Evidence

Landfill methane oxidation techniques

Report – SC160005/R

We are the Environment Agency. We protect and improve the environment.

Acting to reduce the impacts of a changing climate on people and wildlife is at the heart of everything we do.

We reduce the risks to people, properties and businesses from flooding and coastal erosion.

We protect and improve the quality of water, making sure there is enough for people, businesses, agriculture and the environment. Our work helps to ensure people can enjoy the water environment through angling and navigation.

We look after land quality, promote sustainable land management and help protect and enhance wildlife habitats. And we work closely with businesses to help them comply with environmental regulations.

We can’t do this alone. We work with government, local councils, businesses, civil society groups and communities to make our environment a better place for people and wildlife.

Published by:
Environment Agency, Horizon House, Deanery Road,
Bristol, BS1 5AH

http://www.gov.uk/government/organisations/environment-agency

ISBN: 978-1-84911-398-4

Author(s):
Dr Ian Campbell
Neil Robinson

Dissemination status:
Publicly available

Keywords:
waste, landfill, methane, methane oxidation, climate change mitigation

Research contractor:
AECOM INFRASTRUCTURE & ENVIRONMENT UK

Evidence at the Environment Agency

Scientific research and analysis underpins everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

This report is the result of research commissioned by the Environment Agency's Research, Analysis and Evaluation group.

You can find out more about our current science programmes at https://www.gov.uk/government/organisations/environment-agency/about/research

If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact reserach@environment-agency.gov.uk.

Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

Landfill gas is produced as biodegradable organic material in landfilled waste decomposes. Landfill gas is a mixture predominantly made up of methane and carbon dioxide. Controlling landfill gas is necessary to minimise local environmental issues, to manage safety risks and to limit emissions of greenhouse gases. Methane is many times more potent a greenhouse gas than carbon dioxide and the oxidation of the methane (to carbon dioxide) is important in reducing the impact of landfill on the global environment.

Established best practice for managing landfill gas from biodegradable waste landfills in England is to actively collect the gas. The collected gas is either used as an energy source, normally to generate electricity, or is burnt in a flare. Both of these approaches thermally oxidise the methane to carbon dioxide. These established approaches gradually become less effective as gas yields and methane concentrations decline over time. Other methods of landfill methane oxidation exist and will need to be adopted to ensure the ongoing effective management of landfill gas throughout the life-cycle of the landfill.

This report provides evidence for those responsible for the operation or management of biodegradable waste landfills to select appropriate methane oxidation techniques over the whole life-cycle of a landfill, in particular when landfill gas production has declined past its peak. A literature review was undertaken and information gathered from a variety of sources to produce a decision-making framework. This framework is based on the conditions under which different classes of technology would be effective for the oxidation of landfill methane across the life-cycle of individual landfill sites. These technologies comprise heat and power generation on a large to micro-scale, thermal oxidation of methane in different types of flares, and biological methane oxidation techniques.

The key variables identified for use in the decision-making process are:

- methane concentrations and flow rates, which decline over time at closed landfills
- whether the technique requires an active gas extraction system
- whether a landfill site has an electrical grid connection
- the performance of the technology; that is, its ability to oxidise methane and whether it is a tried and tested or emerging technology
- capital and operational costs
- monitoring and maintenance requirements
- emissions from the methane oxidation technology (noise, air quality, odour)

An overview of each methane oxidation technique is presented alongside discussion of the variables affecting their use and information on performance.

A series of flowcharts have been produced that identify decision points and the main factors that need to be considered.

This report identifies and provides detailed information on the currently available technologies for oxidising landfill methane. The flowcharts show where the technologies sit within the life-cycle of the landfill and identify the decision points and the variables relevant to those decisions. The flowcharts, taken together with the information on each technology, provide the framework within which evidence-based decisions can be made on the appropriate methane oxidation techniques at each stage of a landfill's life-cycle.

Contents

List of tables and figures

1 Introduction

1.1 Background

Biodegradable organic material present in landfilled waste undergoes microbial degradation and produces landfill gas. Landfill gas is a mixture, predominantly made up of methane and carbon dioxide, with small amounts of hydrogen. These are typically referred to as bulk gases because they are often present at percentage concentrations (e.g. a landfill gas composition of 60% methane and 40% carbon dioxide). Landfill gas will also contain a wide variety of trace components at low concentrations (Environment Agency 2010a). When collected, the landfill gas may also contain varying amounts of nitrogen and oxygen derived from air that has been drawn into the landfill or collection system.

Control of landfill gas is necessary both to manage local environmental issues and safety risks, and to limit emissions of greenhouse gases. The carbon dioxide emissions from landfills are part of the natural carbon cycle as they derive from the degradation of organic material and are not from a fossil carbon source. Methane emissions from landfills are not part of the natural cycle and the global warming potential of methane is 28 times that of carbon dioxide, over a 100-year lifetime (Myhre et al. 2013). Therefore, efficient collection of the landfill gas and oxidation of the methane to carbon dioxide is necessary to mitigate greenhouse gas emissions.

The established best practice for managing landfill gas from biodegradable waste landfills in the UK is to actively collect the gas. The gas is drawn from vertical pipes in the waste through connecting pipework to a gas management facility. The collected gas is either used as an energy source, normally to generate electricity, or is flared. A high temperature flare is required as a back-up to electricity generation or can be used in parallel where the gas yield exceeds the electricity generation capacity of installed plant. Combustion, either for energy generation or in a flare, oxidises the methane to carbon dioxide.

The detailed requirements for the best practice for the management of landfill gas are set out in Environment Agency guidance LFTGN 03 (Environment Agency 2004) and in an Industry Code of Practice (Environmental Services Association 2012). Non-binding EU guidance (European Commission 2013) sets out the most important criteria in ensuring effective management of landfill gas, which is required until gas production becomes negligible.

The established approaches to use for electricity generation and flaring gradually become less effective as gas yields and methane concentrations decline over time. Other methods of landfill methane oxidation exist and will need to be adopted to ensure the continued effective management of landfill gas.

1.2 Purpose of the report

The purpose of this report is to provide evidence to allow operators of biodegradable waste landfills to select appropriate methane oxidation techniques over the whole life-cycle of a landfill, in particular when landfill gas production has declined past its peak. In addition, implementing methane oxidation techniques at older, closed landfill sites without active gas control measures presents a challenge, which requires investment (often significant) to install and operate the necessary technology. This report provides evidence for those responsible for such sites on the most appropriate and cost-effective techniques which may be used to mitigate significant passive methane emissions.

This report describes these methane oxidation techniques and provides a framework setting out what each can achieve and what conditions each technique is suitable for. The appropriate use of these techniques will help minimise methane emissions from landfills.

1.3 Report structure

Section 2 of this report provides an overview of landfill methane oxidation techniques with details of each technique discussed provided in Appendix A. The suitability of each technique for methane oxidation is discussed in Section 3 and Appendix B provides flowcharts to support technique selection. Section 4 provides a summary and conclusions.

2 Overview of techniques

2.1 Scope

2.1.1 Technologies considered

The principal methane oxidation techniques for landfill gas from biodegradable waste landfills have been identified based on a review of published literature and discussions with landfill operators and technology providers. These are described in this section and summarised in Table 2.1. Datasheets for each technique are provided in Appendix A which provide more detail about the technique and summarise the advantages and disadvantages, effectiveness, costs and environmental performance of each.

Table 2.1 Summary of methane oxidation techniques

Utilisation	Technology	Mode of Combustion
Large to medium-scale generation (≥300 kW)	Reciprocating (spark ignition) engine	Internal combustion
	Gas turbine	External combustion
Small and micro-generation (<300 kW)	Spark ignition engine	Internal combustion
	Micro turbine	
	Free piston engine	
	Stirling engine	External combustion
	Organic Rankine cycle engine	
	Solid state reciprocating engine	
Thermal oxidation	**Technology**	**Mode of operation**
Flaring	High temperature flare	Standard operation
		Modified burner
		Intermittent flaring
		Supported combustion
		Low temperature operation
	Low calorific value flare	Standard operation
		Intermittent flaring
		Supported combustion
Biological oxidation	**Technology**	**Gas extraction system**
Biofilter	Closed bed	Active extraction
		Passive extraction
	Open bed	Active extraction
		Passive extraction
Biocover	Full surface biocover	Passive extraction
	Biowindow system	
	Bioactive intercepting trench	
Emerging techniques		
Landfill aeration		
Regenerative thermal oxidation		

2.1.2 Technologies excluded

The following technologies are excluded from the report:

- Elevated flaring, which is not considered good practice due to poorly controlled or uncontrolled emissions.
- Steam turbines, which are used to generate heat and electricity and are common in large-scale electricity generating plants, but are unsuitable for methane oxidation because landfill gas is not usually of a high enough quality to sustain efficient steam turbine operation (USEPA 2015).
- Techniques which involve the transport of landfill gas for off-site combustion, rather than being an on-site methane oxidation technique:
    - Combustion of landfill gas to power industrial processes. For example, historically, Marshalls used gas from Stairfoot landfill in Barnsley to power kilns on its adjacent brickworks.
    - Use of landfill gas for direct heating applications or, after undergoing a process to remove impurities, to be added to natural gas pipelines.
    - Collection of landfill gas for other off-site uses. For example, see the Department of Transport study of the feasibility and use of biomethane from landfill gas and anaerobic digestion in transport applications (Ricardo-AEA 2015).

2.2 Power generation

Power generation is a well-established technique to manage landfill gas by combustion followed by electricity generation, and it requires the gas to be actively extracted from landfills. The electricity generated is exported to the electricity grid. Generation can be large or small/micro-scale, depending on the volume and quality of landfill gas to be combusted.

2.2.1 Large to medium-scale power generation

For the purposes of this report electrical generation is considered to be large or medium scale if electrical output from the generator is greater than 300 kW. Large-scale generation uses internal combustion technologies. The main choices are spark ignition reciprocating engines and gas turbines.

Reciprocating engines

Reciprocating engines used for combustion of landfill gas are similar in operation to diesel engines, but are configured and calibrated to receive landfill gas as fuel. The landfill gas is drawn into a cylinder, a spark ignites the landfill gas, and the expansion from the combustion reaction drives a piston and turns a camshaft. The rotating shaft can be used to generate electricity, and the reciprocating engine can also be configured to recover waste heat from exhaust gases using a heat exchanger.

Gas turbines

Gas turbines consist of a compressor, a combustion chamber and an expansion turbine. The compressor heats and compresses the inlet air, which enters the combustion chamber with the landfill gas and ignites. This hot air and combustion gas mixture expands through the expansion turbine, rotating the blades and shaft quickly enough to provide shaft-energy to the generator, which generates electricity. The hot expansion gas leaving the turbine can optionally be passed through heat exchangers to produce hot water or use the direct heat in other ways.

2.2.2 Small and micro-generation

Small and micro-generation technologies are smaller than 300 kW and 50 kW respectively, and use either internal or external combustion engines.

Internal combustion engines

Internal combustion engines used for methane oxidation are usually either small-scale spark ignition engines or microturbines. Free piston engines are an emerging internal combustion technology which has yet to be applied to oxidation of methane at landfill sites.

Small-scale spark ignition engines (<300 kW) function in the same manner as larger reciprocating engines.

Microturbines function in the same way as larger scale gas turbines but are usually simpler and much smaller. Certain models have only one moving part, no gearbox or other mechanicals, and use no lubricants, simplifying and reducing the need for maintenance (Figure 2.1). This technology is often used with several lower rated turbines operating in parallel to produce higher electrical and thermal output. Microturbines can also be used in combined heat and power or combined cooling, heat and power settings, where recovered heat is used productively.

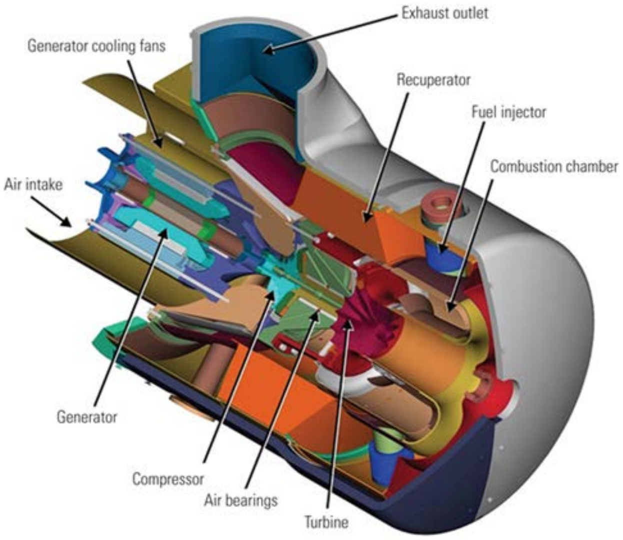


Figure 2.1 Cut-away view of the Capstone C65 microturbine (Gillette 2010, citing Capstone Power Systems)

The free piston engine is an emerging internal combustion technology which uses a linear piston engine. The linear piston engine does not have connecting rods and a crank shaft like a conventional internal combustion engine, so each piston can operate freely. As a result, each piston is free to move along its axis under the action of combustion pressure (Figure 2.2). The piston interfaces with a linear generator to capture power from the piston's movement and generate electricity from various fuels including biogas (Libertine FPE 2016).

Figure 2.2 Free piston engine (Libertine FPE 2016)

External combustion engines

The types of external combustion engines used for methane oxidation are Stirling and organic Rankine cycle (ORC) engines. The solid state reciprocating engine is an emerging external combustion technology which is not currently targeted towards the landfill gas market but could be used for recovery of heat from combustion technologies.

