The targets are expressed as percentage reductions relative to 2005 levels and cover all relevant sectors, including energy, transport, agriculture and waste.

While the NEC Directive does not regulate individual plants, it:

- drives national policies and permitting practices towards lower-emission technologies,
- increases the importance of high-efficiency LFG utilisation with low specific emissions per unit of energy produced,
- indirectly favours advanced combustion concepts that reduce NOx and NMVOC emissions compared to simple flaring or uncontrolled oxidation.

3.2.5. Renewable Energy Directive and Recognition of LFG as a Renewable Fuel

Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II), further updated by RED III, is the central EU instrument for renewable energy policy. It sets a binding EU-wide target for the share of renewables in gross final energy consumption and defines sectoral contributions in electricity, heating and cooling, and transport.

The directive explicitly recognises bioenergy as renewable energy, provided that certain sustainability and greenhouse gas (GHG) saving requirements are met. Landfill gas is included as an admissible bioenergy resource for the calculation of GHG savings and renewable shares, under the condition that its utilisation leads to significant GHG reductions compared to fossil fuels.

Key implications for LFG utilisation are:

- LFG-based electricity and heat can contribute to national and EU renewable energy targets,
- LFG projects may be eligible for support schemes (e.g. feed-in tariffs, premiums, green certificates or auctions) in Member States,

- the directive provides standard methodologies for calculating GHG emission savings from LFG utilisation.

For LoCaGas, the RED framework strengthens the economic and climate rationale for investing in advanced LFG utilisation technologies by:

- enabling recognition of project outputs as renewable energy,
- supporting the quantification of GHG benefits from improved LFG capture and energetic use,
- linking technology performance to broader decarbonisation strategies.

3.3. National implementation in LoCaGas Partner Countries

3.3.1. Germany

In Germany, the Waste Framework Directive is implemented primarily through the *Kreislaufwirtschaftsgesetz* (KrWG). The act codifies the waste hierarchy, obliging waste holders to prioritise recycling and recovery over disposal. Landfilling is only permissible if other forms of recovery are technically or economically infeasible or environmentally less favourable. The KrWG also sets out obligations for waste generators and landfill operators, including requirements for environmental impact assessments, cost coverage and monitoring.

The EU Landfill Directive is implemented in detail by the *Deponieverordnung* (DepV), first adopted in 2009. The DepV:

- defines five landfill classes (0–IV) with increasing hazard potential,
- sets technical requirements for site selection, base and surface sealing, leachate and gas collection systems, and recultivation layers,
- specifies waste acceptance criteria and operational rules (registration, weighing, visual inspection, documentation),
- requires extensive monitoring of precipitation, leachate, groundwater, temperature and gas emissions during operation and aftercare.

With regard to landfill gas, the DepV obliges operators to collect and treat LFG where it is generated, preferably for energy recovery. The use of the recultivation layer for methane oxidation is recognised, and the measurement of LFG quantity and composition is mandatory. Detailed standards for LFG quality and emission control are provided in technical guidelines such as VDI 3790.

For the LoCaGas technologies, the German framework implies:

- a stable regulatory obligation to capture and energetically utilise LFG, including from older sites where feasible,
- stringent technical and monitoring requirements for LFG collection and combustion systems,
- potential classification of engine-based plants within the MCP Directive range, with corresponding emission limits.

3.3.2. Sweden

Swedish environmental law is built around the *Miljöbalken* (Swedish Environmental Code), which consolidates multiple previous acts. It defines fundamental principles such as the precautionary principle, the polluter pays principle, the product selection principle, sustainable resource management and the principle of suitable location. These principles apply to all environmentally hazardous activities, including landfilling and LFG management.

The *Förordning (2001:512) om deponering av avfall* (Landfill Ordinance) directly implements the EU Landfill Directive. It:

- classifies landfills as hazardous, non-hazardous or inert,

- prohibits the landfilling of certain waste fractions, including liquid waste, separately collected combustible and organic waste,
- sets requirements for landfill siting, design, barrier systems and leachate collection,
- defines permit procedures and aftercare obligations (including at least 30 years of post-closure monitoring),
- explicitly requires collection of landfill gas at landfills receiving biodegradable waste.

The *Avfallsförordning (2020:614)* (Waste Ordinance) complements this framework by specifying waste classification, sorting and separate collection obligations, and responsibilities of municipalities, producers and waste holders. Technical details on waste acceptance, sampling and monitoring—including LFG monitoring—are provided in the Swedish Environmental Protection Agency regulations *NFS 2004:10*. These regulations formulate a clear hierarchy for LFG management: utilisation for energy has priority, followed by flaring or other environmentally sound treatment if energy recovery is not feasible.

Guidelines for closed landfills emphasise the risks associated with historical sites and the need for risk-based assessment, inventory and remediation, including LFG control.

For LoCaGas, the Swedish framework creates:

- strong incentives to utilise LFG for energy wherever technically viable,
- a clear regulatory basis for projects that retrofit or upgrade LFG systems at both active and closed landfills,
- a demanding context for environmental performance of combustion-based solutions.

3.3.3. Poland

In Poland, the central legal act for waste management is the *Ustawa o odpadach* (Waste Act) of 14 December 2012. It implements the Waste Framework Directive by establishing the waste hierarchy, defining key terms and setting out obligations for waste producers and holders. Key provisions include:

- definitions of landfills and other facilities,
- prioritisation of waste prevention, reuse and recycling over disposal,
- prohibition of landfilling of certain waste types (e.g. liquid waste, explosive or flammable waste, infectious medical waste, selectively collected biodegradable waste),
- requirements for basic waste characterisation for waste destined for landfill,
- obligations of landfill operators regarding safe operation, monitoring and reporting.

The *Rozporządzenie Ministra Środowiska z dnia 30 kwietnia 2013 r. w sprawie składowisk odpadów* (Ordinance on landfills) translates the technical requirements of the Landfill Directive into national law. It specifies:

- siting criteria and exclusions for landfills,
- technical standards for geological barriers, base and surface sealing,
- operational requirements for limiting exposed waste surfaces, controlling dust and preventing uncontrolled gas emissions and fires,
- detailed monitoring programmes, including LFG monitoring (parameters, frequency, methods).

Both the Waste Act and the Ordinance require the collection, treatment and utilisation or flaring of LFG at landfills receiving biodegradable waste. The *Prawo ochrony środowiska* (Environmental Protection Act) provides the broader framework for environmental permitting and integrated pollution control of larger installations.

The *Ustawa o odnawialnych źródłach energii* (Renewable Energy Sources Act, 2015) recognises biogas from landfills as a renewable energy source and provides support mechanisms for renewable electricity and heat generation. This improves the economic viability of LFG utilisation projects.

For the LoCaGas technologies, the Polish framework:

- secures a regulatory obligation and technical basis for LFG collection and treatment,
- offers opportunities for RES support for LFG-based power and heat generation,
- requires careful integration of combustion plants into the environmental permitting system.

3.3.4. Lithuania

Lithuania's environmental legislation is centred on the *Law on Environmental Protection*, which sets general principles for preserving biodiversity, ecosystems and a healthy environment. It defines rights and obligations of natural and legal persons and explicitly aims to implement EU environmental legislation.

The *Waste Management Act* is the primary legal instrument for waste management. It:

- lays down requirements for waste prevention, collection, sorting, recovery and disposal,
- applies extended producer responsibility to selected products and packaging,
- sets technical regulations for waste treatment and disposal facilities, including landfills,
- prohibits the import of municipal and hazardous waste for disposal or energy generation.

The *Rules for waste management* (Ordinance No. 217 of 14 July 1999) provide detailed procedures for landfill establishment, operation, closure and aftercare. They explicitly aim to implement the Landfill Directive by:

- requiring the reduction of biodegradable waste going to landfills,
- mandating the collection and utilisation of LFG and leachate, and the closure of non-compliant landfills,
- specifying technical and operational requirements for landfill siting, gas and leachate collection, and environmental monitoring.

The *National waste management plan 2021–2027* and the associated waste prevention programme set quantitative targets for reducing municipal waste generation, decreasing the share of waste sent to landfill and increasing reuse and recycling rates. Investments in alternative treatment options (mechanical-biological treatment, incineration with energy recovery) support these goals and indirectly reduce future LFG generation.

For LoCaGas, the Lithuanian framework provides:

- a clear legal basis for LFG collection and utilisation, especially at existing landfills,
- a policy environment focused on minimising landfill disposal, which may limit long-term LFG potential but increases the importance of efficient utilisation of remaining gas,
- opportunities to align LFG projects with national waste and climate strategies.

3.3.5. Denmark

Denmark has pursued an aggressive landfill reduction strategy for decades. A series of waste action plans and strategies (e.g. *Action Plan for Waste and Recycling 1993–1997*, *Waste 21*, *Waste Strategy 2005–2008*, *Waste Strategy 2009–2012*) set ambitious targets for recycling and energy recovery and very low shares of waste sent to landfill. As a result, the proportion of waste landfilled has decreased to approximately 3–4% of total waste generation in recent years.

The policy framework has been complemented by:

- a landfill tax and bans on landfilling certain waste fractions,
- statutory orders on landfills and waste that regulate classification, characterisation and disposal routes for different waste types,
- strong integration of municipal waste incineration with combined heat and power systems.

While these measures significantly reduce the amount of biodegradable waste going to landfills (and thus future LFG generation), they also:

- leave a legacy of existing landfills that still generate LFG,
- create a context where LFG utilisation must compete with very well-developed waste-to-energy infrastructure,
- favour high-efficiency and flexible solutions for smaller, residual LFG streams.

For LoCaGas, Denmark represents a case where LFG resources are comparatively limited but where there is a strong tradition of integrating waste and energy systems and a high level of environmental regulation.

3.4. Implications for LoCaGas Technologies

Across the EU and in all LoCaGas partner countries, the regulatory framework creates a consistent set of drivers and constraints for LFG utilisation technologies:

- Obligatory LFG collection and treatment: Landfill and waste legislation requires the capture and controlled treatment of LFG at landfills receiving biodegradable waste. Energy recovery is generally preferred over flaring where technically and economically feasible. This establishes a stable demand for technologies that can reliably utilise LFG over long time horizons and under changing gas quality.
- Need to handle low-calorific and variable gas: As waste diversion policies reduce the amount of biodegradable waste going to landfill and as landfills age, LFG tends to become more diluted and variable. Technologies such as SFR, dual-fuel engines and oxygen-enriched spark-ignition engines are particularly relevant, as they are designed to extend the operational envelope towards low-calorific gas mixtures and maintain stable combustion under challenging conditions.
- Emission performance requirements: The MCP Directive and national emission legislation impose limits on NOx, SO_2 and particulate matter for combustion plants within the typical size range of LFG engines and boilers. This favours solutions that combine high efficiency with low specific emissions, potentially including staged combustion, optimised air/fuel management and, where necessary, secondary emission control.
- Contribution to renewable energy and climate targets: Under the Renewable Energy Directive and national RES legislation, LFG is recognised as a renewable fuel. Energetic utilisation of LFG delivers significant GHG emission savings by avoiding methane emissions and displacing fossil fuels. This strengthens the climate rationale for LoCaGas technologies and can improve their economic performance through access to renewable support schemes.
- Site-specific permitting and integration: Environmental codes and permitting procedures in the partner countries require that LFG utilisation plants be integrated into the broader environmental management of landfills, including impact assessment, monitoring and aftercare. Technology choices must therefore be compatible with site-specific constraints, existing infrastructure and long-term aftercare plans.

In summary, the regulatory framework in the EU and the LoCaGas partner countries not only justifies but actively encourages the development and deployment of advanced LFG utilisation technologies. The SFR, dual-fuel and oxygen-enriched spark-ignition concepts investigated in LoCaGas respond directly to the regulatory need for robust, low-emission and flexible solutions for the energetic use of landfill gas, including low-calorific and ageing gas streams.

4

Technologies Available for Low Calorific Landfill Gas Utilization

According to VDI3899 the technologies for the transformation of LFG (and LCLFG) can be categorized in three groups [42].

- Thermal Conversion
- Biological treatment
- Physical and chemical upgrading

In the following paragraphs existing technologies for the treatment of LCLFG are presented.

4.1. Gas Processing Systems

A gas processing system is the composition of different steps leading from the degasification of the landfill to the treatment and the processing of the gas (Figure 4.1). The gas is extracted from the landfill by a series of wells and blowers. The gas is thereby transported to a central place where it can be treated and processed. Until this point the gas processing systems on different landfills are mostly similar. After the degassing and the collection, the methods can differ from landfill to landfill. The gas can be simply flared without the recovery of energy to reduce the climate change potential by burning the methane. Otherwise, the gas can be processed for thermal or electrical energy recovery. This might include a pretreatment of the gas to reduce emissions and other unintentional components in the gas. If not recovered on site, the gas can also be treated and fed into the public gas system. Therefore it has to fulfil the requirements which are needed for the natural gas standard.

4.2. Thermal Conversion

Thermal conversion describes the process of burning LFG to reduce the climate change potential. It can be combined with energy and heat recovery [43].

4.2.1. Flare

Flares for LFG combustion are normally designed to work with a range of methane content in the gas between 30%–50%. If the range is lower the combustion can be incomplete and emissions can increase. There are different methods and techniques to adjust the flaring process [43].

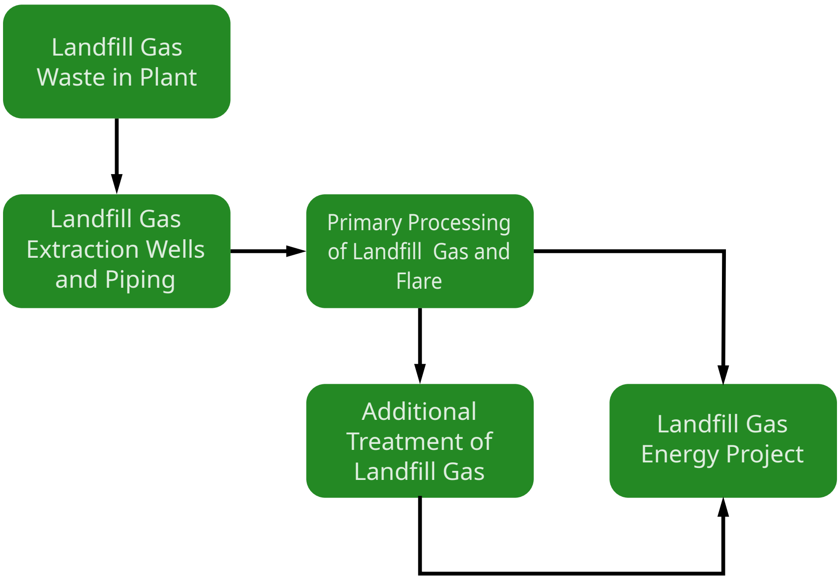

Figure 4.1: General flow of a LFG processing system [43]

Advanced Flares

When the methane content falls below this threshold (30%–50%), the lower heating value of LFG may be insufficient to sustain stable and complete combustion, resulting in flame instability, reduced destruction efficiency, and increased emissions of incomplete combustion products such as CO, VOCs, and unburned methane.

To address these challenges, advanced flare systems incorporate several methods and control techniques that enable effective operation even under fluctuating or low-calorific-value conditions typical for landfill gas. These include automated air–fuel ratio control, variable-speed blowers for maintaining optimal combustion air supply, and gas preheating or enrichment to ensure stable ignition. High-temperature enclosed flares are often equipped with continuous monitoring of temperature, flow, and methane content, allowing dynamic adjustments of combustion parameters. Such control strategies improve overall destruction efficiency, reduce greenhouse gas emissions, and ensure compliance with environmental regulations, particularly when landfill gas quality deteriorates over the lifecycle of a landfill [43].

Modified Flare

Another low-threshold option is to adjust the burners of the flare, although this is only possible for certain flare models. This approach is effective for landfill gas with a methane concentration between 20–50%. The burners regulate the mixture of fuel (landfill gas) and air during combustion. By adjusting this ratio, more efficient combustion can be achieved even at lower methane concentrations. However, if the methane concentration falls below 20%, alternative flare technologies must be used [43].

Low Calorific Value High Temperature Flare

If the methane level is beneath 20% or the burners of the flare are not adjustable alternative flare systems can be used to ensure a well working combustion process.

So called *Low-Calorific Value Hight Temperature Flares* are optimized to operate with LFG with a content of methane between 10-15% and a volumetric flow between 10-100 $m^3\,h^{-1}$. This means that at a flow of 100 $m^3\,h^{-1}$, gas with a content of 10% CH_4 can be burned or a flow of 40 $m^3\,h^{-1}$ gas with a content of 25% can be burned. The operating temperature is between 1000-1200°C. These kinds of flares are mostly individually adapted to work with the specific characteristics at a landfill [43].

The individual adaptations can include the use of supplementary fuel or the preheating of the combustion air through the use of heat exchangers. Also, the method of mixing fuel and air has an impact on the combustion process. There are flares mixing air and fuel prior to the combustion process – so called pre-mixing. On most cases this ensures higher temperatures and a more uniform and complete combustion. In cases of very low methane content (beneath 10%) the mixing of fuel and air by diffusion as the gas leaves the burner, leads to better results [43].

An example for a modern LCLFG flare is the *Flox thermal oxidizer* of the company eflox situated in Renningen, Germany. The flare can operate autothermal (without adding supplementary fuel) with a methane content of as low as 6%. This is possible through burner integrated heat exchangers made of silicon infiltrated silicon carbide (SiSiC). The methane emissions are below 5 ppm. The system is already in operation at landfills. One example is the medium sized landfill Rübenloch which is situated in southern Germany [44].

Open Flares

Manufacturers offer modifications for high-temperature flares to accommodate landfill gas with low methane content. This involves the integration of a secondary combustion source, such as propane, to ensure consistent and efficient high-temperature flaring. These modified flares, known as supported combustion flares, are designed to operate with landfill gas containing methane concentrations below 15% by volume, or in situations where gas composition fluctuates significantly, at flow rates ranging from 50 to 2,500 $m^3\,h^{-1}$. However, the utilization of a supplementary fuel source introduces additional financial and environmental costs [43].

Micro turbines

Micro gas turbines are small, high-speed gas turbines with low combustion chamber pressures and temperatures, typically ranging from 20 to 500 kWel. They are based on turbocharger technology and aviation auxiliary power units and consist of a compressor, combustion chamber, turbine, and generator, as shown in Figure 4.2 [45].

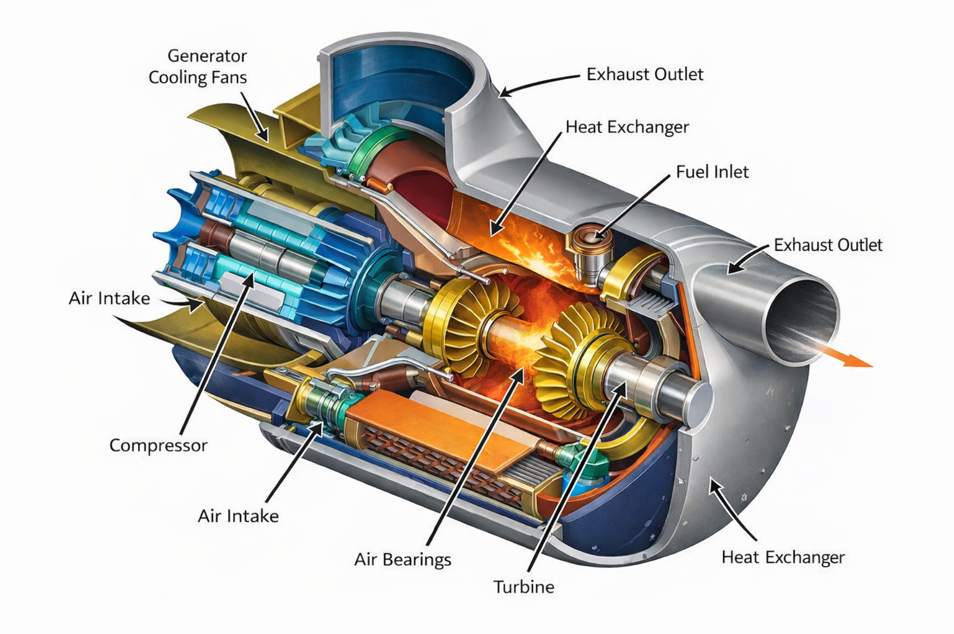

Figure 4.2: Scheme of a gas turbine.

Unlike large power plant gas turbines, micro gas turbines often use recuperators to preheat combustion air which improves the efficiency. Air enters the generator, cooling it before being compressed to about 4 bar [46].

The recuperator transfers heat from exhaust gases to the compressed air before it reaches the combustion chamber, enabling electrical efficiencies of 25–30%. The heated, compressed air is mixed with fuel in the combustion chamber, generating hot gases that drive the turbine, compressor, and generator. Exhaust gases release residual heat in the recuperator before exiting through the stack or heat exchanger. Micro gas turbines operate with a high air-to-fuel ratio, enhancing combustion efficiency [46].

To use landfill gas in a microturbine it has to be pre-cleaned. One possibility is activated carbon filters. Furthermore, the gas has to be compressed and a condensate separation has to be performed. Volker reports that 8% of the net power has to be used for the preparation of the gas [46]. In the same report an efficiency between 26 and 32.5% is mentioned. The minimum methane content for operation is reported to be at 30% CH_4.

Compared to LFG electric power generation technologies microturbines offer a better flexibility on landfills with lower LFG quantities and methane content. Microturbines are also small and have fewer moving parts and no need for lubrication or liquid cooling systems. This leads to a lower maintenance effort. As mentioned before, the microturbines also have a clean burning with low emissions of NO_x and other substances [47].

4.2.2. Gasification and Pyrolysis

Pyrolysis defines the process of cracking chemical molecules by the use of high temperatures. The process is carried out with an absence of oxygen. The products are gases fluids and solid products. The characteristics and the quantity depend on variables like the used input materials, support materials, pressure and process time [48].

There are some examples for waste treatment through pyrolysis for residual waste, sewage sludge and other components. The pyrolysis gas can be used for the heating of the pyrolysis reactor and for energy recovery. As the process works without oxygen, there are no CO_2 emissions [48].

One way to use LCLFG for pyrolysis is researched in [48]. The authors observed how the gas can be used to support the heat supply of the process. As the calorific value of LCLFG is too low to be used directly for pyrolysis, the authors recommend different types of technical modifications or an additive supply with secondary fuels.

On the technical side the authors propose to use the LCLFG to preheat the pyrolysis process by burning the LFG in a separate oxidation process. The process heat can be used for the preheating. This can also be combined in a hybrid process by using LCLFG and electric energy to heat up the pyrolysis process [48].

At the same time the authors report several technical complications like unstable flame building, formation of soot and tar as well as corrosion through sulphur-dioxide and siloxane compounds. A pretreatment of the gas can help to reduce these complications [48].

4.2.3. Stirling Engines

The basic principle of a Stirling Engine is to transform heat into movement. In the case of the Stirling Engine this works without any internal combustion. The engine needs a source of heat and a source of cooling. Additionally, it needs a gas which is encapsulated in the pistons chamber. The heat source heats up the pistons chamber on one side. The heat sink is installed on the other side of the piston chamber. The gas is heated up and expands which makes the pistons move in one direction. Afterwards the heat sink cools down the gas and it contracts again. The piston moves in the other direction. This heating and cooling process causes a continuous cycle of expansion and contraction. It is achieved by the design of the pistons chamber which allows a continuous exchange of the heated and cooled gas [49].

The main advantage of the Stirling Engine is that it runs without any combustion inside of the piston chamber. This leads to a lower erosion compared to internal combustion engines. At the same time, it operates very silent and without a lot of vibration [50].

On the other hand, the Stirling Engine has a lower mechanical efficiency and a higher mass/power ratio compared to internal combustion engines [50].

Stirling Engines are used for LCLFG processing. The Swedish company Cleanenergy has developed a

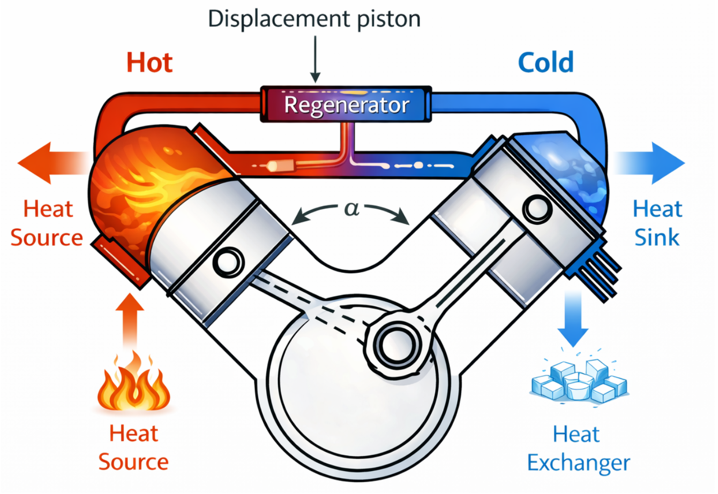

Figure 4.3: Basic principal of a Stirling Engine

generator that can process LCLFG with a methane content of 18%. As a heat source it uses the *Flox thermal oxidizer* which was mentioned in chapter 4.2.1. The Stirling Engine can operate as a link between active LCLFG processing and passive LCLFG elimination [50, 51].

In an example of a landfill in Göritz, Germany, the Stirling Engine of Cleanenergy can operate with 7.6 m^3 h^{-1} of gas. This leads to 7 kWel while the energy density of the gas is at 4 kWh m^{-3} [50].

4.2.4. Catalytic and Low-Temperature Oxidation Systems

Catalytic oxidation units represent an alternative thermal treatment method for LCLFG when the methane concentration is too low to sustain stable combustion in conventional flares. These systems use catalysts such as platinum-, palladium- or manganese-based materials to enable methane oxidation at significantly reduced temperatures (typically 350–600°C). As a result, they can operate autothermally even when the calorific value of the gas is insufficient for flame-based technologies. Catalytic oxidizers are particularly suitable for treating diffuse or declining gas flows in the late phase of landfill operation and for eliminating residual emissions from venting or passive extraction systems. Their compact design and low operating temperatures result in reduced NO$_x$ formation compared to conventional high-temperature flaring.