While internal combustion engines use internally expanding combustion gases, external combustion engines use an externally provided heat source to heat a fluid that is sealed within the engine. While internal combustion engines eject spent exhaust gas from the engine, in external combustion engines there is no exhaust gas. External combustion engines use a combustion chamber to burn the fuel. Heat generated from burning landfill gas is recovered using heat exchangers and this heat source is used to power the engine.

Stirling engines operate by cyclic compression of air or another gas at different temperatures (Figure 2.3). The fluid around one piston is heated (red in Figure 2.3) while the fluid around the other is cooled (blue in Figure 2.3). Stirling engines use a regenerator between the hot and cold fluids. Stirling engines have been successfully used in the UK, including at Docking 2 closed landfill site in Norfolk (ACUMEN 2015) using medium calorific value gas (25 m^3/hr at 32% methane). Stirling engines are also capable of generating electricity and heat on low calorific value gas (around 18–20% methane) albeit with reduced power output.

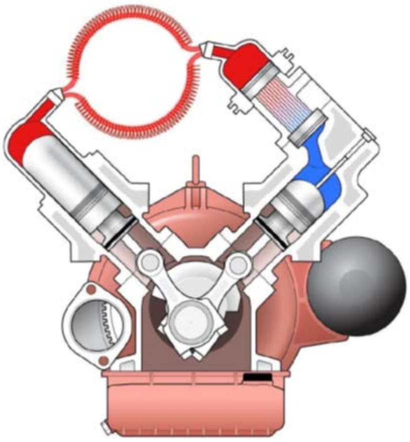


Figure 2.3 Schematic of a C9G Stirling engine (Landfill Systems 2015)

ORC engines are based on the Rankine thermodynamic cycle used by steam turbines. However, instead of using water and steam as the working fluid, the ORC engine contains an organic fluid with a much lower vapour pressure than water. This makes it possible for the fluid in the system to expand into a gas with much less energy input. An external heat source heats the organic fluid in a combustion chamber. The fluid expands and vaporises and drives a turbine which is used to generate electricity. The lower heat input, compared to steam turbines, produces much less electrical output. The hot fluid passes through a condenser, cooling it. The liquid is then pumped back to the combustion chamber and the cycle starts again. Although ORC engines are a viable option for landfill gas utilisation, the only known case study is for a site that started operation in 2004 and has since shut down (USEPA 2016).

The solid state reciprocating engine (Figure 2.4) is an emerging external combustion technology that requires hot water at 90°C to operate. It functions using shape memory alloy which contracts when heated and expands when cooled. Metals usually expand when heated and contract when cooled. Pistons constructed out of the memory alloy contract with extremely high force when heated, driving the pistons that interface with a hydraulic transmission and generator to generate electricity (Exergyn 2016, Langan 2016). A solid state reciprocating engine could potentially be used to recover heat from the exhaust of an external or internal combustion engine after it has passed through a heat exchanger.

Figure 2.4 Cut-away view of the Exergyn solid state reciprocating engine (Exergyn 2016)

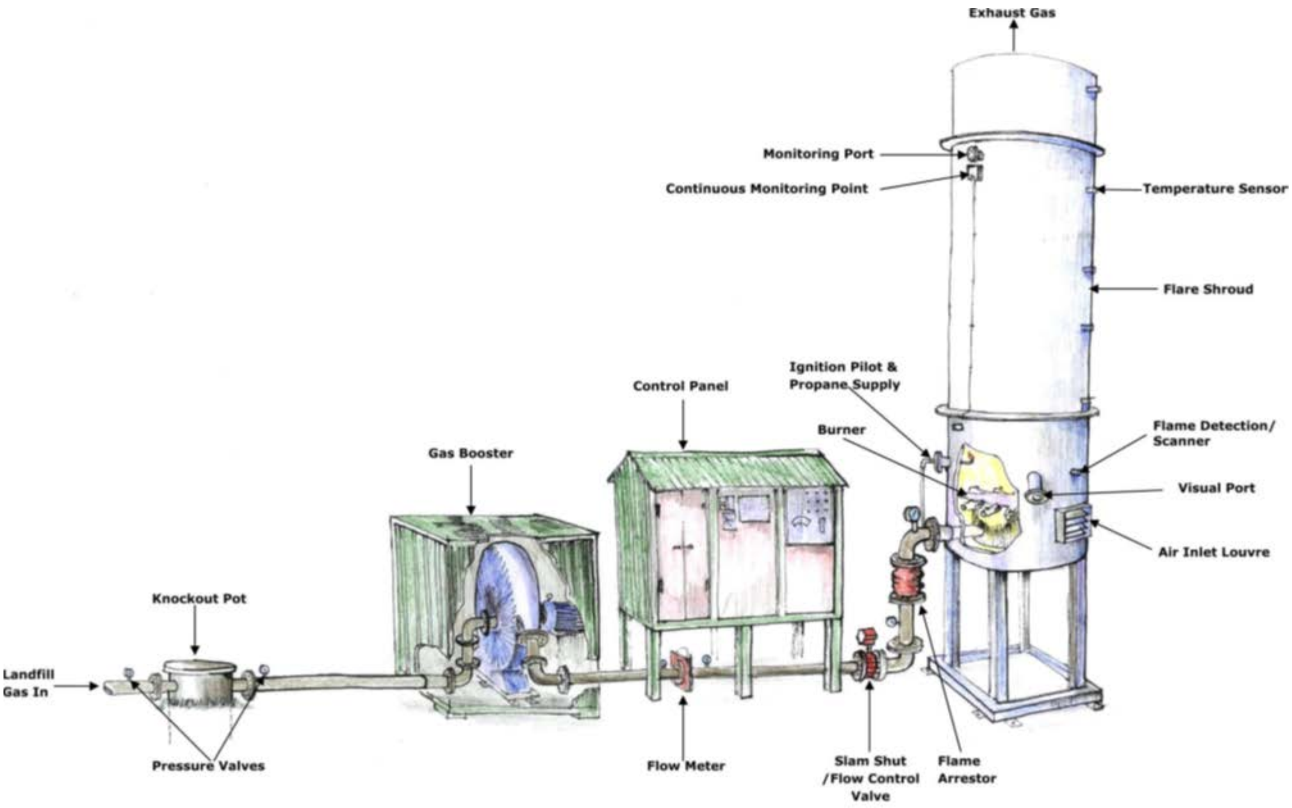
2.3 Thermal oxidation

Flaring is a well-established technique to manage landfill gas actively extracted from landfills by combustion. Flares are required to be used whenever power generation technologies are installed for the combustion of landfill gas, either to combust excess gas or to allow oxidation of methane during periods when power generation technologies are off-line for maintenance or repair. Flares can also be used on a stand-alone basis when other technologies are unsuitable or uneconomic.

The two main types of flares which are effective in combusting landfill gas can be broadly described as either high temperature flares or low calorific value flares respectively.

2.3.1 High temperature flaring

High temperature flares receive landfill gas from the gas collection system, and the gas is passed through a series of burners that are enclosed by an insulated shroud. The insulated shroud is usually a vertical, cylindrical or rectilinear enclosure. The insulated shroud allows the flare to operate at higher temperatures. The landfill gas flow rate and air content are regulated through the flare in order to control combustion conditions and meet emissions standards. The flares are sized dependent on landfill gas flow rates and methane concentrations. Figure 2.5 illustrates the design of a typical enclosed flare.



Note: All landfill gas equipment and monitoring equipment should be compliant with ATEX Regulations

Figure 2.5 Illustration of an enclosed flare (Irish EPA 2012)

Existing flares can be operated in a number of configurations dependent on variations in gas flow rate and calorific value. These configurations include modified burner, intermittent flaring, supported combustion and low temperature operation. Some flares allow modification of the burners to handle reduced gas flow rates.

Intermittent flaring can be used where gas flow has dropped, allowing landfill gas to collect and the flare to operate for only a limited number of hours per day. Supported combustion, where an additional fuel such as propane is used, is necessary to start up the flare for intermittent flaring configurations, or when off-site migration or odour nuisance needs to be controlled. Low temperature operation is possible, but has the drawback that landfill gas will not be completely oxidised and gaseous emissions may fail to meet emissions standards.

2.3.2 Low calorific value flaring

Low calorific value flares operate in fundamentally the same manner as high temperature flares. They are used for the combustion of landfill gas with low methane content and low calorific value. These flares are a mature technology for oxidising gas from old landfill sites or sites with low quality gas. Low calorific value flares differ from high temperature flares in that this technology:

- uses special lean gas burners
- preheats combustion air
- requires supported combustion for ignition and start-up, using fuels such as propane or natural gas

Low calorific value flares are available in a number of configurations from a broad range of suppliers. Units are available in a number of flow rate sizes, and are installed on site either containerised or skid-mounted. Certain low calorific value flares can be adapted for power generation applications, in combination with external combustion engines recovering exhaust heat.

2.4 Biological oxidation

Biofilters and biocovers form a subset of techniques known as bio-mitigation systems. These systems are based on microbial methane oxidation, making use of a matrix of soil, compost, clay pellets or other materials packed into a bed or layer. Biofilters are engineered filters connected to an active gas extraction system or to a passive venting system, while biocovers form part of the capping system of passively venting landfill sites.

2.4.1 Biofilters

In biofilters, landfill gas is either collected in a gas collection system, or directed through preferential pathways towards an engineered filter bed where methanotrophic microbes are present and oxidise the methane present (Kjeldsen and Scheutz 2016).

Biofilter methane oxidation efficiency is variable across case studies and techniques. Considerable work on bio-mitigation techniques to oxidise methane from landfills has been carried out in Denmark. Denmark has published a guideline document on establishing and monitoring biocover systems at waste landfill facilities (Kjeldsen and Scheutz 2016).

The two main configurations for biofilters are open bed biofilters and closed bed biofilters (Figures 2.6 and 2.7). Closed bed biofilters are also referred to as modular biofilters (ACUMEN 2015). Landfill gas can be passed to either configuration by actively pumping the gas, or allowing it to passively flow to the biofilter unit.

For open bed systems (Figure 2.6) the bioactive matrix is open to the atmosphere, and oxygen is allowed to infiltrate the matrix via natural physical processes. Landfill gas is supplied from underneath via a gas distribution layer. In some cases air/oxygen is also added to the matrix via the gas distribution layer.

In the closed bed configuration, air must be actively pumped into the unit to provide oxygen, even if the supply of landfill gas is passive. Landfill gas can be passed to either the top or the bottom of the bioactive matrix in a closed bed system, and Figure 2.7 shows the landfill gas being passed to the bottom of the bioactive matrix.

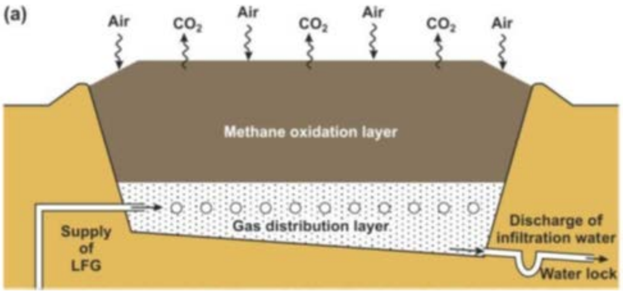


Figure 2.6 Open bed biofilter (Kjeldsen and Scheutz 2016)

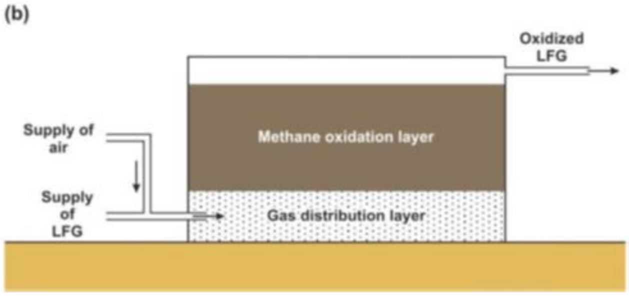


Figure 2.7 Closed bed biofilter (Kjeldsen and Scheutz 2016)

Various operational parameters affect how well a biofilter will function. Oxygen availability is the most important factor affecting the growth of microorganisms responsible for methane oxidation. Soil characteristics are critical, and literature shows that oxidation rates are much higher in sandy soils than in clayey soils. An open soil structure with adequate soil pore spaces needs to be maintained as the soil pores are susceptible to clogging and compaction over time.

Oxygen concentration is known to decline with the depth of the filter bed, unless oxygen is introduced to the filter bed via active means. What is clear is that to achieve higher methane oxidation rates, the oxidation system must be appropriately designed taking account of porosity, moisture and temperature (Gebert et al. 2011). It is well known that gas migrates through the easiest route along preferential pathways (Environment Agency 2004). Therefore, for open bed systems a uniform top cover with highly consistent material is required. The compost in the biofilter matrix decomposes over time due to the ongoing respiration process, and so this may cause progressive deterioration in the biofilter functionality.

Other issues include achieving even gas distribution across the biofilter, particularly for open bed biofilter systems. Open bed systems also need to manage the water infiltration, which takes place due to precipitation. Optimum moisture conditions are considered to be 15–20%. It is therefore important that the biofilter should not either dry out or become saturated with water.

The literature is unclear as to which biofilter technique is most appropriate given any set of landfill conditions. Methane oxidation performance for biofilters is quite variable and highly dependent on individual landfill conditions, and design and operational standards. Some demonstration project studies report up to 99% methane oxidation efficiencies, while some full-scale sites are quite inefficient (around 20% methane oxidation) (Kjeldsen and Scheutz 2016).

2.4.2 Biocovers

Biocovers are in situ systems, and include full surface biocovers, biowindow systems and bioactive intercepting trenches. Biocovers are used on sites without active gas control where landfill gas passively vents through the cap.

For full surface biocovers, the entire landfill surface is covered with a gas distribution layer of gravel, and overlain with a homogeneous layer of bioactive coarse materials. Gas passes passively through the biocover layer where it is oxidised (Figure 2.8).

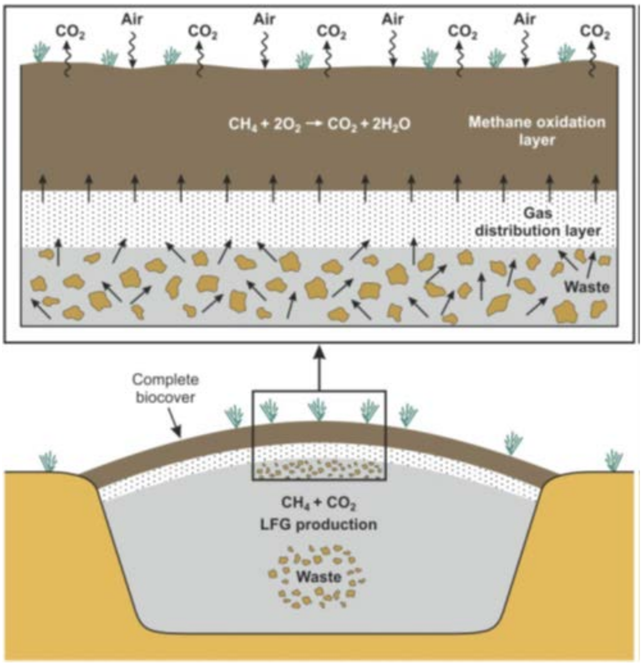


Figure 2.8 Full surface biocover (Kjeldsen and Scheutz 2016)

Biowindow systems work similarly to full surface biocovers but are implemented by incorporating biocovers as ‘windows’ within the landfill’s existing low permeability soil cap. Regions of the existing cap are removed and replaced by a gas-permeable, bioactive material matrix, underlain by a gas distribution layer of gravel (Figure 2.9).

Bioactive intercepting trenches are established to collect and oxidise methane and landfill gas migrating horizontally from the landfill. The trenches are dug around the perimeter of the landfill and may be filled with gas-distributing materials at the bottom and bioactive materials on top. Gas is allowed to migrate passively to the trench.

Research and demonstration projects have shown that effective biocover designs can be implemented at full scale to reduce methane emissions. Use of compost-based materials is an advantage, especially in regions with cold climate during winter time. As the methane oxidation process is exothermal, elevated temperatures have been observed in many examples. This allows high oxidation rates to be maintained, even during cold weather periods, with temperatures within the filter above ambient levels.

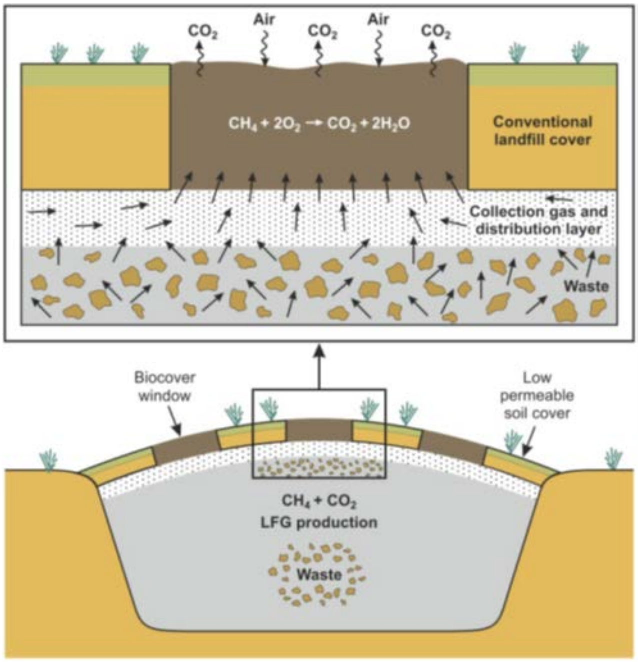


Figure 2.9 Biowindow system (Kjeldsen and Scheutz 2016)

2.5 Other emerging techniques

2.5.1 Landfill aeration

Forced aeration (pumped injection) into landfill sites is an approach for delivering oxygen to oxidising media and maintaining an optimum methane oxidising environment within the landfill and so reducing greenhouse gas emissions from landfills (Ritzkowski and Stegmann 2010). Over-injection of air has the significant drawback in that it could result in landfill heating and landfill fires (Hall et al. 2007). In situ aeration is also only suitable on fully contained sites due to the risk of contaminant mobilisation.

In principle, landfill aeration technology has been shown to be able to degrade up to 90% of the organic carbon present within a landfill site (Heimovaara et al. 2010). A combination of aeration and leachate recirculation appears to be the optimal approach. However, demonstration projects are required to quantify the impact of this reduction on degradable organic carbon on long-term emission potential (Heimovaara et al. 2010).

2.5.2 Regenerative thermal oxidation

Regenerative or non-catalytic thermal oxidation (Figure 2.10) is a specialised technique designed to oxidise volatile organic compounds (VOCs). It is typically used for treatment of coal-bed methane and for removing industrial VOCs from manufacturing processes. It has also been used to oxidise methane from landfill gas, if the methane concentrations are very low (0.3 to 0.8% v/v). Regenerative thermal oxidation can handle higher methane concentrations if the landfill gas is diluted with air prior to entering the process.

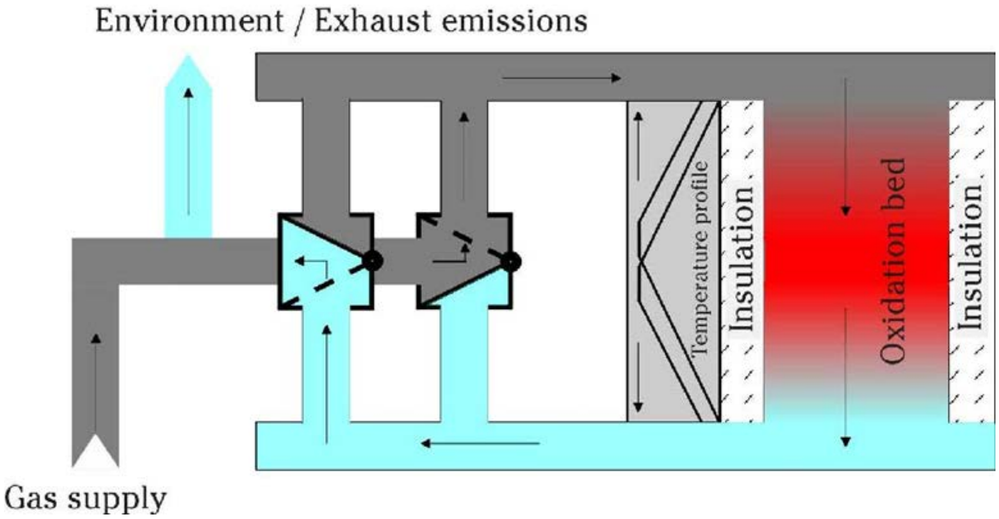


Figure 2.10 Schematic of regeneration thermal oxidation process (Stachowitz 2000)

3 Technology selection

3.1 Introduction

This section sets out the decision-making process for selecting the most appropriate technology (or technologies) for oxidation of methane across the life-cycle of individual biodegradable waste landfill sites. The technique selection process is not suitable for industrial or hazardous waste landfill sites.

The key variables that have been identified are:

- methane concentrations and flow rates
- whether the site has an active extraction system or whether gas is passively vented
- whether the site has an electrical grid connection
- the technical performance of the technology (i.e. its ability to oxidise methane)
- costs (both capital and operational)
- monitoring and maintenance requirements
- emissions

The roles these key factors play in the selection of techniques are set out in detail below for each of the technologies outlined in Section 2 and illustrated using flowcharts in Appendix B.

3.2 Key factors

3.2.1 Methane concentration and flow

Landfill gas flow rate and methane concentration by volume are the principal variables to consider when selecting appropriate methane oxidation techniques for managing landfill gas. It is a given that there should be gas of sufficient quality at a sufficient flow rate for a particular technology to operate effectively. Conversely the methane content and/or gas flow rate should not exceed the capacity of the oxidation technology.

Landfill sites accepting biodegradable waste generate landfill gas during waste decomposition. The conceptual model for gas production from landfill includes four phases. Aerobic digestion takes place in Phase I, at the beginning of the life of the landfill, resulting in carbon dioxide emissions. During Phase II oxygen concentrations reduce to near zero and carbon dioxide concentrations increase while hydrogen emissions peak. During Phase III carbon dioxide concentrations continue to increase and methane production starts as the landfill becomes anaerobic. During Phase IV methane and carbon dioxide concentrations increase to a relatively constant level. Peak methane concentration will be around 50 to 65% v/v (Environment Agency 2009). Once the landfill is closed (Phase V), anaerobic digestion continues but methane concentrations slowly decline over many decades (Figure 3.1). Methane oxidation technologies are necessary during Phases IV and V.

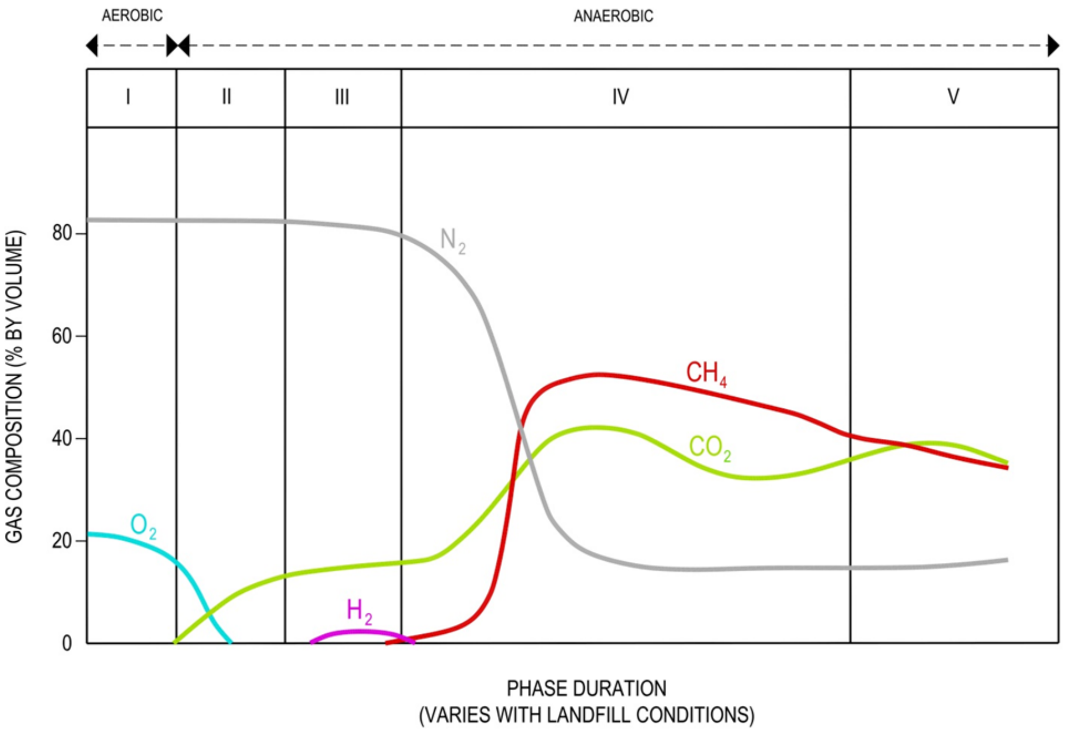
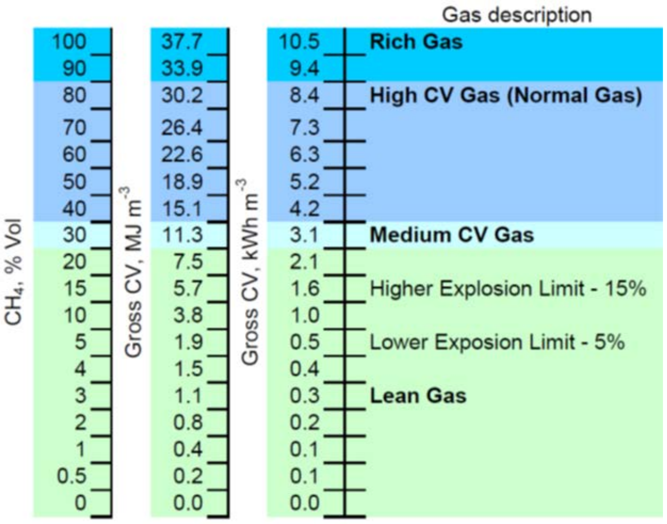


Figure 3.1 Municipal solid waste landfill gas production (adapted from Pohland and Harper 1986)

The methane content of gas is important for technology selection, because the higher the methane content, the higher the calorific value of the gas. Figure 3.2 shows indicative methane content and calorific values for landfill gas. High calorific value gas typically has methane content within the range of 30 to 80%. Medium calorific value gas contains between 20 and 30% methane, and gas with concentrations of methane less than 20% are classified as lean gas. Landfill gas characteristics will vary over the life of the landfill. Lean gas at the beginning of the anaerobic digestion phases will improve in quality becoming medium calorific value and then high calorific value gas. Once the landfill stops receiving biodegradable waste, the landfill gas quality will decline over time, eventually deteriorating back to lean gas in the final phases of the landfill's life.