4.2.5. Regenerative Thermal Oxidizers

Regenerative thermal oxidizers provide another robust method for methane destruction in low calorific landfill gas streams. RTO systems use ceramic beds to recover and store thermal energy from the exhaust gases, allowing high destruction efficiencies even for gas with limited heating value. The regenerative heat exchange enables autothermal operation after start-up and makes RTOs suitable for highly diluted LCLFG or for treatment of mixed gas streams containing air, for example from surface ventilation or low-pressure extraction wells. RTO technology is commonly used as polishing treatment, complementing other upgrading or collection systems.

4.2.6. Co-Firing Applications

In some cases, LCLFG can be used as a supplementary fuel in industrial combustion systems such as boilers, cement kilns, or lime furnaces. Although the low heating value of the gas typically requires blending with a higher calorific fuel (e.g. natural gas, propane or oil), co-firing may reduce fossil fuel consumption and provide a cost-effective utilization route. This approach is most applicable at landfills located near industrial facilities with continuous heat demand and well-controlled combustion systems capable of accommodating fluctuating LCLFG quality.

4.2.7. Waste Heat Utilization

When high-temperature thermal oxidation or microturbine systems are installed, the waste heat from exhaust gases can be recovered using Organic Rankine Cycle units. ORC systems convert low- and medium-grade waste heat into electricity, increasing the overall energy recovery from LCLFG-based systems. Although ORC units are generally not directly fuelled by LCLFG, they can play a role in enhancing the utilization efficiency of existing thermal conversion technologies, particularly in small or declining landfill sites.

4.3. Biological Treatment

4.3.1. Biological Methanation

Biological methanation describes a process where CO_2 and H_2 are brought into reaction to produce CH_4. This power to gas technology can be a sustainable energy source, if the H_2 is produced from natural energy sources by water electrolysis and the CO_2 is captured in an industrial process or comes from biogas [52].

The process can be performed in in-situ reactors or ex-situ reactors. There are also hybrid variants. Inside of the reactor are *Methanobacteria* which are responsible for the reaction [52].

LCLFG can be used as a feedstock for biological methanation, especially when the methane content in the gas is too low for flaring or for use in other energy recovery methods. By adding H_2 to in-situ or ex-situ reactors to achieve a stoichiometric ratio of 4:1 (H_2:CO_2), the methane content can be increased to approximately 98% [53].

4.3.2. Biofilters

Biofilters are widely used to treat LCLFG by oxidating the methane and cleaning pollutants in the gas. The filters operate by biologically oxidating the methane and other harmful substances in the gas. There are active and passive filters. While active filters are actively permeated by increasing the pressure of the LFG on the input side, passive filters work by using the pressure gradient between the landfill body and the landfill surface. Passive filters are more common than active filters. The filters can be linked directly to the degassing system of the landfill. They are filled with high surface biological materials like wood chips, bark mulch or compost. In this aerobe environment methanotroph bacteria oxidate the LFG. The efficiency of methane oxidation can be up to 100% [54, 55].

In contrast, passive systems such as biocovers or biowindows generally do not guarantee such high and stable methane conversion efficiencies. Their performance is strongly affected by non-uniform gas distribution, preferential gas pathways, cover material heterogeneity, seasonal variations, and potential leakages or bypass flows. As a result, the actual annual average methane oxidation efficiency reported for these systems is often significantly lower (e.g. around 30% in some field studies).

This distinction is important in the context of the LoCaGas project. While passive oxidation systems can reduce methane emissions, their performance is typically less controllable and less predictable than active gas utilisation technologies. The LoCaGas concepts aim not only at methane mitigation, but also at controlled energy recovery and improved overall environmental performance, particularly for low-calorific landfill gas streams.

Prechtl et al. tested different materials to reduce pollutants of LCLFG [56]. In one filter they used a base of compost and wood shaving combined with activated carbon and in the other filter a mixture of compost and wood shavings with peat. Both filters performed efficiently and were able to reduce up to 80% of the pollutants in the gas. The peat-filter had a better performance in reducing VOCs and the activated carbon filter performed better in reducing H_2S.

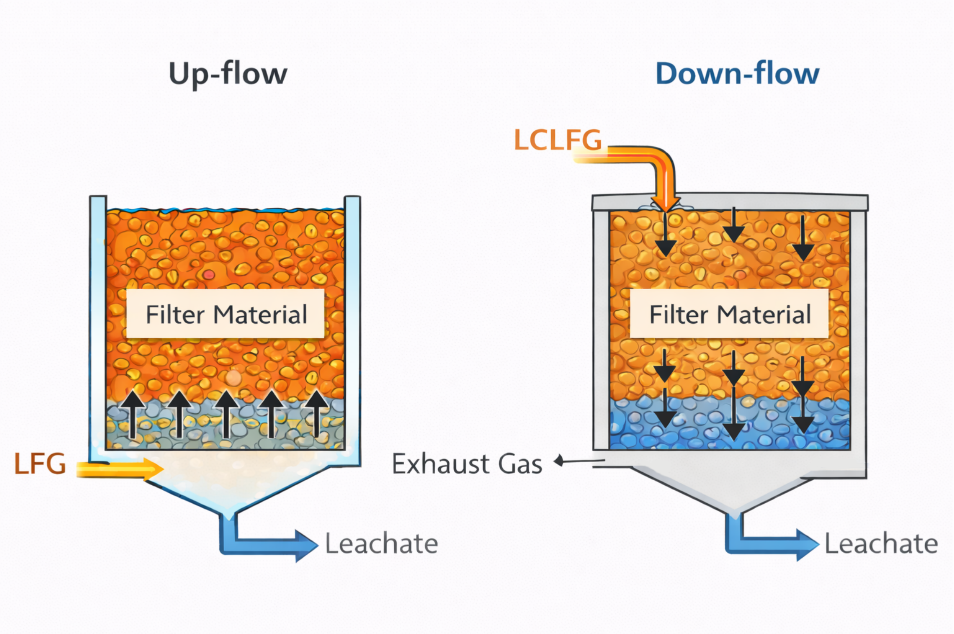

Figure 4.4: Scheme of two biofilter variants (upflow and downflow).

4.3.3. Biocovers and Biowindows

Biocovers and biowindows are engineered soil-based systems designed to promote microbial oxidation of methane emitted from landfills. They consist of layers of compost, wood chips, or other porous media that provide a habitat for methanotrophic bacteria. These bacteria convert methane to carbon dioxide under aerobic conditions. Biocovers are applied over large landfill surface areas, while biowindows are smaller, strategically located treatment zones connected to passive gas vents. Such systems are particularly effective during the late operational phase of a landfill, when gas generation becomes too low or too diffuse for active gas extraction or thermal treatment. Methane oxidation efficiencies exceeding 80–100% have been observed under favourable temperature and moisture conditions [55, 57, 58].

4.3.4. In-Situ Biostimulation of Methane Oxidation

In-situ biostimulation refers to operational strategies that enhance the natural activity of methane-oxidizing microorganisms within landfill cover materials. Methods include moisture control, nutrient supplementation and structural modification of cover layers to improve aeration and gas transport. While not a standalone technology, biostimulation can significantly increase methane removal efficiency in both passive biofilters and biocover systems. This approach is particularly relevant for landfills in the late aftercare phase where gas flows are low and intermittent [55, 58, 59].

4.3.5. Other Biological Treatment Methods

There are several other biological treatment processes which are still in research or development. One example is algae bioreactors. The algae fix CO_2 during the growth process. The biomass can be further processed. Methane to protein bioreactors is a method where methane oxidizing bacteria convert methane into single cell proteins. The proteins can be further processed, for example as animal food [60].

4.4. Physical and Chemical Upgrading

4.4.1. Pressure Swing Adsorption

Pressure swing adsorption is a method used to purify biogas by removing carbon dioxide and other impurities based on their differing adsorption behaviors. Materials like activated carbon, molecular sieves, and carbon molecular sieves serve as adsorbents. Since CO_2 binds more easily to these materials than methane does, it can be selectively removed. The process operates under low temperatures (around 5°C) and elevated pressures (2–7 bar), which enhance adsorption efficiency. Before PSA treatment, the raw biogas must be pre-cleaned to remove contaminants such as dust, sulphur compounds, and moisture. This involves compressing the gas, desulfurizing it, cooling it to condense out water, and then feeding it into the adsorber. The adsorbers often contain specially treated hard coal or zeolite materials that can last up to 20 years if the gas is sufficiently clean. During operation, CO_2 and other larger molecules are captured in the adsorber material, while purified methane passes through. To ensure a continuous process, several adsorbers are used in rotation: once one is saturated, the gas flow switches to another while the saturated unit is regenerated. Regeneration begins by reducing the pressure to near ambient levels, releasing residual methane, which is returned to the process to minimize losses. For full regeneration, the system is evacuated to about 100 mbar using a vacuum pump. The resulting off-gas still contains traces of methane and must be treated further to meet emission regulations, for instance via regenerative thermal oxidation or catalytic combustion [61].

4.4.2. Membrane-Based Separation and Upgrading of Landfill Gas

Membrane processes are widely considered a compact and modular option for upgrading landfill gas and related biogases. Their primary role is to separate CO_2 from CH_4 to increase methane content (and thus the lower heating value) without the large solvent inventories typical of absorption systems. Technology overviews and process reviews point out that membrane systems are especially attractive at small-to-medium flow rates because the hardware is modular, scalable, and readily packaged in containerised skids [62, 63].

Membrane processes separate gas mixtures using the kinetic selectivity of the membrane material (see Figure 4.5). Gas transport rates vary based on the membrane, gas type, and process conditions, leading to selective enrichment of certain gases [64].

Membranes are semi-permeable barriers that selectively allow certain gas components to permeate faster than others due to differences in solubility and diffusivity within the membrane material. In landfill gas upgrading, membrane systems are typically used to separate CO_2 from CH_4, resulting in methane enrichment of the product gas [64].

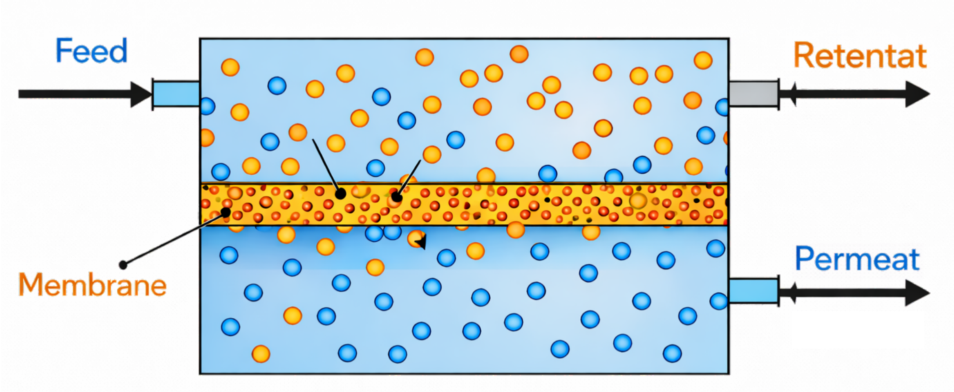

Figure 4.5: Schematic presentation of a membrane separation process

In Rautenbach & Welsch present the treatment of LFG using a membrane-based gas permeation process. The process is designed to produce synthetic natural gas by removing both toxic compounds and carbon dioxide from raw landfill gas. It consists of two main stages: a two-step adsorption system and a membrane separation unit [65].

In the first two stages, H_2S is oxidized and adsorbed on activated carbon, while halogenated hydrocarbons are captured using thermally regenerable activated carbon. After this purification, the gas enters the membrane stage, where CO_2 is selectively separated from methane. The membranes used are non-porous polyamide hollow fibers based on the solution-diffusion mechanism. The efficiency of the separation depends on parameters such as feed pressure, temperature, and membrane surface area. Lower operating temperatures and higher pressures were found to enhance methane purity and overall system stability [65].

Importantly, the membrane system demonstrates high adaptability to fluctuating gas compositions, making it suitable for LCLFG treatment. Even at lower methane concentrations, the system can effectively enrich CH_4 to pipeline standards, especially when supported by multi-stage or reflux cascade configurations, in which the retentate stream is partially recirculated and passed through the membrane system multiple times. However, such cascade operation increases the overall energy demand due to additional gas compression and recirculation requirements. Nevertheless, membrane-based upgrading remains a reliable option for the treatment and utilisation of LCLFG [65].

Principle and Typical Process Configurations

Most commercial units rely on polymeric membranes operating via the solution–diffusion mechanism, in which the more affinity to the membrane material (CO_2) permeates faster than CH_4. Typical process layouts include single-stage modules, two-stage cascades, and multi-stage systems with recycle and/or sweep to increase methane recovery while limiting methane slip in the off-gas [62, 66]. Multi-stage designs can achieve high product purities, but they generally require higher compression ratios, additional interstage equipment, and careful optimisation of stage-cut and recycle to balance methane recovery against specific electricity use.

Membrane Materials and Performance Trends

Cellulose acetate and polyimide families are frequently reported in biogas/LFG upgrading, alongside PDMS and thin-film composite architectures. Recent reviews highlight rapid progress in advanced polymers (e.g. fluorinated polyimides and polymers of intrinsic microporosity) and mixed-matrix membranes incorporating porous fillers (e.g. zeolites and MOFs) [67, 68]. These developments aim to improve the permeability–selectivity trade-off and to maintain performance under realistic conditions, including exposure to water vapour and acid gases, and to mitigate long-term effects such as physical ageing and CO_2-induced plasticisation.