CH_4, % Vol	Gross CV, MJ m^{-3}	Gross CV, kWh m^{-3}	Gas description
100	37.7	10.5	**Rich Gas**
90	33.9	9.4	
80	30.2	8.4	**High CV Gas (Normal Gas)**
70	26.4	7.3	
60	22.6	6.3	
50	18.9	5.2	
40	15.1	4.2	
30	11.3	3.1	**Medium CV Gas**
20	7.5	2.1	
15	5.7	1.6	Higher Explosion Limit - 15%
10	3.8	1.0	
5	1.9	0.5	Lower Exposion Limit - 5%
4	1.5	0.4	
3	1.1	0.3	**Lean Gas**
2	0.8	0.2	
1	0.4	0.1	
0.5	0.2	0.1	
0	0.0	0.0	

Figure 3.2 Methane content and calorific values for landfill gas (Environment Agency 2009)

Based on the above and Figure 3.2, the stages defined in Table 3.1 are used in this report to represent changes in landfill gas quality over the productive lifespan of a typical municipal solid landfill site.

Table 3.1 Stages of landfill gas production

Stage	Description	Gas type
1	Landfill gas production during Phase IV: landfill gas reaches peak flow rates and concentration	High calorific value gas
2	Early part of landfill gas production during Phase V: landfill gas production rate drops from peak rates of Phase IV, and methane concentration begins to decline	Medium calorific value gas, declining to lean gas
3	Long tail of landfill gas production during Phase V: landfill gas production rate is very low, but methane continues to be produced, although in low concentrations	Lean gas with very low methane concentration

Landfill gas flow rates also change in tandem with methane concentrations over the lifetime of a landfill site. This is illustrated in Figure 3.3, which shows gas generation rates in m^3/hr calculated using the landfill gas generation module in the Environment Agency's GasSim model. The flow rate of landfill gas from biodegradable waste landfills rises quickly to a peak (or peaks depending on the rate of infill), and then declines exponentially with time, with gas production continuing for many years after the landfill stops accepting new waste. The peak flow rate and duration of high and medium calorific value gas will be dependent on the volume of waste disposed of and its composition (i.e. the content of biodegradable materials).

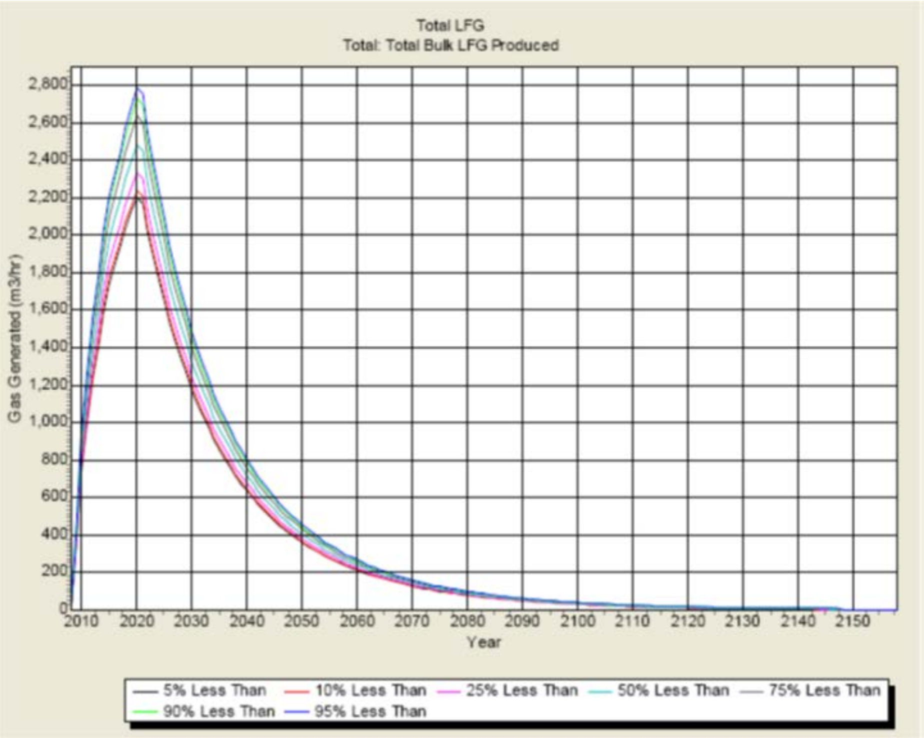


Figure 3.3 GasSim model estimated output of landfill gas generation rate from a theoretical site (Environment Agency 2009)

3.2.2 Active/passive extraction system

Active system

The majority of methane oxidation techniques rely on the presence of an active gas collection system. In an active gas collection system, landfill gas is extracted from the landfill site either mechanically (using pumps for example) or under its own pressure and driven in pipes to the oxidation technology equipment. Active extraction systems are required for power generation, flaring and some biofilter systems. Modern biodegradable waste landfills and some older landfills will have active gas collection systems installed.

Passive system

A passive gas system is one in which gas passes to the methane oxidation technology without the benefit of a mechanical driver. Instead, natural physical processes such as increasing pressure from gas build-up and preferential pathways through the landfill material are used to direct the landfill gas to the methane oxidation technology. Techniques treating passive gas flow can be applied to landfills both with or without a decommissioned gas collection system. Where existing pipework from a collection system is present, gas will collect in the system preferentially and flow through natural pressure gradients towards the passive treatment equipment. If no gas collection system is present, additional earthworks, landfill cap modifications and leachate monitoring well capping may be necessary to ensure that preferential gas pathways direct landfill gas to the passive treatment system.

3.2.3 Grid connection and utilisation

A landfill's proximity to an electrical grid connection is an important consideration for power generation and associated revenue generation. Grid connections are required for large-scale power generation and can be expensive or difficult to install dependent on landfill location in relation to the electrical grid and local/regional generation and demand balance.

A new electrical grid connection may not be required for small or micro-generation as these technologies can use distributed power supply systems.

3.2.4 Technical performance

The technology selected must be able to adequately mitigate methane emissions by oxidation in the conditions present at a particular site. The technology must be robust in a landfill environment and be fully tested at bench, demonstration and trial stages.

3.2.5 Costs (capital and operational)

Capital costs (CAPEX)

The collection and oxidation of landfill methane is an integral part of operating a modern landfill and the cost of this requirement over the life-cycle of the landfill must be reflected in the financial plans of the operator. However, the choice of technique should consider the relative costs of the various technologies. To assist in decision making, a cost-benefit tool for landfill gas management techniques was developed by the ACUMEN project (Environment Agency 2015)

The capital costs of large-scale and small/micro-generation (including installation of flares required as back-up) may be partially or wholly offset by the revenue generated by electricity sales.

As gas flows progressively decrease there may be costs associated with resizing the gas collection system to match predicted gas production rates and the requirements of the adopted methane oxidation technology.

For old sites which are passively venting but which are still producing significant amounts of methane, installation of an active extraction system may be necessary if there is evidence of potentially significant environmental damage or harm to human health (as demonstrated by monitoring and risk assessment). The costs for this may be partially offset if power generation is also installed.

The capital costs for biocovers which involve recapping a site may be significant.

Operational costs (OPEX)

The relative operational costs of the techniques also need to be considered. These are:

- maintenance and repair
- electricity usage
- monitoring costs
- periodic replacement and upgrade costs

3.2.6 Environmental performance

The technology should have good environmental performance in terms of national and international standards and the environment in which it is used. The following emissions need to be controlled to acceptable levels:

- exhaust gas quality from combustion processes
- noise and vibration
- odour

3.3 Decision-making framework

A decision-making framework for biodegradable waste landfills has been developed for each of the following classes of technology:

[A] Large-scale heat and power generation

[B] High temperature flares

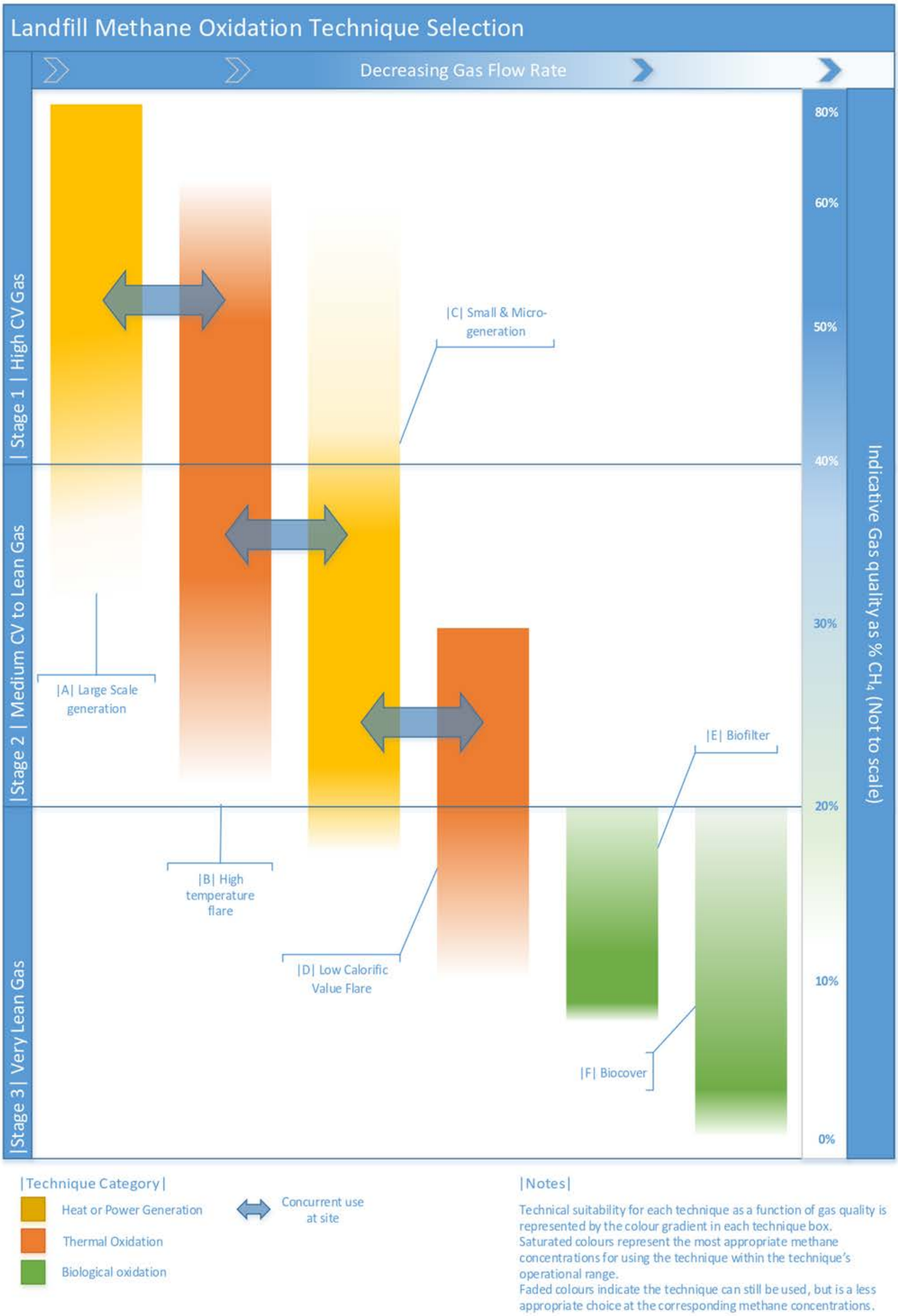
[C] Small or micro-scale generation

[D] Low calorific value flares

[E] Biofilters

[F] Biocovers

The relationship between these technologies and gas composition or flow rate is shown schematically in Figure 3.4.



Technical suitability for each technique as a function of gas quality is represented by the colour gradient in each technique box. Saturated colours represent the most appropriate methane concentrations for using the technique within the technique's operational range. Faded colours indicate the technique can still be used, but is a less appropriate choice at the corresponding methane concentrations.

Figure 3.4 Selection of methane oxidation technique in terms of gas composition and flow rate

Table 3.2 Factors to consider when selecting landfill methane oxidation technology

Key factors	Flowchart icon
Methane concentration and flow	
Landfill gas flow rate	
Methane concentration	
Active/passive extraction system	
Active gas collection	🚰
Passive gas collection	∅
Grid connection and utilisation	
High capacity grid connection	⚡
Distributed power	⋇
Combined heat and power (CHP)	🔥
Technical performance	
Established technology	⚙
Emerging technology	🧪
Uncertain technical performance	⏲
Monitoring and measurement	🔍
Costs and revenue	
Variable or elevated capital costs	£
Variable or elevated operating costs	£
Revenue generation	📈
Environmental performance	
Air quality	🌬
Noise nuisance	🔊
Odour nuisance	♨
Other	
Regulatory requirement or approval needed	☑

The key factors that must be taken into account when selecting technology are tabulated in Table 3.2. A description of these factors, as they relate to each technology, is given in the sections following the table. The key factors for each technique should be read with reference to the technique selection flowcharts in Appendix B.

[A] Large and medium-scale heat and power generation with high calorific value gas

High calorific value gas is produced in quantity both during and after landfill filling operations and during this time large-scale electricity generation with associated revenue generation is possible (see Flowchart A in Appendix B and Table 3.3). Electricity generation is not essential for the purposes of methane oxidation and associated climate change benefits (a flare will serve a similar purpose) but the revenue generation will make it more cost-effective.

Reciprocating engines and gas turbines are the most common technology choices for generating electricity and heat. The selection of a reciprocating engine or gas turbine is dependent on a number of technical factors, and site conditions. Generally, reciprocating engines start up quickly and have high electrical efficiencies compared to turbines of comparable size. Gas turbines have high thermal output with lower electrical efficiencies, and so are best suited to combined heat and power applications (USEPA 2015).

Once a landfill stops accepting biodegradable waste, landfill gas flow rates and methane concentrations will begin to decline. As methane gas production shifts to Stage 3 (see Table 3.1 above), large-scale generation will become less financially viable as gas flow rates become more variable, and the calorific value of the gas is no longer sufficient for the large-scale equipment to operate efficiently and without significant emissions. At this point the landfill gas can be flared using a modified high temperature flare [B], small and micro-generation can be used [C] or, alternatively, a low calorific value flare can be installed [D].

Table 3.3 Supporting information for Flowchart A

Key factors for large-scale power generation	Flowchart icons
Requires an active gas extraction system	🚰
A grid connection is required	⚡
Gas turbines may be used to supply combined heat and power if a heat user is available	🔥
Large-scale heat and power generation is an established technology	⚙
Revenue generation	📈
Potential for noise impacts from engine and generator operation	🔊

[B] High temperature flares

For sites operating under an Environmental Permit it is always necessary for power generation to be backed up by flares to allow oxidation of excess gas and at times when on-site power plant is either under maintenance or repair (see Flowchart B in Appendix B and Table 3.4). High temperature flaring may also be used as the primary means of methane oxidation during Stage 1 of the landfill life-cycle if power generation is not installed (due to the lack of a grid connection for example).

Modifying the burners in a high temperature flare gives the operator the flexibility to continue using the high temperature flare at full capacity once landfill gas production begins to decline in Stage 2.

With the approval of the Environment Agency, intermittent flaring can also be used as gas quality declines. In this case the high temperature flare is only operated for a limited number of hours per day, and only activates when enough gas pressure has built up in the gas collection system, switching off once gas pressure drops again. Since high temperature flares are designed to operate continuously, start–stop operation leads to wear on flare components and increased maintenance requirements.

When gas concentration and flows decline, supported combustion, where a supplementary fuel (e.g. propane) is added to the flare, can also keep the flare running continuously, but at the cost of the additional fuel. Use of supplementary support fuels incurs an additional cost, but this may be justified in particular cases to control odour nuisance or off-site gas migration.

Eventually, with gas quality continuing to deteriorate, using high temperature flares in any configuration becomes inefficient, and another technique is required. The next option is to install either a low calorific value flare [D], or switch to small or micro-scale generation [C].

Table 3.4 Supporting Information for Flowchart B

Key factors for high temperature flaring	Flowchart icons
Requires an active gas extraction system	🚰
High temperature flaring is an established technology	⚙
Intermittent or supported combustion using for example propane will entail additional operational costs	£
Potential air quality and noise impacts (for intermittent or low temperature operation)	🌬 🔊
For high calorific value gas, a flare is always required, either as the primary methane oxidation technology or as a back-up to power generation technologies	🗹
Regulatory approval required for intermittent flaring	🗹

[C] Small and micro-scale generation

With medium calorific value gas, or once large-scale generation or high temperature flaring become inefficient, small-scale or micro-scale generation can be used (see Flowchart C in Appendix B and Table 3.5). If gas flow rates are relatively stable, microturbines can be used. If gas flow rates from the landfill are more variable, external combustion options can be preferable as combustion does not take place within the engine itself and consequently the technology is more robust and will not be damaged by variable flows or contaminants present in the gas.

Microturbines are usually configured in banks operating in parallel to generate heat and electricity from landfill gas (USEPA 2016). This approach is quite versatile because as gas flows decline over time the operator can take microturbines off-line and not suffer any efficiency penalties or damage to the turbines by operating them below capacity.

Small or micro-scale generation will fulfil the function of methane oxidation, but if grid connection is available revenue generation may be possible. Small or micro-scale generation should be backed up by modified high temperature or low calorific value flares.

Eventually, gas quality will decline to such an extent that even small-scale generation will no longer operate efficiently and power generation is no longer possible. In this case, either a low calorific value flare alone [C] or a biofilter [E] should be considered.

Table 3.5 Supporting information for Flowchart C

Key factors for small and micro-scale generation	Flowchart icons
Requires an active gas extraction system	🚰
A grid connection is required for larger power generation – no grid connection may be required for smaller scale generation	⚡ 🔗
Microturbines may be used to supply combined heat and power if a heat user is available	🔥
Small/micro-scale power generation is a mixture of established (spark ignition engines/microturbines) and emerging (Stirling and ORC engines) technologies	⚙ 🧪
Choice of internal combustion engine is dependent on gas flow and quality. The technical performance of external combustion engines in a landfill context is currently uncertain	⏲
Revenue generation	📈
Potential for noise impact from engine and generator operation	🔊

[D] Low calorific value flares

Low calorific value flares, operating using medium to lean gas, can either be used on a stand-alone basis or be used as back-up for small/micro-generation (see Flowchart D in Appendix B and Table 3.6). Where active extraction systems remain operational low calorific value flares may be the most effective means of methane oxidation, particularly where small/micro-generation is no longer possible. As gas flow rates decrease and the produced gas becomes increasingly lean, low calorific value flares can also be used in an intermittent flaring configuration or require use of supplementary fuel for continuous supported combustion.

Even low calorific value flares stop working effectively once landfill gas quality becomes very lean (less than 10% methane v/v). Use of biofilters [E] allows continued methane oxidation during lean gas production where either active or passive gas extraction systems are operational. Alternatively, where maintaining an active extraction system is not practicable, it could be decommissioned and a biofilter installed to oxidise passively venting methane [E].

Table 3.6 Supporting information for Flowchart D

Key factors for low calorific value flares	Flowchart icon
Requires an active gas extraction system	⛽
Low calorific value flaring is a mature technology	⚙
Supported combustion using for example propane will entail additional costs	£
Air quality (for intermittent operation)	🌬

[E] Biofilters

Biofilters can be used to oxidise methane from active gas extraction systems once flaring or power generation becomes no longer possible or practicable but where an extractive gas system is in place (see Flowchart E in Appendix B and Table 3.7). Biofilters can also be used for sites where methane is passively venting, if it is possible to direct the gas towards the biofilter.

Table 3.7 Supporting information for Flowchart E

Key factors for biofilters	Flowchart icon
Generally used with active gas extraction system, but can be used on passively venting sites if suitable	⛽ ∅
Biofilters are an emerging technology whose technical performance is uncertain	🧪 ⏲
High monitoring and maintenance requirement	🔍
While capital costs may be lower than other technologies, there will also be a high monitoring and maintenance requirement to confirm that the biofilter system is operating as planned	£
Air quality and odour issues if biofilter is poorly designed or maintained	🌬 ♨

[F] Biocovers for passive landfill gas management on old landfills

For old landfill sites in which the active gas extraction system has either been decommissioned, or has never been installed, the choice of methane oxidation technique is limited to passive bio-oxidation (see Flowchart F in Appendix B and Table 3.8).

Where a landfill has not been capped, a full surface biocover may be cost-effective. For capped sites, it may be possible to engineer a secondary full surface biocover over the existing cap or, alternatively, a biowindow system could be installed. In cases where there is a lateral migration risk a bioactive intercepting trench could be used.

As with biofilters, maintaining the effectiveness of biocovers entails long-term monitoring and maintenance/repair liabilities.

Table 3.8 Supporting information for Flowchart F

Key factors for biocovers for passive landfill gas management	Flowchart icon
Suitable for passively venting sites	∅
Biocovers are an emerging technology whose technical performance is uncertain	🧪 ⏲
High monitoring and maintenance requirement	🔍
Capital costs will be high for full biocover systems. There will also be a high monitoring and maintenance requirement to confirm that the biocover system is operating as planned	£ £
Air quality and odour issues if biocover is poorly designed or maintained	🌬 ≀≀≀

4 Summary

This report identifies the currently available technologies for oxidising landfill methane. Detailed information on each of these technologies is provided in Appendix A to the report. The flowcharts set out in Appendix B show where the technologies sit within the life-cycle of the landfill and identify the decision points and the variables relevant to those decisions.

A decision-making framework has been developed to identify when each of the following classes of technology may be used:

- large and medium-scale heat and power generation
- high temperature flares
- small or micro-scale heat and power generation
- low calorific value flares
- biofilters
- biocovers

The decision-making framework is built on the applicability of each of these techniques for oxidation of methane across the life-cycle of individual landfill sites. The key variables identified for use in the decision-making process are:

- methane concentrations and flow rates
- whether a landfill site has an active extraction system or whether gas is passively vented
- whether a landfill site has an electrical grid connection
- the technical performance of the technology (i.e. its ability to oxidise methane and whether it is a tried and tested or emerging technology)
- costs (both capital and operational)
- monitoring and maintenance requirements
- emissions from the technology (noise, air quality, odour)

Table 4.1 provides a summary for the key variables for each of the identified classes of technology.

The information on each technology, taken together with the flowcharts, provide the framework within which evidence-based decisions can be made on the appropriate methane oxidation techniques at each stage of a landfill's life-cycle.

Table 4.1 Technology summary table

	[A] Large to medium-scale generation	[B] High temperature flare	[C] Small or micro-scale generation	[D] Low calorific value flares	[E] Biofilters	[F] Biocovers
Methane (CH_4) concentration and flow	>45% CH_4 >120 m^3/hr*	30–50% CH_4 20–6,000 m^3/hr	>20% CH_4 >24 m^3/hr [microturbines] >10 m^3/hr [Stirling]	10–50% CH_4 >20 m^3/hr	Loading rates of between 2 and 20 g/m^2/hr CH_4	Not identified[€]
Active or passive gas collection	Active	Active	Active	Active	Active or passive	Passive
Grid connection	Yes	No	Yes[$]	No	No	No
Established technology	Yes	Yes	Varies^	Yes	No	No
Relative costs	Baseline	Baseline	Higher than baseline flaring	Baseline	Lower capital, higher operational	Higher capital for full surface[%]
Monitoring and maintenance	Covered by EA monitoring guidance (Environment Agency 2010b)	Covered by EA monitoring guidance (Environment Agency 2010b)	Bespoke monitoring regime required	Can comply with EA flaring guidance	Bespoke monitoring regime required	Bespoke monitoring regime required
Emissions	Methane destruction of around 98.5%. NO_x the main emission of concern	Methane destruction >99% 50 mg/m^3 CO at 3% O_2 150 mg/m^3 NO_x at 3% O_2 10 mg/m^3 VOCs at 3% O_2	>99% methane destruction 19 mg/m^3 NO_x at 15% O_2	Methane destruction >99% 11.2 mg/m^3 NO_x 13.7 mg/m^3 CO 0.25 mg/m^3 VOCs	Highly variable depending on system maintenance and operational conditions	Highly variable depending on system maintenance and operational conditions

Notes

* Typical operational parameters for a 1 MW spark ignition engine

[$] May not be required for smaller generation capacity

% This does not reflect the fact that these techniques do not require the cost of a gas collection system

^ External combustion engines, such as Stirling and ORC, not yet fully proven

€ The loading rates for biocovers can be anticipated to fall towards the lower end of those for biofilters

References

ACUMEN (2015) *ACUMEN project report – managing landfill gas at closed and historic sites*. EU LIFE+ project for 2012–2015: LIFE11 ENV/UK/402. ACUMEN (Assessing, Capturing and Utilising Methane from Expired and Non-operational landfills).

DEVER, S.A., SWARBRICK, G.E. AND STUETZ, R.M. (2011) Passive drainage and biofiltration of landfill gas: results of Australian field trial. *Waste Management*, 31(5), 1029–1048.

ENTSORGA (2016) [online]. Available at: http://www.entsorga.it/ENG/technologies/emissions/geco2.php [Accessed 22 December 2016].

ENVIRONMENT AGENCY (2002) *Guidance on landfill gas flaring*.

ENVIRONMENT AGENCY (2004) *Management of landfill gas*. LFTGN 03.

ENVIRONMENT AGENCY (2009) *Control of landfill gas containing low concentrations of methane.* Science Report – SC030305/SR2.

ENVIRONMENT AGENCY (2010a) *Guidance for monitoring trace components in landfill gas*. LFTGN 04.

ENVIRONMENT AGENCY (2010b) *Guidance for monitoring enclosed landfill gas flares*. LFTGN 05 v2.

ENVIRONMENT AGENCY (2015) *ACUMEN Cost Benefit Tool* [online]. Available from: https://landss.soton.ac.uk/cost-benefit-analysis-tool [Accessed 3 May 2017].

ENVIRONMENTAL SERVICES ASSOCIATION (2012) *Landfill Gas Industry Code of Practice – The Management of Landfill Gas.*

EUROPEAN COMMISSION (2013) *Landfill gas control – guidance on the landfill gas control requirements of the Landfill Directive*.

EXERGYN (2016) [online]. Available at: https://www.exergyn.com/ [Accessed 14 November 2016].

FELLNER, J., PRANTL, R., BERGER, H., BUDISCHOWSKY, A., DANZER, M., DÖBERL, G., DONAT, C., FISCHER, B., GRAUS-GÖLDNER, A., HAGER, S., HUBER-HUMER, M., KERSCH, P., LETZ, C., MAHRINGER, K., MITTERWALLNER, J., OBERLEITNER, F., PIPPICH, B., REICHENAUER, K., ROLLAND, C., SCHARF, W., SCHEDL, A., TESAR, M., WURMETZBERGER, J. AND OTTERSBÖCK, M. (2008) *Konzeptionelle überlegungen zur entlassung aus der deponienachsorge*. ÖWAV-Positionspapier [online]. December 2008. Vienna. Available from: http://www.oewav.at/Page.aspx_param_target_is_159248.v.aspx

FELSKE, C., HAUBRICHS, R. AND WIDMANN, R. (2005) Engineering strategies for efficient methane oxidation in landfill cover liners and biofilter systems. In: Proceedings Sardinia 2005, *Tenth International Waste Management and Landfill Symposium*, S. Margherita di Pula, Cagliari, Italy, 3–7 October 2005.