Role of LFG Pretreatment and Impurity Management

Compared with digester biogas, LFG often exhibits higher and more variable levels of N_2/O_2 (air ingress), water vapour, particles, and trace contaminants (notably H_2S, VOCs, and siloxanes). These species can accelerate membrane ageing, contribute to performance loss through swelling or plasticisation in some polymers, and degrade downstream conversion devices. Consequently, pretreatment (dewatering, particulate filtration, and targeted trace-gas control) is commonly implemented upstream of membrane upgrading [63, 66]. For sulphur control in particular, broad reviews of H_2S capture and separation technologies emphasise the need for robust and highly selective approaches, often combining bulk removal with polishing to meet equipment and emissions constraints [69].

Trace Contaminant Separation with Membranes

Beyond CO_2/CH_4 upgrading, membranes have been investigated for selective removal of siloxanes, which form abrasive silica deposits in engines and turbines upon combustion. PDMS-based rubbery membranes show very high siloxane permeability and can achieve meaningful purification in sweep-assisted operation; however, methane losses may become relevant depending on the desired purification level and process configuration [70]. In practice, this means membrane-based LFG upgrading is commonly integrated with dedicated pretreatment (e.g. adsorption or absorption) when strict limits on siloxanes and VOCs are required.

Membrane Contactors and Hybrid LFG-to-biomethane Schemes

Hollow-fibre gas–liquid membrane contactors provide an alternative ”membrane-enabled” route in which CO_2 and H_2S are transferred into a solvent while the membrane supplies high interfacial area and helps avoid flooding typical of packed columns. Hybrid LFG-to-biomethane schemes have been proposed that combine membrane contactors for decarbonation/desulfurization with complementary unit operations for trace organics (e.g. physical absorption for siloxanes), illustrating the suitability of hybrid concepts when stringent product specifications must be met [71].

Implications for Low-calorific Landfill Gas

For low-calorific landfill gas (LCLFG), membranes can support methane enrichment by partial CO_2 removal to reach engine-grade fuel, or stream conditioning (partial CO_2 removal and impurity control) to stabilise fuel quality for conversion technologies tolerant to dilution and variability. The optimal choice depends on inlet methane level, air ingress (N_2/O_2), target methane recovery, and the economic trade-off between compression energy, membrane area, and off-gas handling [62, 66].

4.4.3. Cryogenic Separation

Cryogenic separation is a method used to clean gas mixtures by cooling them down to very low temperatures so that certain components freeze out. CHANG et al. designed a special heat exchanger where CO_2 from LFG is directly removed by freezing it onto the cold walls of the exchanger. At the same time, the remaining CH_4 is cooled down for liquefaction into liquefied natural gas (LNG) [72].

The process works by letting the LFG flow through one side of the exchanger while cold nitrogen gas flows in the opposite direction on the other side. When the gas mixture becomes cold enough, CO_2 begins to freeze out as frost, while methane continues to cool down until it can be turned into LNG [72].

This technique has several advantages. It combines CO_2 removal and methane cooling in one step, works at moderate pressures and avoids the need for large adsorption systems. The study shows that the method can reduce CO_2 levels to below 5.7 parts per million, which is suitable for LNG production. Although the method was developed for LFG with typical methane levels between 50–70%, the paper does not specifically address LCLFG with much lower methane content [72].

4.4.4. Water Scrubbing

Water scrubbing is a physical gas upgrading process that removes CO_2 and H_2S from raw biogas by using water as a solvent. Since CO_2 and H_2S are much more soluble in water than CH_4, they can be absorbed when the gas is brought into contact with water under pressure. The purified methane then remains in the gas phase and is collected as the product gas [73].

In the paper of Läntelä et al., a pilot-scale water scrubbing system was tested for upgrading LFG with a methane content of about 55%. The results showed that the method could effectively increase methane concentration up to over 90% under optimal conditions, while also removing a significant portion of CO_2 and trace compounds like siloxanes. However, the performance strongly depended on process parameters such as water flow, pressure, and temperature [73].

A key limitation highlighted in the study is that N_2, which is often present in large amounts in LCLFG, cannot be removed by water scrubbing because it is not soluble in water. As a result, nitrogen remains in the product gas, reducing the overall methane purity and energy content [73]. This makes water scrubbing less suitable for upgrading LCLFG, especially when high methane concentrations are required for grid injection or fuel use [73].

In summary, while water scrubbing is a reliable and effective method for upgrading standard landfill gas, its inability to remove nitrogen makes it a less relevant option for treating LCLFG [73].

4.4.5. Chemical Absorption (Amine Scrubbing)

Chemical absorption using aqueous amine solutions (e.g. MEA, DEA, MDEA or blended formulations) is a well-established method for removing carbon dioxide and hydrogen sulfide from gas mixtures. In landfill gas upgrading, amine scrubbing can increase methane concentration to levels suitable for grid injection or high-quality fuel applications. However, because amine systems do not remove nitrogen, their applicability to LCLFG is limited unless combined with upstream or downstream nitrogen separation. The technology requires significant thermal energy for solvent regeneration and high standards of gas pre-cleaning to avoid degradation and corrosion. Despite these constraints, amine scrubbing remains one of the most mature upgrading technologies and is often used in hybrid configurations for achieving pipeline-quality biomethane.

4.4.6. Hybrid Upgrading Systems

Hybrid upgrading configurations combine complementary separation principles to increase efficiency and achieve higher methane purity from LCLFG. Examples include membrane separation followed by PSA for nitrogen removal, or amine scrubbing combined with membrane polishing stages. Hybrid systems allow each technology to operate within its optimal range, compensating for variability in gas composition and improving overall product quality. Such configurations are particularly attractive for LCLFG applications where nitrogen content is high and methane enrichment requires multi-step processing.

4.4.7. Nitrogen Removal Technologies

Landfill gas with low calorific value frequently contains elevated nitrogen concentrations resulting from air intrusion into the waste body or leaks in the collection system. As nitrogen cannot be removed using water or amine scrubbing, specialised nitrogen removal technologies are required when high methane purity is needed. Options include cryogenic NRU and pressure/temperature swing adsorption designed for N_2/CH_4 separation. These systems are technically mature but often economically viable only for large gas flows. In smaller installations, nitrogen removal is typically achieved by hybrid membrane–PSA systems or by improving landfill gas collection efficiency to reduce air ingress.

5

Technologies Analysed in the LoCaGas Project

5.1. Introduction

The LoCaGas project focuses on the development and assessment of technological solutions for the utilisation of low-calorific landfill gas, characterised by a low and highly variable methane content. Such gas streams are typically unsuitable for conventional gas utilisation technologies and therefore require adapted or novel approaches to ensure stable operation, acceptable efficiency and compliance with environmental regulations.

This chapter presents and analyses selected technologies that are considered relevant within the framework of the LoCaGas project. The analysed solutions cover a broad range of technological approaches, including chemical gas treatment, thermal utilisation, advanced combustion concepts and engine-based energy conversion systems. Particular emphasis is placed on technologies capable of operating under low methane concentrations and fluctuating gas compositions, which are typical for landfills in the late operational or aftercare phase.

The chapter begins with a detailed description of the Spinning Fluids Reactor, an innovative gas treatment technology developed at Gdańsk University of Technology, focusing on the removal of acidic gas components such as CO_2 and H_2S. Subsequently, Dual Fuel Engines are discussed as a flexible solution for power generation using low-quality gaseous fuels in combination with liquid pilot fuels. The third section addresses oxygen-enriched combustion as a method to enhance combustion stability, heat transfer and overall efficiency when using LCLFG.

Finally, an overview section summarises and compares the discussed technologies, highlighting their main advantages, limitations, minimum methane requirements and possible combinations. This structured assessment provides the basis for evaluating suitable technology pathways for the efficient and sustainable utilisation of LCLFG within the LoCaGas project.

5.2. Spinning Fluids Reactor

The LoCaGas project addresses the challenge of managing and utilising low-calorific landfill gas (LCLFG), which is characterised by low and fluctuating methane concentrations as well as elevated contents of inert and acidic components. Such gas streams are typically unsuitable for conventional energy recovery or upgrading technologies and require innovative, flexible and robust process solutions.

Within this context, the Spinning Fluids Reactor (SFR) represents a novel gas–liquid contacting technology that enables intensified mass transfer under extremely short residence times. The SFR was developed at Gdańsk University of Technology as an alternative to conventional absorption columns, particularly for applications where compact design, low pressure drop and fast gas treatment are required. In the LoCaGas project, the SFR is primarily considered as a pre-treatment or conditioning technology for landfill gas, focusing on the partial removal of acidic gas components such as CO_2 and H_2S, thereby increasing methane concentration to a level suitable for downstream utilisation technologies.

5.2.1. Design and Operating Principle of the Spinning Fluids Reactor

The Spinning Fluids Reactor is a compact gas–liquid reactor that combines features of hydrocyclone-type devices with intensified multiphase contact. The reactor consists of three main components: (i) a reactor head introducing the liquid phase tangentially at high velocity, (ii) a reactor body that forces the gas phase into a swirling motion, and (iii) an inner porous partition (IPP) that separates the gas and liquid phases while enabling their interaction (see Figure 5.1).

Both phases are introduced tangentially on opposite sides of the IPP and swirl in countercurrent rotational motion. The liquid phase reaches linear velocities of up to 10 m s^{-1}, generating high centrifugal and shear forces. Gas passing through the porous partition is dispersed into extremely fine bubbles, while the liquid forms thin rotating films. This hydrodynamic configuration results in an exceptionally high gas–liquid interfacial area within a very small reactor volume [74].

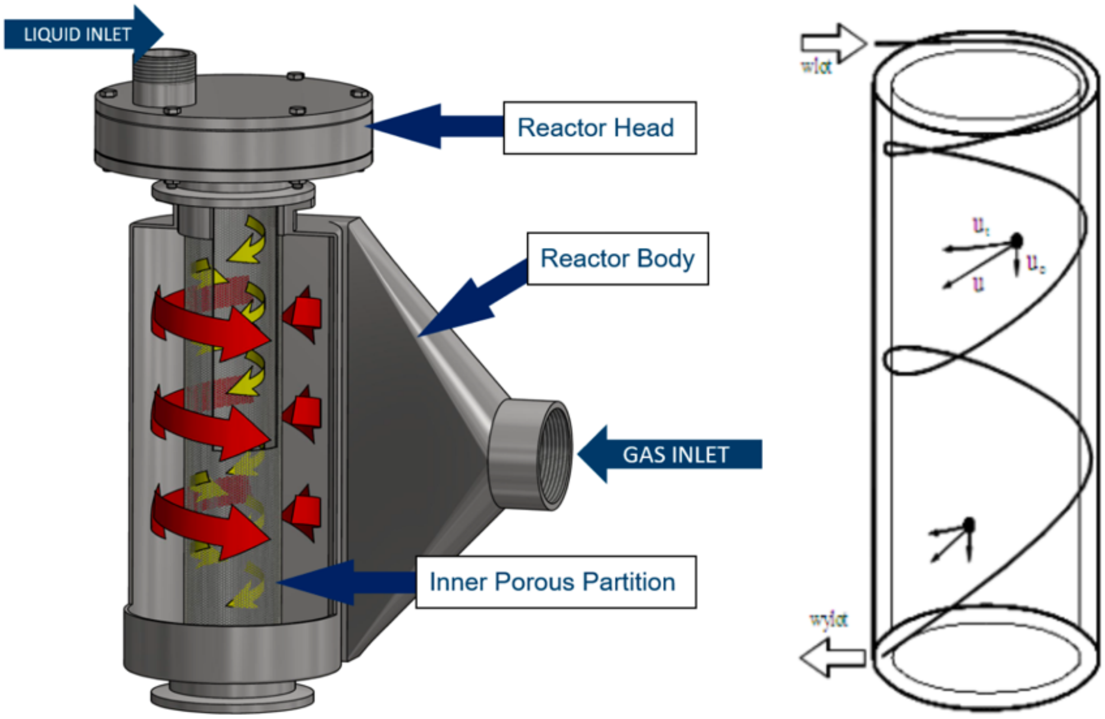

Figure 5.1: Principle of a Spinning Fluids Reactor (Robert Aranowski)

The counter-rotating flow pattern distinguishes the SFR from classical bubble columns or packed absorbers and is responsible for the intensified mass and heat transfer characteristics observed in the reactor. Depending on the orientation of the reactor body, co-rotating or counter-rotating flow can be achieved, allowing additional flexibility in process design.

5.2.2. Hydrodynamics and Residence Time Characteristics

One of the defining features of the SFR is its extremely short hydraulic residence time. Experimental studies have demonstrated that the mean residence time of the liquid phase typically lies in the range of 0.3–0.6 s, depending on operating conditions and reactor internals. Such residence times are orders of magnitude shorter than those encountered in conventional absorption columns and place the SFR among the fastest continuous gas–liquid reactors reported in the literature [75].

Due to these short residence times, conventional residence time distribution measurement techniques based on ideal tracer pulses cannot be applied. In the case of the SFR, the tracer injection duration may exceed the actual residence time of the reactor. To overcome this limitation, an imperfect pulse method combined with frequency-domain deconvolution using Fast Fourier Transform was successfully applied for the first time to determine the true RTD of the reactor [75].