GEBERT, J., HUBER-HUMER, M., OONK, H. AND SCHARFF, H. (2011). *Methane oxidation tool: An approach to estimate methane oxidation on landfills. Methane Oxidation Tool, Version 1, August 2011* [online]. http://www.afvalzorg.nl/Libraries/Publications_Methane_oxidation/Methane_Oxidation_Tool_explanatory_note.sflb.ashx [Accessed 4 May 2017]

GILLETTE, S. (2010) *Microturbine technology matures* [online]. Available at: http://www.powermag.com/microturbine-technology-matures/ [Accessed 22 December 2016].

HALL, D. H., DRURY, D., GRONOW, J. R., POLLARD, S. J. T. AND SMITH, R. (2007). Estimating pollutant removal requirements for landfills in the UK: III. Policy analysis and operational implications. Environmental Technology, 28, (1), 25-32.

HEIMOVAARA T., OONK H., VAN DER SLOOT H. A. AND VAN ZOMEREN A. (2010) *Reduction of the long-term emission potential of existing landfills, Final Report Phase 2* Dutch Sustainable Landfill Foundation

IRISH ENVIRONMENTAL PROTECTION AGENCY (2011) *Management of low levels of landfill gas*. Republic of Ireland: Environmental Protection Agency (Office of Environmental Enforcement).

IRISH ENVIRONMENTAL PROTECTION AGENCY (2012) *Guidance Note on Landfill Flare and Engine Management and Monitoring*. Republic of Ireland: Environmental Protection Agency (Office of Environmental Enforcement).

HAUBRICHS, R. AND WIDMANN, R. (2006) Evaluation of aerated biofilter systems for microbial methane oxidation of poor landfill gas. *Waste Management*, 26(4), 408–416.

KJELDSEN, P. AND SCHEUTZ, C. (2016) *Etablering og monitering af biocoversystemer på affaldsdeponerings-anlæg [Establishment and Monitoring of Biocover systems on landfills]* In Danish. Miljøprojekt nr. 1817, 2016 Miljøstyrelsen [Danish Environmental Protection Agency]

LANDFILL SYSTEMS (2015) *C9G Stirling engine* [online]. Available at: http://www.landfillsystems.co.uk/_webedit/uploaded-files/All%20Files/Brochure%20Downloads/C9G%20Stirling%20Engine%20v6.pdf [Accessed 22 December 2016].

LANGAN, M. (2016) Private telephone interview. Exergyn Head of Product Development. [Interview] (14 November 2016).

LIBERTINE FPE (2016) *Libertine Free Piston Engine* [Online]. Available at: http://www.libertine.co.uk/libertine-fpe [Accessed 16 November 2016].

MILLARD, J. (2015) Extending renewable electricity generation for decades at closed landfill sites with gas below 30% methane. Sardinia 2015, *Fifteenth International Waste Management and Landfill Symposium*, S. Margherita di Pula, Cagliari, Italy, 5–9 October 2015. CISA, Environmental Sanitary Engineering Centre, Italy.

MYHRE, G., SHINDELL, D., BRÉON, F.-M., COLLINS, W., FUGLESTVEDT, J., HUANG, J., KOCH, D., LAMARQUE, J.-F., LEE, D., MENDOZA, B., NAKAJIMA, T., ROBOCK, A., STEPHENS, G., TAKEMURA, T. AND ZHANG, H. (2013) Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgleywa, P.M. (eds) *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, USA: Cambridge University Press.

NEWENCO (2016) *The E-Rational ORC Range* [online]. Available at: http://www.newenco.co.uk/organic-rankine-cycle/e-rational-orc-range [Accessed 22 December 2016].

Nobis, H. L. (2011). *Eskesberg: Eine deponie mit der folgenutzung naturschutzgebeit [Eskesberg: A landfill with the consequences of nature conservation]* [online]. In German. http://www.nua.nrw.de/fileadmin/user_upload/NUA/Veranstaltungen/Veranstaltungsberichte/2011-10-11%20Workshop/Eskesberg%20-%20Eine%20Deponie%20mit%20der%20Folgenutzung%20Naturschutzgebiet%20(PDF,%202,1%20MB).pdf.

PARK, S., BROWN, K.W. AND THOMAS, J.C. (2002) The effect of various environmental and design parameters on methane oxidation in a model biofilter. *Waste Management & Research*, 20(5), 434–444.

PBO (2007) *Construction of a new regenerative thermal oxidiser at the Eskesberg site, Wuppertal* [online]. Available at: https://www.pbo.de/en/core-competenciesreferences/references-from-a-z/landfill-gas-treatment-eskesberg-landfill/ [Accessed 22 December 2016].

POHLAND, F.G. AND HARPER, S.R. (1986) *Critical review and summary of leachate and landfill gas production from landfills*. US Environmental Protection Agency.

POWELSON, D.K., CHANTON, J., ABICHOU, T. AND MORALES, J. (2006) Methane oxidation in water-spreading and compost biofilters. *Waste Management & Research*, 24(6), 528–536.

RICARDO-AEA (2015) *Biomethane for transport from landfill and anaerobic digestion*. Report for the Department of Transport. PPRO 04/91/63.

RITZKOWSKI M. AND STEGMANN R. (2010) *Generating CO_2 credits through landfill in-situ aeration.* Waste Management 30, 702-706

STACHOWITZ, W. (2000) *VocsiBox – Filling a gap... Landfill Gas Oxidation System for low calorific value* [online]. Haase Energietechnik GmbH and Clarke Energy Ltd. Available at: http://www.das-ib.de/vortraege/fillinggap_cel_het_Launch.pdf [Accessed 2 May 2017].

STEGMANN, R. (2006) *Deponienachsorge – Handlungsoptionen, dauer, kosten und quantitative kriterien für die entlassung aus der nachsorge [Landfill management - options for action, duration, costs and quantitative criteria for the release from aftercare]* [online]. In German. Umweltbundesamt FKZ 204 34 327. Hamburg. Available at: http://www.ifas-hamburg.de/pdf/UFOPLAN_IFAS.pdf [Accessed 3 May 2017].

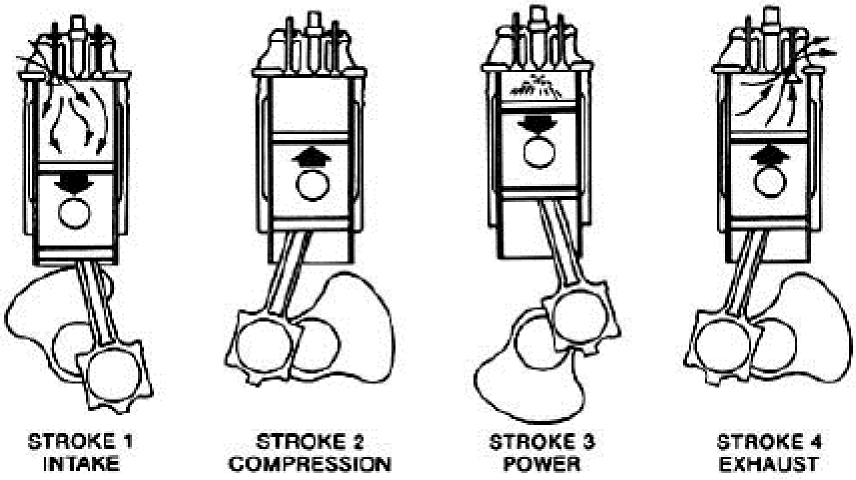
USEPA (2015) *Catalog of CHP Technologies* [online]. Combined Heat and Power Partnership, United States Environmental Protection Agency. Available at: https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf [Accessed 3 May 2017].

USEPA (2016) *Landfill Methane Outreach Program (LMOP)* [online], United States Environmental Protection Agency. Available at: https://www.epa.gov/sites/production/files/2016-08/opprjslmopdata.xlsx [Accessed 22 December 2016].

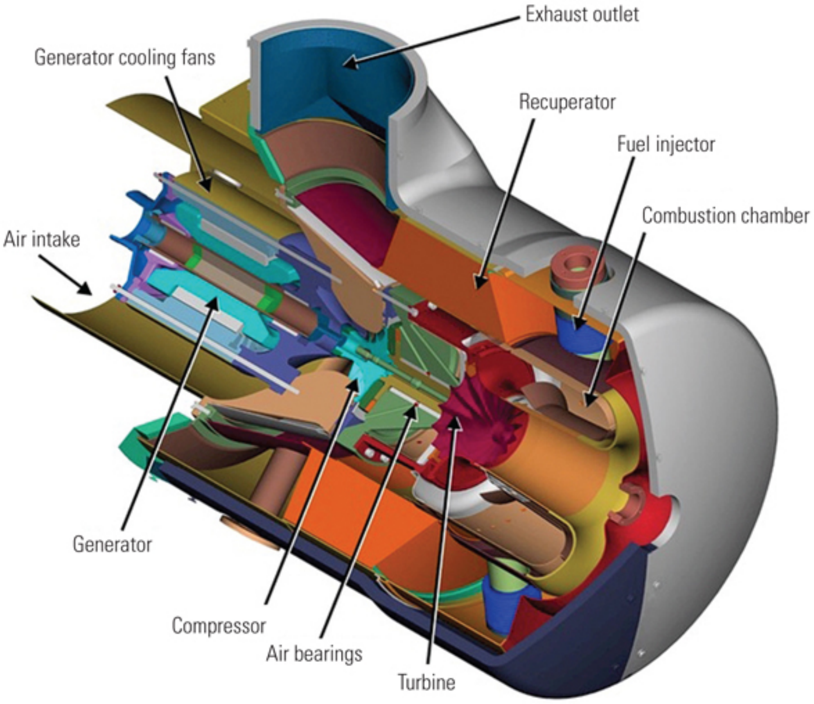
WASTESERV (2016) *Magħtab Environmental Complex* [online]. Available at: https://www.wasteservmalta.com/maghtab [Accessed 22 December 2016].

WILSHUSEN, J.H., HETTIARATCHI, J.P.A., DE VISSCHER, A. AND SAINT-FORT, R. (2004) Methane oxidation and formation of EPS in compost: effect of oxygen concentration. *Environmental Pollution*, 129(2), 305–314.

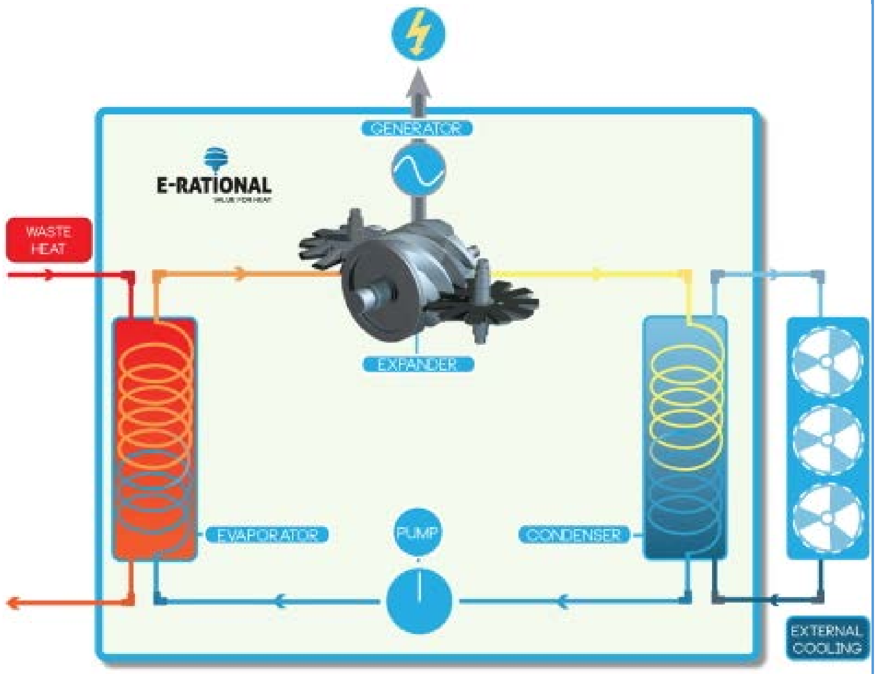
Appendix A: Technique data sheets

LARGE TO MEDIUM-SCALE GENERATION	
Technique	Internal combustion
Types	Reciprocating engine Gas turbine
Gas collection	Active
Process type	Thermal
Description	Although gas turbines and reciprocating engines operate using different mechanics, both techniques generate mechanical work that can be used to produce electricity, and both techniques produce thermal output that can be utilised for volume heating, drying or other functions. Spark ignition reciprocating engines are suitable for landfill gas utilisation when specially modified and tuned to accept landfill gas. Landfill gas must be compressed before delivery to the engine. Reciprocating engines are available in sizes from 10 kW to over 18 MW.  Basically a turbine consists of a shaft with an assembly of blades attached to it. The blades are arranged in such a manner that when a fluid passes over the blades, the shaft and blades rotate and generate shaft work. The simplest gas turbines (or combustion turbines) have only one moving part, in contrast with the mechanically more complex internal combustion engine. The gas turbine consists of a compressor, a combustion chamber and an expansion turbine. The compressor heats and compresses the inlet air, which enters the combustion chamber with the fuel and is ignited. The hot air and combustion gas mixture expands through the expansion turbine, rotating the blades and shaft fast enough to provide shaft-energy to the generator, which generates electricity. The hot expansion gas leaving the turbine can optionally be passed through heat exchangers to produce hot water or use the direct heat in other ways. Gas turbines are available in sizes from 500 kW to over 300 MW, but sizes up to 5 MW are used for landfill gas, Generation capacity up to 20 MW is noted in the USA where multiple turbines operate in parallel.
Advantages	Reciprocating engines: quick start-up and high electrical efficiencies compared to turbines of comparable size Gas turbines: high thermal output with lower electrical efficiencies so best suited to combined heat and power applications

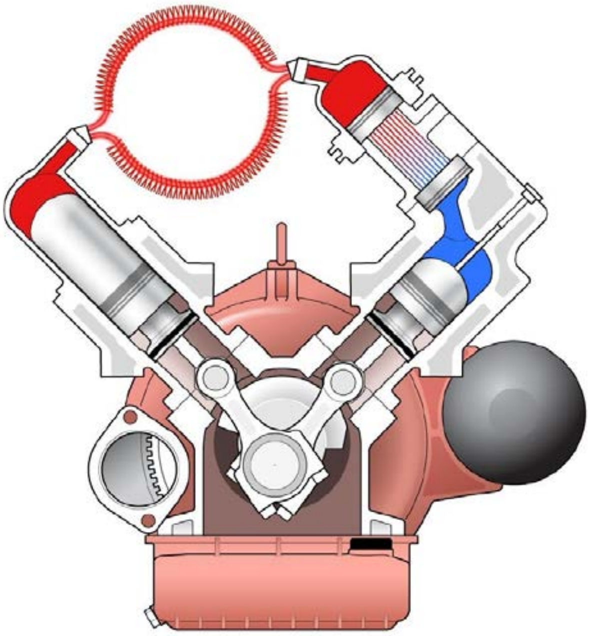
Disadvantages	Contaminants in landfill gas can impact engine life and increase maintenance requirements of reciprocating engines Require steady, predicable gas flow. Not robust in handling unplanned shut-downs should gas flow rates drop or methane concentrations falter
Operational range and parameters:	
Input CH_4	>45%
Input Flow rate	>120 m^3/hr ~89 m^3/hr at Columbus County ARS, USA, but unusual Gas turbines require higher gas flowrates
Methane destruction efficiency	~100%
Environmental performance	Due to high temperature controlled combustion, emissions from the process usually lie below acceptable emission limits for ambient air quality. Issues such as nuisance odour and subsurface migration of landfill gas are not experienced using these techniques. Nuisance noise can potentially be of concern, depending on the proximity of receptors, but enclosing engines and turbines in buildings and applying other noise attenuation techniques usually reduces noise to acceptable levels.
Indicative costs	**CAPEX** Depends on sizing and configuration. Check with suppliers **OPEX** Depends on sizing and configuration. Check with suppliers
References	**Data references** ACUMEN (2015), USEPA (2015), USEPA (2016)
Technology providers (not an exhaustive list)	Many suppliers, including: Reciprocating engines: • Caterpillar (http://www.cat.com/en_US/by-industry/electric-power-generation/electric-power-industries/landfills.html) • Jenbacher (https://powergen.gepower.com/products/reciprocating-engines.html) Gas turbines: • Solar (https://mysolar.cat.com/en_US/products/gas-turbine-overview.html)

MICROTURBINES	
Technique	Internal combustion with microturbines
Gas collection	Active
Process type	Thermal
Description	Microturbines function in the same way as the larger scale gas turbines described previously. They are usually simple and much smaller. Certain models have only one moving part, no gearbox or other mechanicals, and use no lubricants, simplifying and reducing the need for maintenance. Microturbines can accept fuels such as natural gas, propane, landfill gas, digester gas, diesel, aviation fuel and kerosene. Microturbines are often set up in parallel, with a number of lower rated turbines set up to produce higher electrical and thermal output. Microturbines can be used in combined heat and power or combined cooling, heat and power scenarios where the exhaust heat can be recovered. The diagram below shows the internal elements of a microturbine.  **Cut-away view of Capstone C65 microturbine (source: Gillette 2010, citing Capstone Power Systems)**
Advantages	Low gas emissions Versatile. Microturbines can be brought on-line or taken off-line as gas flow changes, allowing continued efficient operation Generate revenue through electricity and waste heat utilisation Does not necessarily require grid connection
Disadvantages	More expensive than flaring
Operational range and parameters:	
Input CH_4	>20%
Input flow rate	>24 **m^3/hr**

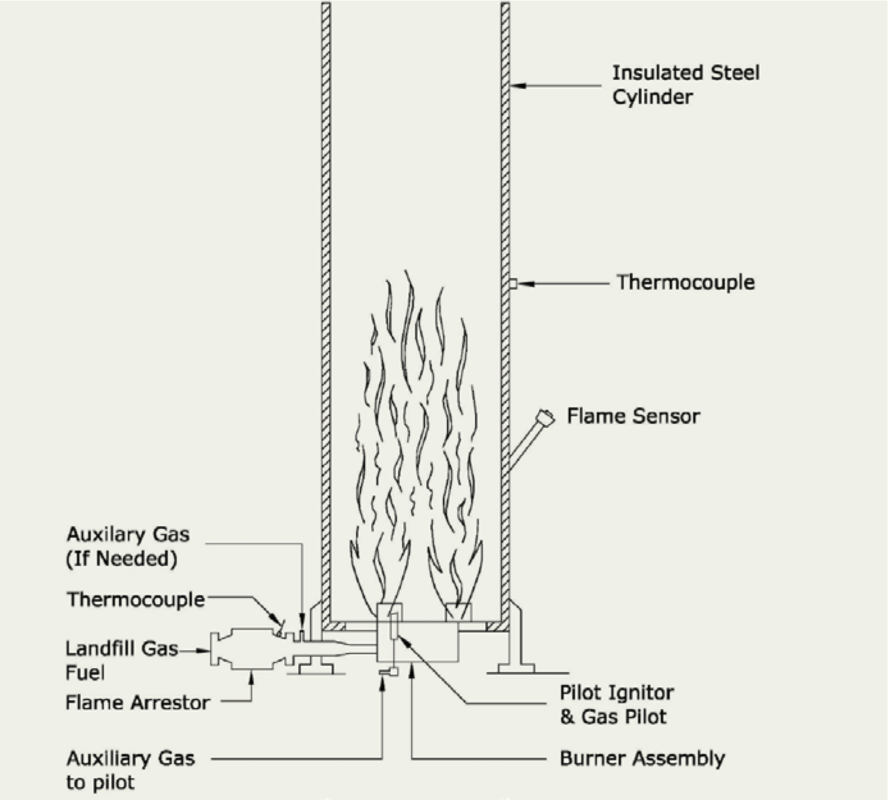
Methane destruction efficiency	Unreported, but likely >99% due to high thermal output
Other	Design life approximately 20 years
Environmental performance	Emissions 19 mg/m^3 NO_x at 15% O_2 Potential noise from fan and burner. 70 dB(A) at 10 m
Indicative costs	**CAPEX** Typically ~£100,000. Varies depending on number of turbines installed and gas supply. Check with suppliers **OPEX** £5,000 to £10,000 per annum, based on servicing once every 6 months and activated carbon consumables. Check with suppliers for exact costs
References	**Data references** Gillette (2010), NewEnCo (http://www.newenco.co.uk/), USEPA (2016)
Technology providers	Capstone Turbine Corporation (https://www.capstoneturbine.com/) UK distributors of Capstone microturbines: • Turner Engine Powered Services (http://www.turner-eps.co.uk/microturbines.aspx) • NewEnCo (http://www.newenco.co.uk/)

ORGANIC RANKINE CYCLE ENGINES	
Technique	External combustion with ORC
Gas collection	Active
Process type	Thermal
Description	The ORC makes use of an organic fluid with a boiling point lower than water. The fluid enables recovery of heat from lower temperature sources such as industrial waste and geothermal heat. The low temperature heat is used to drive a turbine and create electricity. An example of ORC technology is the ORMAT® Energy Converter, a proprietary implementation of ORC technology. The ORC is a thermodynamic process where heat is transferred to a fluid at a constant pressure. The fluid is vaporised and then expanded in a vapour turbine that drives a generator, producing electricity. The spent vapour is condensed to liquid and recycled back through the cycle. ORC machines are based on the simple thermodynamic principle shown in the picture below.  The cycle is started at the pump, which is pumping the refrigerant – the fluid of the internal circuit of the machine – to the evaporator. At this first heat exchanger the available waste heat is used to evaporate the refrigerant. The saturated gas at the outlet of the evaporator is sent to the expander. The expansion of the gas is delivering the work to drive the generator, resulting in the production of electricity. Supersaturated low pressure gas is leaving the expander to be condensed. At a second heat exchanger, the condenser, external cooling is used to condense the gas. The fluid leaving the condenser will be pumped up again to restart the cycle. In some cases a third heat exchanger, the recuperator, can be integrated to optimise machine efficiency. This recuperator cools down the low pressure gas leaving the expander prior to entering the condenser. The extracted heat is used to preheat the fluid pumped by the pump prior to

	entering the evaporator. This extra heat exchanged maximises overall performance of the machine.
Advantages	Simple operation. Long plant life. Tolerant to poorer quality gas
Disadvantages	Not widely adopted at landfills for heat recovery or power generation
Operational range and parameters:	
Input CH_4	>20% – Sufficient methane to generate waste heat input at 80°C to 150°C
Input flow rate	>100 m^3/hr – Require sufficient to generate waste heat input at 80°C to 150°C
Methane destruction efficiency	Approximately 98%
Other	Temperature heat input: 80°C to 150°C (not gas combustion temperature) Potential nuisance noise: <70 dB at 10 m
Indicative costs	**CAPEX** Check with supplier for specific application **OPEX** Check with supplier for specific application
References	**Known operational plant** No known sites in UK for application at landfills Brickyard Landfill Units 1 and 2, Danville, Illinois, US operational in 2003, but shutdown. USEPA (2016)
Technology providers	ORMAT® (http://www.ormat.com/organic-rankine-cycle) E-Rational ORC (http://www.newenco.co.uk/) Turboden (http://www.turboden.eu/en/rankine/rankine-turbodenorc.php)

STIRLING ENGINES	
Technique	External combustion with Stirling engine
Gas collection	Active
Process type	Thermal
Description	The following information has been published by a supplier of Stirling engines: C9G is an external combustion engine using the Stirling cycle for micro-scale electricity generation. The C9G works on gases with low methane contents which are not able to be used by conventional spark ignition engines. A C9G will typically use around 12 m^3/hr gas (calorific value dependent) and will produce 7.2 kWe on a continuous basis. Can be run to generate electricity for export or on-site use or run off-grid if necessary. The C9G also generates heat and therefore has combined heat and power capability and can be used to heat buildings such as recycling plants, leachate treatment plants etc. Requires propane for ignition. As Stirling engines are external combustion engines, they are less vulnerable to trace contaminants in landfill gas than spark ignition engines or gas turbines.  **Schematic of a C9G Stirling engine (Landfill Systems 2015)**
Advantages	Generates electricity and heat from lean gas More robust than internal combustion engines (more tolerant to impurities and variations in landfill gas flow) Modular installation allowing expansion C9G model has combustion chamber integrated into unit
Disadvantages	Needs grid connection at larger scale or nearby user able to accept transmission
Operational range and parameters:	
Input CH_4	>20%

Input flow rate	>10 m^3/hr
Methane destruction efficiency	~98%
Environmental performance	Emissions: CO: <95 ppm according to manufacturer. Docking Landfill Site test reported 75–206 ppm (ACUMEN 2015) NO_x: <10 ppm according to manufacturer. Docking Landfill Site test reported: 46–127 ppm (ACUMEN 2015) Noise: <47 dB(A) at 10 m
Indicative costs	**CAPEX** £214,000 (ACUMEN 2015) Academic demonstration site – commercial costs likely to be less **OPEX** £15,000 per annum (ACUMEN 2015) Academic demonstration site – commercial costs likely to be less
References	**Known operational plant** Docking Landfill Site near King's Lynn **Data references** ACUMEN (2015)
Technology providers	Cleanergy C9G Stirling engine, distributed in UK by Landfill Systems (http://www.landfillsystems.co.uk)

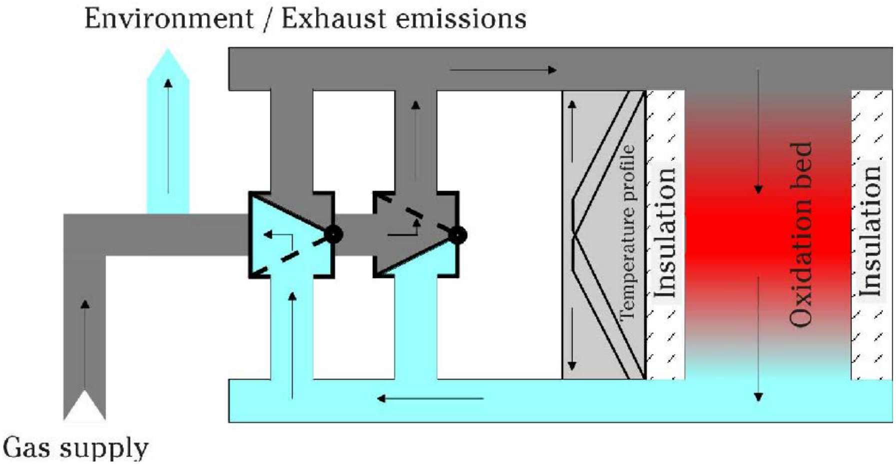
HIGH TEMPERATURE FLARES	
Technique	High temperature flare
Configurations	Standard operation Modified burner Intermittent flaring Supported combustion Low temperature operation
Gas collection	Active
Process type	Thermal
Description	**Standard operation** High temperature enclosed flares receive landfill gas from the gas collection system, and pass the gas through a series of burners that are enclosed by an insulated shroud. The insulated shroud is usually a vertical, cylindrical or rectilinear enclosure. An insulated enclosure allows the flare to operate at higher temperatures. The landfill gas flow rate and air content are regulated through the flare in order to control combustion conditions and meet emissions standards. The diagram below illustrates a flare in operation.  **Schematic illustration of an enclosed flare (source: Irish EPA 2011)**