The obtained RTD curves reveal relatively narrow distributions, indicating limited back-mixing and well-defined hydrodynamic behaviour despite the highly turbulent multiphase flow. Validation by reconvolution of inlet tracer signals with the extracted RTD functions showed excellent agreement with experimental outlet signals, confirming the reliability of the applied methodology.

5.2.3. Influence of Operating Conditions and Reactor Internals

Systematic investigations were conducted over wide ranges of liquid flow rates (18.75–75 $dm^3\ min^{-1}$) and gas flow rates (16.75–100 $m^3\ h^{-1}$), using different inner porous partitions with varying pore diameters, open areas and porosities. The results demonstrate that the liquid flow rate is the dominant parameter governing both the mean residence time and the dispersion of the RTD.

Increasing liquid flow intensifies centrifugal forces acting on the rotating liquid film, which leads to longer residence times while simultaneously reducing RTD dispersion due to stronger flow segregation. In contrast, the influence of gas flow rate on the mean residence time is relatively minor, reflecting the lower kinetic energy of the gas phase compared to the liquid phase. However, gas flow rate has a noticeable effect on RTD variance, as increased gas throughput enhances bubble generation and local micromixing phenomena within the reactor [75].

The properties of the inner porous partition play a crucial role in shaping reactor performance. Larger pore diameters and higher open areas promote the formation of larger gas bubbles, which increase buoyancy forces and locally slow down the liquid phase, resulting in increased residence time and dispersion. Conversely, finer porous structures generate smaller and more uniformly distributed bubbles, stabilising the multiphase flow and reducing RTD variance.

5.2.4. Predictive Modelling and Sensitivity Analysis

To support reactor design and scale-up, non-linear predictive models for the mean residence time and RTD variance were developed using evolutionary algorithms. These models relate the hydrodynamic descriptors of the reactor, including gas and liquid flow rates as well as IPP parameters, to the observed RTD characteristics.

The models achieved good predictive performance, with coefficients of determination exceeding 0.8 for the mean residence time. Validation using independent data sets and y-randomisation tests confirmed that the identified relationships are statistically significant and not artefacts of random correlation [75].

Sensitivity analyses revealed that liquid velocity is the most influential parameter affecting both mean residence time and dispersion. Gas flow rate primarily affects dispersion, while IPP porosity and pore diameter introduce secondary but non-negligible effects. These insights provide valuable guidance for reactor optimisation and process control.

5.2.5. Gas Treatment Potential for Landfill Gas

From the perspective of the LoCaGas project, the SFR is particularly attractive as a gas treatment technology for landfill gas conditioning. The reactor has been demonstrated to be effective for the absorption of acidic gas components such as CO_2 and H_2S using chemical absorbents, including amine-based solutions. Due to the extremely short contact times, chemical enhancement of absorption is required to achieve meaningful separation performance.

Unlike conventional absorption columns, the SFR does not aim for near-complete removal of acidic components. Instead, it enables partial upgrading of landfill gas, increasing methane concentration to moderate levels that are sufficient for utilisation in technologies such as dual-fuel engines or modified combustion systems. This approach aligns well with the characteristics of LCLFG, where complete upgrading is often economically or technically unjustified.

The compact design, low pressure drop and scalability through parallel reactor units make the SFR well suited for decentralised landfill gas applications. Furthermore, its ability to operate under highly variable gas compositions and flow rates is particularly relevant for landfills in the late operational or aftercare phase.

5.2.6. Comparison With Conventional Gas--Liquid Contactors

Compared to traditional packed columns or tray absorbers, the SFR offers significantly reduced reactor volume and residence time while maintaining high mass transfer rates. This intensification comes at the cost of shorter contact times, necessitating the use of reactive absorbents or enhanced mass transfer driving forces.

In contrast to membrane or adsorption-based upgrading technologies, the SFR is less sensitive to contaminants and does not require extensive pre-treatment of the gas stream. This robustness is a key advantage for landfill gas applications, where gas quality can fluctuate significantly over time.

5.2.7. Relevance for Process Integration Within LoCaGas

Within the LoCaGas project, the SFR is envisioned as a modular component that can be integrated with other technologies, such as conventional gas engine. By partially removing CO_2 and H_2S, the SFR improves gas quality and stabilises downstream processes, enhancing overall system efficiency and operational reliability.

The flexibility of the SFR allows its operation to be tailored to project-specific requirements, including targeted methane enrichment levels and integration with existing landfill gas infrastructure. As such, the SFR represents a key enabling technology within the LoCaGas concept for the sustainable utilisation of low-calorific landfill gas.

5.2.8. Limitations and Risks Associated With the Spinning Fluids Reactor

Despite the significant advantages of the Spinning Fluids Reactor in terms of process intensification, compact design and high gas–liquid mass transfer rates, several limitations and potential risks must be considered when evaluating its applicability within the LoCaGas project.

One of the fundamental limitations of the SFR arises from its extremely short residence time, typically in the range of 0.3–0.6 s. While this characteristic enables rapid gas treatment, it inherently limits the achievable separation efficiency for purely physical absorption processes. As a result, effective removal of acidic gas components such as CO_2 and H_2S generally requires the use of chemically reactive absorbents, for example amine-based solutions. This introduces additional process complexity, including solvent management, regeneration requirements and potential chemical degradation.

The reliance on chemical absorbents also entails operational risks related to solvent loss, foaming, corrosion and contamination by landfill gas impurities. Although the SFR itself is less prone to fouling than packed columns due to the absence of structured internals, long-term operation with raw landfill gas may still lead to gradual performance deterioration if adequate gas pre-treatment and solvent monitoring are not ensured.

Another limitation concerns the sensitivity of the reactor hydrodynamics to liquid flow conditions. Experimental studies have shown that liquid flow rate is the dominant parameter influencing both mean residence time and dispersion. Consequently, deviations from the optimal operating window may result in reduced mass transfer efficiency or unstable multiphase flow patterns. For landfill gas systems, where gas and liquid flow rates can fluctuate over time, appropriate process control strategies are required to maintain stable reactor performance.

From a mechanical and operational perspective, the inner porous partition represents a critical component of the SFR. Its pore size, porosity and thickness strongly affect bubble formation and hydrodynamic behaviour. Inappropriate selection or degradation of the IPP material may lead to increased pressure drop, non-uniform gas distribution or accelerated wear. Furthermore, the use of fine porous structures, while beneficial for mass transfer, may increase the risk of clogging when exposed to particulate matter or condensates present in landfill gas streams.

Scaling and integration also pose potential challenges. Although the SFR is well suited for parallelisation through multiple reactor units, the technology has so far been demonstrated primarily at laboratory and pilot scales. Large-scale deployment therefore involves uncertainties related to long-term reliability, maintenance requirements and overall system economics. These aspects are particularly relevant for decentralised landfill applications, where operational simplicity and robustness are critical.

Finally, from a system-level perspective, the SFR should be regarded as a partial gas treatment solution rather than a complete upgrading technology. The reactor is particularly attractive when integrated with conventional gas engines or other combustion-based energy recovery systems, where moderate methane enrichment is sufficient for stable and efficient operation. In this context, increasing the methane concentration, for example from approximately 20% to 40%, may already provide significant practical benefits, even though it remains far below natural gas quality $\sim$97% CH_4. Applications requiring high-purity biomethane would still necessitate additional upgrading steps, which may reduce the overall economic attractiveness of the SFR-based process chain.

In summary, while the Spinning Fluids Reactor offers significant advantages for the treatment of low-calorific landfill gas, its implementation within the LoCaGas project requires careful consideration of solvent management, flow control, reactor internals and system integration. Addressing these limitations through appropriate design choices and operational strategies is essential to minimise risks and ensure reliable long-term performance.

5.2.9. Summary

The Spinning Fluids Reactor is a highly intensified gas–liquid reactor characterised by extremely short residence times, high interfacial area and predictable hydrodynamic behaviour. Extensive experimental and modelling studies have demonstrated its suitability for fast gas treatment applications, particularly under conditions where conventional technologies are ineffective.

In the context of the LoCaGas project, the SFR offers a flexible and compact solution for partial landfill gas upgrading, enabling the utilisation of low-calorific gas streams in downstream energy conversion technologies. Its unique combination of process intensification, robustness and scalability makes it a promising component of integrated LCLFG utilisation strategies.

5.3. Dual Fuel Engines

Dual Fuel Engines are part of the gas-diesel engine family, which can be divided in two categories. Category one is the so-called Ignition Jet Engine that operates exclusively with gas. The diesel is only needed for the ignition process. The engines cannot be run with diesel. Category two are the DFEs which operate with both, diesel and gas. This means that either gas or diesel can be used as main fuel but also a mixture is possible, which is called fuel sharing [76].

There are different engine types for the DFE principle but it is based on an ignition of a fuel with a high octane number (for example methane) and a fuel with a low octane number (Diesel). The fuel with the hight octane number is the primary fuel and the one with the low octane number is called secondary fuel. The primary fuel gets mixed with air and injected into the piston chamber. Fuel gases containing hydrocarbons are generally chemically stable which is why they do not self-ignite. For this reason, the secondary fuel is injected at the compression phase. It is thereby mixed with the primary fuel and self-ignites. The following Figure 5.2 shows the scheme of a Reactivity Controlled Compression Ignition Engine which is one variant of an DFE [76].

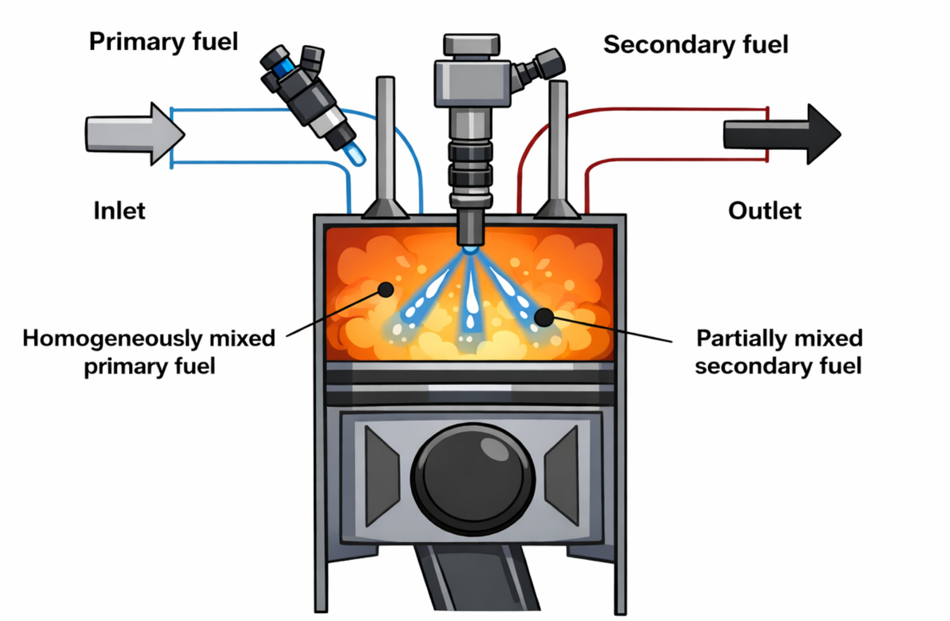

Figure 5.2: Scheme of a Dual Fuel Engine.

In the paper of Rahman& Ramesh the authors investigate how varying the methane content in biogas and adjusting injection strategies affect the performance of a DFE. The research is therefore particularly relevant for LCLFG [77].

In the dual-fuel setup examined, biogas is premixed with intake air and introduced into the combustion chamber, while diesel is injected through a common rail system to initiate ignition. This diesel injection timing, known as the Start of Injection Timing, plays a crucial role in optimizing combustion and efficiency [77].

The core variable assessed throughout the study is the Biogas Energy Share, which represents the percentage of total fuel energy derived from biogas. BGES is calculated based on the chemical energy contributions of both biogas and diesel [77].

$$\text{BGES} = \frac{\text{Energy from Biogas}}{\text{Energy from Biogas} + \text{Energy from Diesel}} \cdot 100 \tag{5.1}$$

In the first phase of testing, the researchers evaluated how different methane concentrations (ranging from 24% to 68%) at various BGES levels [77].

The results showed that thermal efficiency remained nearly constant up to a BGES of 60%, even at very low methane contents. However, when operating with low methane and high CO, the diesel injection had to be advanced to compensate for ignition delays. Notably, NO_x emissions decreased as methane content dropped, largely due to the thermal-dilution effect of CO_2, which reduces the temperature in the combustion chamber. Meanwhile, methane and CO emissions increased at high BGES due to incomplete combustion, especially when diesel quantities were low. Smoke emissions decreased as diesel use dropped, staying at acceptable levels even with high CO_2 biogas [77].

In the second phase, the study explored two alternative injection strategies - post-injection (PI) and early pilot injection - to improve combustion stability and emissions at higher BGES levels. While post-injection reduced NOx slightly, it also lowered thermal efficiency and led to increased unburned hydrocarbons and smoke due to late, diffusion-dominated combustion. Early pilot injection showed marginal benefits in terms of reducing smoke but offered no significant improvements over single injection [77]. In conclusion, the paper demonstrates that dual-fuel diesel engines can operate efficiently even with biogas containing very low methane levels, as long as the injection timing is properly optimized [77].

A BGES of up to 60% is achievable without significant performance loss, making the system suitable for the utilization of LCLFG. Although advanced injection strategies can provide minor enhancements, simple single-injection modes remain the most balanced in terms of efficiency and emissions [77].

The findings confirm that dual-fuel operation is a robust and flexible solution for using variable-quality biogas in internal combustion engines [77].

In Denmark, the Danish company ApS has developed a DFE for operation with LCLFG. The engine is capable of operating with methane concentrations as low as 10%. As described previously, diesel is used only for the ignition process. The engine can operate over a wide range of loads, while the diesel consumption remains approximately constant regardless of engine load. Consequently, operating the engine at higher loads reduces the relative share of diesel in the total energy input and maximises the overall energy production efficiency [78].

In the LoCaGas project, renewable fuels such as RME and blends of RME with pyrolysis oil will be used for the ignition process in order to produce green power (and heat).

5.4. Oxygen-Enriched Combustion

5.4.1. Technology Overview and Operating Principle

Oxygen-Enriched Combustion

Energy is produced by combined heat and power systems, which often use internal combustion engines. The minimum typically methane concentration for ICE is 40% vol. If the methane content is lower, a significant CO_2 and/or N_2 content lowers its calorific value, which becomes too low to sustain stable combustion and alters its combustion characteristics. Extremely low CH_4 content landfill gas presents technical challenges for ICE, leading to reduce in-cylinder peak pressure [79] and a lower heating value of the air-fuel mixture [80]. Gas with low methane content has a high self-ignition temperature, which directly results in a high antiknock index.

To address these challenges, multiple technologies have been investigated with the potential to enhance combustion stability and reduce emissions. To improve the combustion process and performance of the gases with low CH_4 content, enrichments such as propane or hydrogen can be introduced to raise their LHV [81]. However, propane is incompatible with the ”Green Deal” ideology, and hydrogen technologies are still in the development stage. Alternatively, enriching compositions with low hydrocarbon content with 1–2% additional oxygen can extend the lean ignition limit [82]. Also, these methods generally reduce CO and HC emissions [81–83]. For this reason, it is proposed that these problems could be solved using oxygen-enriched combustion technology. An oxy-fuel combustion system, initially designed for solid fuel combustion, showed significant improvements in energy production [84]. However, the use of pure oxygen resulted in issues such as flame instability and locally high temperature gradients. To mitigate these problems and control the flame, recycled flue gas, mainly composed of CO_2, is mixed with the oxy-fuel mixture [85]. Numerical simulations have found that methane combustion with a CO_2/O_2 oxidizer mixture is most effective and stable when oxygen concentrations range from 28 to 32% vol [86]. Experimental studies, however, indicated slightly higher limits (31–35% vol.) for stable combustion [87]. In both cases, lower oxygen concentrations in the CO_2/O_2 mixture resulted in reduced stability, and stable flames could not be sustained with oxygen levels above 23% vol.

Also, oxygen-enriched combustion has been extensively studied for spark ignition engines, showing potential for reducing emissions while enhancing engine performance. Investigations using oxygen-enriched air with 23–25% O_2 (v/v) have reported power increases ranging from 5% to 17%, along with a 25–32% reduction in CO emissions and a 30–40% decrease in HC emissions when combined with three-way catalysts [88]. Bench tests demonstrated that higher oxygen enrichment ratios lead to increased combustion temperatures, improved power output, and significant reductions in HC and CO emissions. At OER=25%, HC emissions decreased to 58–87 ppm and CO emissions dropped to 5.71–8.60% of baseline levels. However, NO_x emissions increased substantially. Particulate number emissions initially rose with OER but declined at higher manifold absolute pressure and OER=25%. For biogas-fueled SI engines, increasing oxygen concentration in the intake air extends the lean combustion limit, enhances combustion rates, and improves thermal efficiency and power output. Oxygen concentrations above 23% reduce HC and CO emissions significantly but cause a sharp rise in NOx emissions. At an equivalence ratio of 0.95, increasing oxygen from 21% to 23% at full throttle raises brake thermal efficiency from 26.2% to 28%, increases power output from 5 kW to 5.35 kW, and reduces HC and CO emissions by 41% each. Additionally, the peak heat release rate improves from 63.6 J/°CA to 76.3 J/°CA, and the combustion duration shortens from 36textdegree to 31° [82]. However, NO_x emissions increase by 45.6%, rising from 3,440 ppm to 5,010 ppm and show a need for controlled combustion temperature to detain thermal NO reaction rate.

These findings underscore the potential of oxygen-enriched combustion technology to enhance combustion stability and extend the operational limits of ultra-low-calorific landfill gas (below 40%), where high heat capacity of CO_2 cause reduction of the combustion temperature which then affects the NO formation extinguishing the technology drawbacks.

The oxygen-enriched combustion will be applied for landfill gas combustion in a spark ignition internal combustion engine. Due to this, the biogas power generator (CHP unit) consisting of 4-cylinder spark ignition engine, an electrical generator, a cooling system and a secondary cooling circuit output was purchased. The unit is designed to combust 60% vol. CH_4 in CO_2 and produce 30 kW electrical power. It will be modified to work under oxygen-enrichment and to achieve stable combustion of LCV gases with methane content of 20% vol. in CO_2.

Operating principle

The start-up of the CHP unit is forecast to use natural gas. The engine is started on natural gas under no load. After the engine and other equipment reach a sufficient operating temperature, the fuel is switched to biogas (60% val. CH_4 in CO_2). The methane concentration in the gas stream is determined by an analyzer installed in the gas line.

Once the engine is operating on biogas, the electrical load is applied by increasing it from 4.5 kW to 27 kW. At the highest load, the gas composition is gradually changed by reducing the CH_4 content from 5% vol, down to 30% vol. CH_4 in CO_2, and the engine parameters are adjusted accordingly, including the air–fuel ratio, gas supply valve flap positions, ignition timing, etc.

At this stage, oxygen enrichment is applied by supplying pure oxygen to the intake downstream of the flap valve. Since the engine operates under suction, a flap valve body is installed in the air intake line, and a controllable oxygen flow is introduced downstream of the flap. The flap valve body regulates the amount of air supplied to the engine and enables controlled adjustment of the AFR when varying the methane concentration and oxidizer oxygen concentration.

While the engine operates at constant load with a gas mixture of 30% vol. CH_4 in CO_2, the oxygen concentration in the combustion air is increased in 1% vol. increments. After each adjustment, several minutes are allowed to monitor engine parameters. This procedure continues until the catalytic converter temperature approaches, but does not exceed, 600°C.

Subsequently, the CO_2 flow rate is increased by 0.1 $m^3\,h^{-1}$, and the oxygen concentration is adjusted according to engine performance. These steps are repeated until the engine is operating with a gas mixture containing 20% vol. CH in CO_2. If necessary, the engine load is reduced by decreasing electrical power output.

Once the optimal operating point is identified, the CHP unit is operated continuously for several hours to collect all relevant measurable data, including AFR, catalytic converter temperature, ignition timing, flap valve positions, inlet and outlet temperatures, electrical power production, and emissions of CO, CO_2, NOx, HCN, and other species.

5.4.2. Technical Maturity (TRL) and Current Development Status

The purchased biogas power generator/CHP unit is a commercially available system and therefore corresponds to TRL 9 (actual system proven in an operational environment). It is originally designed for operation on biogas containing 60% vol. CH_4 in CO_2.

Following modifications for oxygen-enriched combustion and recalibration for operation on low-calorific-value (LCV) gases containing 20% vol. CH_4 in CO_2, the modified system is considered to be at TRL 4 (technology validated in a laboratory environment).

The engine is currently prepared for laboratory-scale validation under oxygen-enriched conditions using CH_4/CO_2 mixtures with methane concentrations below 40% vol. Successful completion of these laboratory tests will advance the technology to TRL 5 (technology validated in a relevant environment).

Achievement of TRL 6 (technology demonstrated in a relevant environment) is planned once the key engine parameters for stable and efficient operation on LCV gases have been established and the CHP unit has been demonstrated during pilot-scale testing under representative operating conditions.

5.4.3. Feedstock Requirements and Operating Conditions

Natural gas or methane is required for engine start-up and shutdown and will also be used during operation until the engine is capable of stable combustion of low-calorific-value (LCV) gas containing 20% vol. CH_4 in CO_2. Supply via a natural gas pipeline or compressed gas cylinders is sufficient. The maximum methane requirement is up to 10 $m^3\,h^{-1}$ for a duration of up to two hours.

For CHP operation, landfill gas or biogas will be supplied to the engine. These gases must be appropriately conditioned prior to engine supply. The specific gas quality requirements are presented in Table 5.1.

Table 5.1: The specific gas quality requirements for OEC.

Parameter	Unit of measure	Value
The least admissible methane content	(% vol.)	50
Low heat value	MJ/m^3	>18
	kWh/m^3	>5
Chlorine	mg/10 kWh	<100
Fluorine	mg/10 kWh	<50
Chlorine and fluorine	mg/10 kWh	<100
Sulphur in total	mg/10 kWh	<350
Silicon	mg/10 kWh	<1
Ammonia	mg/10 kWh	<30
Relative humidity	%	<60

To achieve oxygen enrichment up to 40% vol. O_2 in the oxidizer, an external oxygen supply is required. Based on preliminary calculations, the oxygen demand at full load (100% output of approximately 30 kWel) is about 20 $m^3\,h^{-1}$. For an 8-hour operating period, this corresponds to a total oxygen consumption of approximately 160 m^3. At lower CHP unit loads, oxygen consumption is expected to decrease to approximately 10–15 $m^3\,h^{-1}$. The actual oxygen demand will be determined more precisely following the laboratory-scale experiments.

5.4.4. Performance Characteristics

The performance data of the CHP unit supplying biogas as fuel is presented in the Table 5.2.

Table 5.2: The performance data of the CHP unit supplying biogas as fuel.

Parameter	Units	Value		
Load	%	100	75	50
Electrical output	kW	30	22.5	15
Heat output	kW	59	45.6	37.5
Electrical efficiency	%	30.9	30.1	26
Heat efficiency	%	60.8	61	65.1
Total efficiency	%	91.7	91.1	91.1
Fuel input	kW	97.1	74.7	57.6
NOx emission at 5% of O_2 in exhaust	$mg\,Nm^{-3}$		500	
CO emission at 5% of O_2 in exhaust	$mg\,Nm^{-3}$		250	
HCHO emission at 5% of O_2 in exhaust	$mg\,Nm^{-3}$		60	

The performance characteristics of the unit operating under oxygen-enriched conditions and supplied with LCV gases will be determined during laboratory-scale testing. According to preliminary calculations, combustion of a gas mixture containing 20% vol. CH_4 and 80% vol. CO_2 is expected to result in reduced engine efficiency, with a maximum electrical output of approximately 22–24 kW when oxygen-enriched air containing up to 40% vol. O_2 is supplied.

5.4.5. Infrastructure Requirements and System Integration

For operation of the CHP engine under oxygen-enriched conditions, the CHP unit must be installed indoors or within a container. The indoor space or container shall maintain a minimum internal temperature of 5–10°C to prevent damage to electrical components, sensors, and measuring devices during cold seasons. The engine air intake should be located within the same enclosed space; otherwise, the combustion air must be preheated to at least 10°C. In enclosed installations, electric air heaters may be used for this purpose. The CHP unit is equipped with a secondary heating circuit connected to a heat exchanger. To ensure adequate cooling temperatures of 70/90°C, the heat exchanger is fitted with two fans and temperature switches and requires auxiliary electrical power. Therefore, the CHP installation site must provide an auxiliary power supply of up to 4 kW at 230 V. If the secondary heating circuit is connected to an existing heating or cooling system, the required auxiliary electrical power is reduced to approximately 3 kW for electric heaters and auxiliary equipment.

The CHP unit can operate in two modes: island mode and grid-connected mode. In island mode, various three-phase and single-phase electrical devices can be connected, with a total electrical load of up to 30 kW. The load imbalance between phases must not exceed 30%. If it is necessary to reduce power demand from the grid, the CHP unit can be connected to the existing electrical grid. In this case, electrical cables with a cross-sectional area of 6 mm^2 shall be used, together with dedicated circuit breakers and switches.

5.5. Overview of Technologies

The following Table 5.3 provides an overview of the discussed technologies. It is sorted in the main categories thermal, biological and chemical/mechanical. There is an extra category for the project specific technologies. The column possible combinations shows if certain technologies can be combined with others.

Table 5.3: Overview of the project technologies

Categories	Technology Name	Type	Min. CH_4%	Advantages	Disadvantages	Possible Combinations	Practical application
Thermal	Low-Temp Flare	Utilization	$\geq$25%	Simple setup, can use existing infrastructure, effective for controlled emissions.	Unstable combustion below 25% CH_4, high emissions if not tuned.	-	Commonly used
	Modified Flare	Utilization	$\geq$20%	Improved combustion through tailored burners, more stable at lower CH_4.	Requires specific burner designs; moderate cost.	-	Commonly used
	Low CV High Temp Flare	Utilization	10–15%	Maintains flame at very low CH_4, reduced methane slip	High temp design increases complexity and cost.	Stirling Engine	In use: Example Eflox flare at Rübenloch
	Open /Supported Flare	Utilization	<15%	Works with additional fuel input even for very low CH_4.	Relies on external fuel, high operational cost.	-	-
	Microturbines	Utilization	$\geq$30%	Compact, low emissions, electricity generation.	Requires clean and compressed gas; lower efficiency at low loads.	Gas Processing	In use: For example Landfill Eichelbruck in Freiburg
	Thermal Oxidizers	Utilization	-	Effective VOC and CH destruction, low emissions.	High temperature operation, high energy demand	-	-
	Pyrolysis (with LCLFG support)	Utilization	<20% (w/assist)	LCLFG can be reused as heat carrier, enables material recovery.	Needs secondary energy input or enriched air.	Oxygen Enrichment, Hybrid Heating	Pilot testing. Not in big scale
Biological	Biofilter	Utilization	-	Passive system, low energy, removes odors and CH_4 biologically.	Large footprint, limited efficiency under cold/wet conditions.	-	-
	Biological Methanation	Upgrading	<20%	Increases CH_4 content significantly, CO_2 converted to CH_4	Needs constant H_2 supply, sensitive microbes, slow dynamics.	-	-
	Algae Reactors	Upgrading	N/A	Captures CO_2, potential biomass valorization.	Still under research, needs large surface and light.	-	-
Physical /Chemical	PSA	Upgrading	$\geq$30%	High CH_4 purity, proven in industry, no chemicals required.	Sensitive to contaminants, energy-intensive, high upfront cost.	Cryogenic, Membrane	-

Continued on next page

Table 5.3 – continued from previous page

Categories	Technology Name	Type	Min. CH_4%	Advantages	Disadvantages	Possible Combinations	Practical application
Physical /Chemical	Membrane Separation	Upgrading	$\geq$30% lower w/cascade	Modular, low maintenance, handles variable flow.	Lower selectivity for CH_4 at low concentrations.	Adsorber, Reflux	-
	Cryogenic Separation	Upgrading	30%	Produces LNG, removes CO_2 by freezing, compact product.	Very high energy use, complex machinery, not ideal for small plants.	Membrane, PSA	-
	Water Scrubbing	Upgrading	55%	Simple setup, low technical demand, works continuously.	Does not remove N_2, limited CH_4 enrichment.	Drying Unit	-
Project specific	Spinning Fluids Reactor	Upgrading	$\geq$45%	Compact, rapid gas-liquid contact, low pressure drop.	Needs amines, still in development phase for large scale.	Otto Engine, Gas Pretreatment	-
	Dual Fuel Engine	Utilization	$\geq$10%	Efficient energy use, can switch to full diesel if needed.	Complex control, tuning required for injection strategy.	SFR, Gas Pretreatment	-
	Oxygen -Enriched Combustion	Utilization	LCLFG with 30% CH_4 has same characteristics like LFG with 60% CH_4	Higher flame temperature, enables LCLFG combustion at low CH_4.	Requires oxygen supply, safety systems needed.	Flare, Pyrolysis	-

6

Technology Risk Analysis

This chapter presents a structured analysis of the technological risks associated with the three utilisation pathways investigated within the LoCaGas project: Dual Fuel Engine (DFE), Oxygen-Enriched Combustion (OEC), and the Spinning Fluids Reactor (SFR) combined with downstream energy conversion. The analysis is intended to support ex-ante decision-making by identifying potential technical, operational, environmental, and regulatory risks, as well as corresponding mitigation strategies.

Given the focus of LoCaGas on low-calorific landfill gas (LCLFG), characterised by low and variable methane content, air ingress, and elevated levels of contaminants, particular attention is paid to risks arising from gas quality variability and system integration.

6.1. General Risk Framework

The risk analysis follows a qualitative approach, distinguishing between:

- technical and process-related risks,
- operational and reliability risks,
- environmental and health-related risks,
- regulatory and permitting risks,
- integration and scalability risks.

Risk severity is assessed qualitatively in terms of potential impact on system performance, environmental compliance, and long-term operability. As the technologies are at different levels of maturity, the nature and magnitude of risks vary significantly between concepts.

6.2. Dual Fuel Engine

6.2.1. Technical and Operational Risks

The DFE concept is generally regarded as a robust and mature technology for the utilisation of low-quality gaseous fuels. However, several risks remain relevant in the LoCaGas context. A key technical risk is the dependence on pilot fuel (typically diesel or renewable substitutes), which introduces additional complexity in fuel supply, injection control, and combustion stability. Variations in methane content and oxygen concentration in the landfill gas may lead to unstable combustion, increased knock tendency, or reduced efficiency if not properly controlled.

Long-term engine wear represents another operational risk, particularly due to trace contaminants such as H_2S, siloxanes, and particulates. Insufficient gas cleaning may accelerate corrosion, deposit formation, and lubricant degradation, leading to increased maintenance requirements and reduced engine lifetime.

6.2.2. Environmental and Regulatory Risks

From an environmental perspective, the use of pilot fuel leads to additional CO_2, NOx, and SOx emissions. This may pose challenges in meeting increasingly stringent emission limit values, especially for small and decentralised installations. Furthermore, the classification of electricity generated using a mixed fossil–renewable fuel may be ambiguous in some regulatory frameworks, potentially affecting eligibility for renewable energy incentives.

6.2.3. Integration Risks

While DFEs are well suited for retrofitting existing landfill gas installations, integration risks may arise when attempting to maximise renewable content by substituting diesel with alternative pilot fuels (e.g. biofuels or pyrolysis oils). Fuel compatibility, long-term engine durability, and warranty considerations remain areas of uncertainty.

6.3. Oxygen-Enriched Combustion

6.3.1. Technical and Operational Risks

The OEC concept aims to increase combustion efficiency and extend the operability of spark-ignited engines towards lower methane contents. A central technical risk is the increased combustion temperature associated with oxygen enrichment, which can lead to elevated NOx formation, higher thermal loads on engine components, and reduced material lifetime if not adequately managed.

The reliability and energy demand of the oxygen supply system constitute another critical risk. On-site oxygen generation (e.g. via pressure swing adsorption or membrane separation) introduces additional auxiliary equipment, increasing system complexity and potential failure points. Any interruption in oxygen supply may directly result in system shutdown.

6.3.2. Environmental and Safety Risks

Higher combustion temperatures increase the risk of thermal NOx formation, potentially compromising local air quality compliance. From a safety perspective, handling oxygen-enriched streams requires careful design to avoid fire and explosion hazards, particularly in environments already associated with combustible gases.

6.3.3. Regulatory and Integration Risks

The regulatory acceptance of oxygen-enriched combustion in decentralised power generation is not uniform across jurisdictions. Additional permitting requirements may apply due to oxygen handling and modified combustion conditions. Integration with existing engines may also be limited by manufacturer specifications and certification constraints.

6.4. Spinning Fluids Reactor

6.4.1. Technical and Process Risks

The SFR represents the most innovative and least mature technology among the LoCaGas concepts. Its core function–intensified CO_2 removal prior to energy conversion–introduces risks related to process stability, solvent management, and rotating equipment reliability. Mechanical wear, seal integrity, and long-term stability under continuous operation are key uncertainties at higher technology readiness levels.

Another significant risk arises from the high auxiliary energy demand of the gas pretreatment step. If the required electricity is not supplied from low-carbon sources, the environmental benefits of CO_2 removal may be substantially reduced or negated.

6.4.2. Operational and Environmental Risks

Solvent degradation and potential solvent losses represent both operational and environmental risks. Improper solvent management could lead to increased operating costs, waste generation, and environmental impacts. Additionally, the overall system complexity increases due to the need to integrate gas pretreatment with downstream engines or turbines.

6.4.3. Scalability and Integration Risks

The scalability of the SFR to different landfill sizes and gas flow rates remains to be demonstrated under real operating conditions. Integration with conventional gas engines requires careful matching of gas quality, pressure, and flow stability. Any mismatch may compromise engine performance or negate the benefits of upstream CO_2 separation.

6.5. Cross-Cutting Risks for LCLFG Utilisation

Across all three technologies, several cross-cutting risks are identified. The most prominent is the high temporal and spatial variability of landfill gas composition, including fluctuations in methane content, oxygen ingress, and contaminant levels. Such variability challenges process control, performance prediction, and long-term reliability.

Another overarching risk relates to data uncertainty. Limited availability of long-term operational data for LCLFG applications introduces uncertainty in performance projections, cost estimates, and environmental indicators.

6.6. Risk Mitigation Strategies

Potential mitigation measures include:

- advanced gas monitoring and control systems to manage variability in LFG composition,
- modular system design allowing staged deployment and gradual scaling,
- integration of low-carbon electricity sources to offset auxiliary energy demand,
- comprehensive pilot testing and long-term monitoring to generate high-quality primary data,
- early engagement with regulators and technology providers to clarify permitting and certification requirements.

6.7. Summary

The technology risk analysis highlights that no single LoCaGas technology is universally optimal under all conditions. DFEs offer high robustness but face environmental and regulatory challenges. OEC provides high efficiency but introduces thermal, safety, and oxygen supply risks. The SFR has strong potential for emissions reduction but is associated with higher technical complexity and energy demand.

Consequently, technology selection should be site-specific and supported by detailed gas characterisation, system integration studies, and risk-informed decision-making. The pilot activities within the LoCaGas project are therefore essential to reduce uncertainty and to enable a robust ex-post assessment of technological and environmental performance.

7

Ex-Ante Evaluation

This ex-ante assessment is based on the results presented by Janek Sasse [89], who conducted a comparative environmental impact assessment of three innovative technologies for the utilisation of landfill gas with a low methane content (20% vol.). The analysed technologies include a dual-fuel engine, oxygen-enriched combustion, and a Spinning Fluids Reactor coupled with downstream energy conversion.

The purpose of this chapter is not to reproduce the full life cycle assessment in detail, but rather to summarise, contextualise, and critically reflect on the methodological approach and the key results of the underlying study. The ex-ante character of the evaluation implies that the results should be interpreted as indicative trends rather than definitive performance indicators.

The presented assessment is based on simulation results and forecasts provided by the project partners and therefore does not represent a final or definitive analysis. The ex-ante analysis will be further refined and, where necessary, corrected once real operational data from laboratory-scale and pilot installations become available.

7.1. Methodology of the Underlying Study

The study conceptualises an LCA in accordance with ISO 14040/44 and presents an exemplary assessment based on simplified system boundaries. The functional unit is defined as the utilisation of 1 Nm^3 of landfill gas with a methane content of 20 vol.%. This gas composition is representative of low-calorific landfill gas, which is increasingly relevant for ageing landfills and sites affected by significant air ingress.

A *gate-to-gate* approach was adopted, focusing primarily on the operational phase of each technology. Upstream processes such as plant construction, decommissioning, and infrastructure were excluded. For the SFR configuration, gas pretreatment (notably CO_2 separation) was assumed to be an integral part of the system boundary, whereas for the DFE and OEC cases the landfill gas was assumed to be supplied with only basic conditioning.

Due to the limited availability of primary measurement data for the innovative technologies, the life cycle inventory relies predominantly on literature values, secondary data sources, and engineering extrapolations. Emission factors were taken mainly from biogas and combustion studies and scaled to landfill gas conditions. As a result, the assessment should be understood as a screening-level LCA.

The following impact categories were considered:

- Global Warming Potential over 100 years,
- Pollutant emissions (NOx, CO, SOx, CH_4, and particulate matter),
- Energy performance (gross and net electrical energy yield),
- Resource consumption (auxiliary electricity and operating materials).

These categories are aligned with the sustainability criteria defined in the previous chapter. While the ReCiPe methodology, which will be applied in the comprehensive LCA, includes a much broader set of midpoint and endpoint indicators, the reduced set used here is considered appropriate for an ex-ante comparison.

Key assumptions of the study include:

- Uniform and constant landfill gas composition over time,
- An operational lifetime of 15 years with 6,000 full-load hours per year,
- Electrical efficiencies of 38% (DFE), 51.22% (OEC), and 38.2% (SFR-based system), Answer for Jörgen comment:The efficiency values were calculated by Sven, and I am not fully aware of the exact methodology or system boundaries that were applied. However, if these values refer only to the engine electrical efficiencies, without considering the upstream process steps, they appear realistic to me. Although the DFE operates according to the diesel cycle, which generally enables higher efficiencies, the OEC concept may achieve improved performance due to the lower nitrogen content in the oxidant stream. Similarly, the SFR-based system increases the calorific value of the fuel through methane enrichment, which can also contribute to improved engine efficiency compared to raw landfill gas utilisation.
- Emission factors derived from EPA guidelines and biogas literature, scaled to landfill gas conditions.

7.2. Key Results of the Exemplary Life Cycle Assessment

7.2.1. Greenhouse Gas Emissions

The results indicate substantial differences in climate-related impacts between the three technologies (Figure 7.1):

- The SFR-based system shows the lowest GWP (0.64 kg CO_2-eq Nm^{-3}), mainly due to upstream CO_2 separation, which reduces direct CO_2 emissions during combustion.
- The DFE exhibits a GWP of 0.72 kg CO_2-eq Nm^{-3}, with additional emissions associated with the combustion of pilot fuel used for ignition. However, within the LoCaGas project, renewable pilot fuels will be investigated for DFE operation, which may significantly reduce the overall environmental impact of the system.
- The OEC configuration results in the highest GWP (1.78 kg CO_2-eq Nm^{-3}), primarily because enhanced oxidation leads to more complete conversion of CH_4 to CO_2.

7.2.2. Pollutant Emissions

Clear differences are also observed with respect to pollutant emissions (Table 7.1):

- The DFE emits the highest levels of NOx, CO, and SOx, which can be attributed to the high compression ratios characteristic of diesel-cycle engines. The elevated combustion temperatures and pressures promote NOx formation, while the absence of advanced gas cleaning contributes to increased CO and SOx emissions. .
- The OEC concept shows negligible CO emissions, but elevated NOx formation as a result of higher combustion temperatures.
- The SFR performs most favourably across almost all pollutant categories, benefiting from upstream gas cleaning and more controlled combustion conditions.

7.2.3. Energy Efficiency

The comparison of energy performance highlights a trade-off between efficiency and auxiliary energy demand:

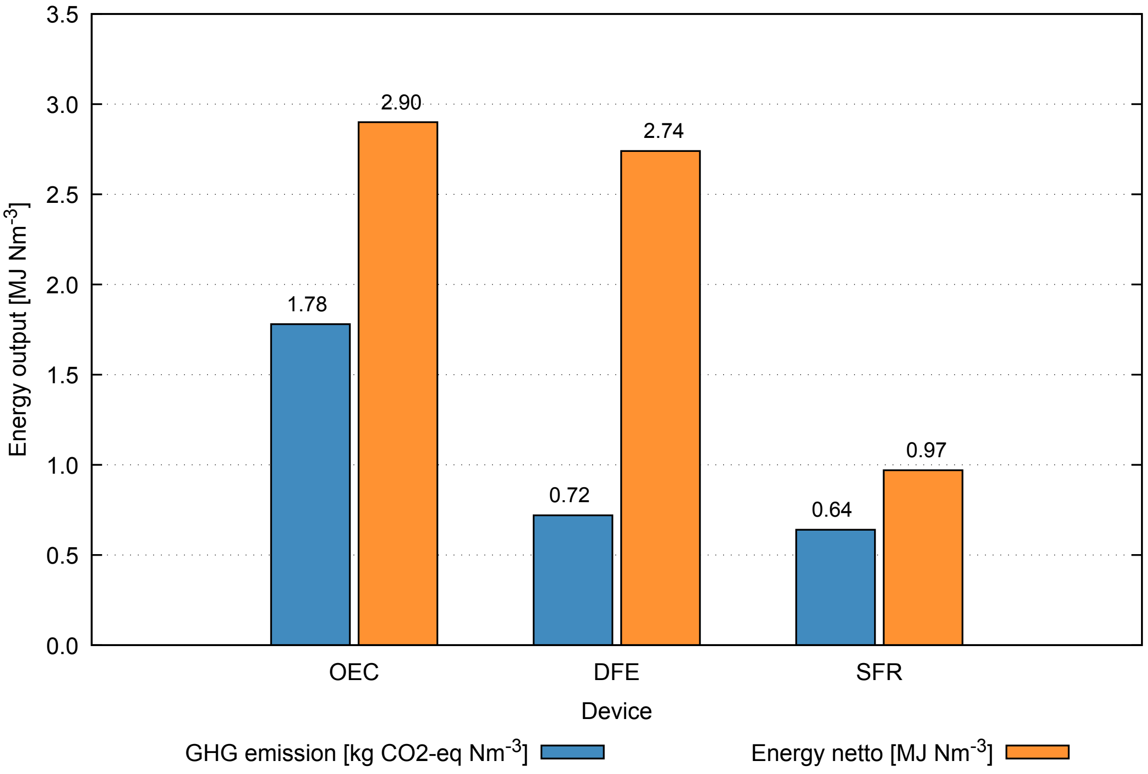

Figure 7.1: Greenhouse gas emissions normalised to energy output for the analysed technologies [89].

- OEC achieves the highest net electrical energy output (2.90 MJ Nm^{-3}) and the highest efficiency (51.22%). The value of 51.22% should be considered as the gross efficiency or the efficiency of the engine system itself. After accounting for the auxiliary energy demand associated with oxygen enrichment, the realistic net efficiency of the OEC system may decrease to approximately 42–49%, depending on the degree of oxygen enrichment and the oxygen separation technology applied.
- For the DFE system, the reported electrical output of 2.74 MJ Nm^{-3} should be interpreted with caution, since part of this output is associated with the additional pilot fuel required for ignition. Assuming an electrical efficiency of 38%, the total fuel energy input corresponds to approximately 7.21 MJ Nm^{-3}. If the pilot fuel accounts for 5–15% of this input, the net electrical output attributable to landfill gas alone would decrease to approximately 2.33–2.60 MJ Nm^{-3}. Therefore, the DFE performance strongly depends on the share and type of pilot fuel used. In the LoCaGas project, renewable pilot fuels will be investigated, which may reduce the fossil contribution and improve

Table 7.1: Pollutant emissions per technology [89].

Parameter	Dual-Fuel Engine	Oxygen-Enriched Combustion	Spinning Fluids Reactor
NOx	$1.08 \cdot 10^{-2}$	$1.38 \cdot 10^{-3}$	$6.33 \cdot 10^{-4}$
CO	$2.40 \cdot 10^{-3}$	0	$3.33 \cdot 10^{-4}$
SO_2	$2.51 \cdot 10^{-3}$	$6.00 \cdot 10^{-5}$	$2.00 \cdot 10^{-5}$
CO_2	0.577	1.677	0.490
CH_4	$7.78 \cdot 10^{-5}$	$2.98 \cdot 10^{-4}$	$2.99 \cdot 10^{-4}$
Particles	$3.68 \cdot 10^{-4}$	$1.46 \cdot 10^{-6}$	$2.80 \cdot 10^{-6}$

the overall environmental performance of the DFE concept.

- The SFR-based system exhibits the lowest net energy output (0.97 MJ Nm^{-3}), mainly due to the auxiliary electricity demand associated with gas pretreatment and methane enrichment. However, this value should be interpreted as a net system-level performance indicator rather than engine efficiency alone. The reported value of 0.97 MJ Nm^{-3} was calculated assuming a methane concentration of approximately 20% vol. in the raw landfill gas. The SFR increases the calorific value of the fuel gas, which may improve combustion stability and enable utilisation in conventional or slightly modified gas engines, but this benefit is partly offset by the energy required to operate the pretreatment unit. Moreover, the overall system performance strongly depends on the methane concentration in the raw landfill gas. For methane contents of approximately 45% and higher, the resulting engine efficiency is expected to be comparable to that of conventional spark-ignition gas engines.

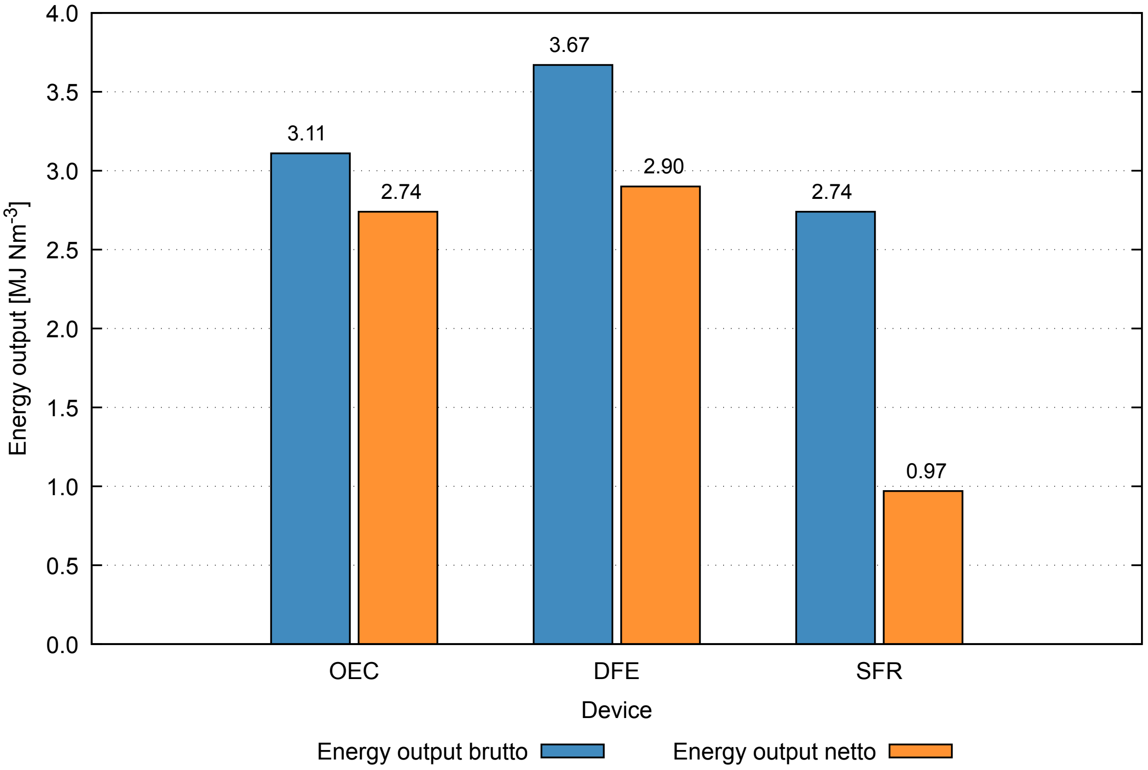

Figure 7.2: Comparison of gross and net electrical energy output for the analysed technologies [89].

7.2.4. Resource Consumption

The assessment of resource use further illustrates system-level trade-offs:

- The SFR has the highest auxiliary electricity demand (1.77 MJ Nm^{-3}), but comparatively low direct emissions.
- The DFE requires minimal auxiliary energy but exhibits significant upstream impacts associated with diesel supply.
- The OEC configuration shows moderate operating material demand, but a considerable electricity requirement for oxygen production.

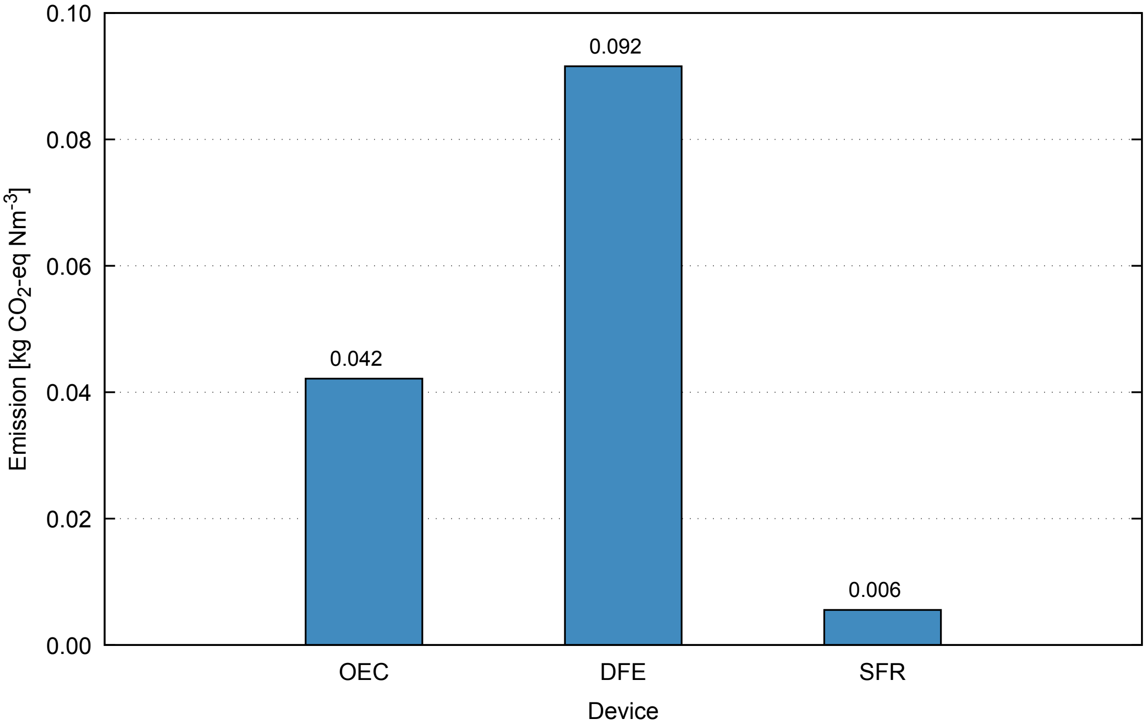

Figure 7.3: Comparison of resource-related emissions for the analysed technologies [89].

8

Conclusion

The ex-ante evaluation suggests that the SFR-based concept may be environmentally favourable if its high auxiliary energy demand can be supplied from low-carbon electricity. The OEC approach appears particularly attractive from an efficiency perspective, but its climate performance is limited by high CO_2 emissions. The DFE represents a compromise solution, offering robustness for very low methane contents, but its reliance on pilot fuel leads to elevated pollutant emissions.

However, the assessment is subject to significant limitations. The reliance on secondary data, simplified system boundaries, and numerous assumptions introduces considerable uncertainty. Maintenance, component replacement, and long-term performance degradation were not considered, and the *gate-to-gate* perspective excludes potentially relevant upstream and downstream effects.

For the comprehensive LCA planned within the LoCaGas project, extensive primary data collection and a more detailed modelling framework will be required. This will include refined system boundaries, additional impact categories, and sensitivity analyses to robustly assess the environmental performance of low-calorific landfill gas utilisation technologies.

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