	Modifying burner Some suppliers offer high temperature flare customisations, to allow flares to be integrated into heat or power generation systems, or to allow existing flares to operate with reduced gas flow rates. Not all models support these modifications, and so confirmation should be sought from the flare equipment manufacturer or supplier. Specifically, the size and shape of individual burner jets can be modified to allow standard high temperature flares to function effectively on landfill gas qualities outside their normal design range. **Intermittent flaring and supported combustion** Intermittent flaring is an option for managing landfill gas of either low volume or low methane concentration. The principle is to store the landfill gas, allowing gas pressure and potentially methane concentrations to build, and operate the flare for a limited number of hours per day. Intermittent flaring will require supplementary fuels to start up combustion and, as gas flow rates and methane concentration drop, maintain it. Existing flares can be modified to support a secondary combustion source, such as propane. The purpose of this is to provide enough energy to keep the combustion temperature within the conventional 1,000 to 1,200°C range, despite reduced methane concentrations in the landfill gas. Use of supplementary support fuels to prolong flaring periods indefinitely is not economically sustainable, but may be justified to: • control odour nuisance • control off-site migration • commence timely active gas management as full-scale methanogenesis becomes established in the earlier stages of the landfill life **Low temperature operation** High temperature flares can be operated at temperatures lower than 1,000°C, and this becomes necessary as methane concentrations in the landfill gas decline. At around 25% methane, flare combustion temperatures are approximately 850 to 900°C. Such operation is not sustainable as operational difficulties and maintenance costs increase. Flare ignition begins to fail, necessitating more frequent application of supported combustion burns. Without using supported combustion, the landfill gas will not be completely oxidised and gaseous emissions will fail to meet standards.
Advantages	Equipment available to operate over a wide range of landfill gas flow rates and methane concentrations Mature technology and techniques Consistently meets regulatory emissions standards
Disadvantages	Not suitable for low landfill gas flow rates or low methane concentrations
Operational range and parameters:	
Input CH_4	30–50% (25% for low temperature flaring, but not advised) (15% for supported combustion)
Input flow rate	20–6,000 m^3/hr

Methane destruction efficiency	>99%
Other	Temperature range 1,000°C to 1,200°C Residence time >0.3 s
Environmental performance	Sound pressure level <69 dB from burners and fans Intermittent flaring increases nuisance odour risk Supplementary combustion necessary when there is an increased odour risk Active pumping, so subsurface migration risks reduced. However, intermittent flaring configuration can increase subsurface migration risk as gas pressure builds up between flaring periods Example emissions (Uniflare UF10 brochure, undated) • 50 mg/m^3 CO at 3% O_2 • 150 mg/m^3 NO_x at 3% O_2 • 10 mg/m^3 VOCs at 3% O_2
Indicative costs	**CAPEX** £50,000 to £150,000 depending on size and telemetry options. Contact suppliers for details **OPEX** £5,000 to £10,000 per annum, based on servicing once every 6 months and activated carbon consumables. Check with suppliers for exact costs
References	**Known operational plant** Multiple applications nationally and internationally. Contact suppliers for details Intermittent flaring case, providing heat and power: Schinnen Landfill (Millard 2015) **Data references** Environment Agency (2002), Irish EPA (2011)
Technology providers	Landfill Systems Maintenance (http://www.landfillsystems.co.uk/our-services/biogas-flares/) Biogas Technology (http://www.biogas.co.uk/flare.htm) Automatic Flare Systems (http://www.afs-group.co.uk/what_flare.php) Uniflare: UF10; UF12 (http://www.uniflare.co.uk/Flare-Stacks.aspx) Hofstetter: HOFGAS Efficiency; HOFGAS Sparky (http://hofstetter-uwt.com/index.php/en/) HAASE Energietechnik (http://www.bmf-haase.de/en/)

LOW CALORIFIC VALUE FLARES	
Technique	Low calorific value flare
Configurations	Standard operation Intermittent flaring Supported combustion
Gas collection	Active
Process type	Thermal
Description	Low calorific value flares operate in a similar fashion to high temperature flares. These flares are a mature technology for oxidising gas from old landfill sites or sites with low quality gas. Low calorific value flares differ from high temperature flares in that they: • use special lean gas burners • preheat combustion air to the system • require supported combustion for ignition and start-up, with fuels such as propane or a natural gas Low calorific value flares are available in a number of configurations from a broad range of suppliers. Units are available in a number of flow rate sizes, and are installed on site either containerised or skid-mounted. Certain low calorific value flares can be adapted for power generation applications, in combination with external combustion engines. As gas flow rates drop off over time, low calorific value flares can also be used in an intermittent flaring configuration, but more regular start-ups will require additional supported combustion.
Advantages	Small, compact footprint Relatively fast construction and set-up Meets environmental gas emission requirements Can handle lean and low quality landfill gas flows up to a point
Disadvantages	Requires supported combustion for start-up
Operational range and parameters:	
Input CH_4	10–50% Dependent on manufacturer. Lower methane requires higher input gas flow rate to be effective
Input flow rate	>20 m^3/hr. Certain suppliers claim as high as 2,000 m^3/hr
Methane destruction efficiency	>99%
Other	Combustion temperature: 1,000°C Retention time: 0.3 s
Environmental performance	With correct operation and process control, adheres to emissions standards for enclosed landfill gas flares (Environment Agency 2010b), and eliminates nuisance odours Potential noise nuisance from fan and burners, but typically low (>70 dB(A) at 1 m)

Indicative costs	**CAPEX** Typically £40,000 to £70,000 Dependent on manufacturer and size of equipment **OPEX** Approximately £10,000 per annum. Based on servicing once every 6 months; annual emissions monitoring; and import electricity for fan <5 kW
References	**Known operational plant** Multiple applications internationally. Contact suppliers for details **Data references** Landfill Systems Maintenance (http://www.landfillsystems.co.uk/our-services/biogas-flares/) Biogas Technology (http://www.biogas.co.uk/flare.htm) Automatic Flare Systems (http://www.afs-group.co.uk/what_flare.php) Uniflare: UF10; UF12 (http://www.uniflare.co.uk/Flare-Stacks.aspx) Hofstetter: HOFGAS Efficiency; HOFGAS Sparky (http://hofstetter-uwt.com/index.php/en/) HAASE Energietechnik (http://www.bmf-haase.de/en/)
Technology providers (not an exhaustive list)	Landfill Systems Maintenance (http://www.landfillsystems.co.uk/our-services/biogas-flares/) Biogas Technology (http://www.biogas.co.uk/flare.htm) Automatic Flare Systems (http://www.afs-group.co.uk/what_flare.php) Uniflare: UF10; UF12 (http://www.uniflare.co.uk/Flare-Stacks.aspx) Hofstetter: HOFGAS Efficiency; HOFGAS Sparky (http://hofstetter-uwt.com/index.php/en/) HAASE Energietechnik (http://www.bmf-haase.de/en/)

REGENERATIVE THERMAL OXIDATION	
Technique	Regenerative thermal oxidation
Gas collection	Active
Process type	Thermal
Description	Regenerative or non-catalytic thermal oxidation is a specialised technique designed to oxidise VOCs. It is typically used for coal-bed methane and for removing industrial VOCs from manufacturing processes. It can also be used to oxidise methane from landfill gas, if the methane concentrations are very low (0.3 to 0.8% v/v). Regenerative thermal oxidation can handle higher methane concentrations if the landfill gas is diluted with air prior to entering the process. Regenerative thermal oxidation works by using hot ceramic plates to oxidise gas containing VOCs and methane. This releases energy, transferring heat to the ceramic bed and cooling the gas. After initial start-up the process is thermally self-sustaining, but the energy content of the gas must be tightly controlled to prevent overheating. The heat stored in the ceramic plates provides enough energy to the gas to sustain the oxidation reactions. The reaction zone within the ceramic bed tends to move along the bed in the same direction as the gas flow, so the unit is designed to reverse the gas flow direction at regular intervals in order to keep the reaction zone in the centre of the ceramic bed (see figure below).  **Schematic of regeneration thermal oxidation process (Stachowitz 2000)**
Advantages	No auxiliary energy inputs. Specialist applications for treating VOCs, possibly pathogens
Disadvantages	Can only treat low concentration of methane. To treat higher methane concentrations air dilution is required which increases unit size and capital cost
Operational range and parameters:	
Input CH_4	0.3–0.8%. Feed up to 28% methane if landfill gas diluted with air prior to entering oxidation bed
Input flow rate	500 to 50,000 m^3/hr

Methane destruction efficiency	>99%
Other	Typically 15 to 20 years design life Operational temperature 900°C to 1,000°C
Environmental performance	There is potential for nuisance noise to be generated by fans and the gas dilution system Active gas collection for this technique removes the risk of subsurface gas migration Destroys VOCs, although combustion emission monitoring required
Indicative costs	**CAPEX** Depends on size. Typically more than £250,000 **OPEX** 6-monthly servicing and annual emissions monitoring. Import electricity for fans (~10 kW)
References	**Known operational plant** Magħtab Environmental Complex, in Malta, treating landfill gas from an uncontrolled dumpsite that closed in 2004 (WasteServ 2016) Eskesberg-West Landfill, Wuppertal, Germany (PBO 2007, Nobis 2011) **Data references** Stachowitz (2000), Nobis (2011), BMF Haase (2016)
Technology providers (not an exhaustive list)	BMF Haase (http://www.bmf-haase.de) PBO (https://www.pbo.de/)

BIOFILTERS	
Technique	Biofilter
Types	Open bed and closed bed
Gas collection	Active OR passive
Process type	Biological
Description	**Biofilter active: open bed (BF-AO)** A system consisting of a volume of bioactive materials where landfill gas is actively pumped from below through a gas distribution layer. The biofilter surface is open to the atmosphere so oxygen can diffuse into the bioactive material from above. Oxygen can also be introduced with the landfill gas into the base of the biofilter. **Biofilter passive: open bed (BF-PO)** A system consisting of a volume of bioactive materials where landfill gas is fed passively from below through a gas distribution layer. Open to the atmosphere so oxygen can diffuse into the bioactive material from above. **Biofilter active: closed bed (BF-AC)** A system consisting of a volume of bioactive materials where landfill gas is actively pumped from below/above through a gas distribution layer. The biofilter is enclosed (for instance in a container) so oxygen is to be part of the loading gas (maybe supplied by a second pump). **Biofilter passive: closed bed (BF-PC)** A system consisting of a volume of bioactive materials where landfill gas is fed passively from below/above through a gas distribution layer. As the filter is closed to the atmosphere (for instance in a container) it is necessary for oxygen to be part of the loading gas.
Advantages	Closed bed has smaller footprint than open bed systems Closed bed is a modular system. Can be installed by established supplier Can oxidise methane in landfill gas at lower quality than conventional methods (such as low calorific value flares)
Disadvantages	Emerging technique. Uncertainties regarding technique efficacy for methane oxidation. Difficulties with monitoring methane destruction efficiency effectively. Potentially expensive monitoring requirements Passive systems still need maintenance, and biofilter matrix needs to be replaced periodically
Operational range and parameters:	Variable, but lower methane concentration requires smaller volumes of bio-oxidation media, and therefore footprint
CH_4 loading	Biofilters perform successfully with a measured methane loading rate of 2–20 g/m^2/hr However, not all data is from full-scale operational sites. Data supporting this is also sourced from demonstration, pilot and laboratory scale work Austrian guideline: <0.5 m^3 CH_4/hr/hectare (CH_4 oxidation rate of at least 90%) (Fellner et al. 2008) German guideline: <7.7 g CH_4/m^2/day (with CH_4 <25 ppm in soil cover measured by FID) (Stegmann 2006)
Methane destruction efficiency	Up to 90% Methane loading less than 2 g/m^2/hr generally yields more variable methane destruction efficiencies

Other	Operational life of biofilter matrix approximately 5 years With point emissions from flares, monitoring methods are established and known to work well. Monitoring the distributed fugitive emissions from a biofilter is technically more complex, and has high uncertainties in the results and potentially higher costs because of the specialised methods
Environmental performance	Potential nuisance odour if technique does not perform effectively Variable methane oxidation performance
Indicative costs	Capital and operating costs are variable and uncertain, and depend on size of landfill, methane loading rates and surface area of the biofilter itself. There are no known established technology providers for open bed systems in the UK
References	**Case study** Strumpshaw Landfill, Norfolk (ACUMEN 2015) Maesbury Road Landfill, Oswestry, Shropshire (ACUMEN 2015) **Other known full-scale operational sites** Klintholm, Denmark (Kjeldsen and Scheutz 2016) **Data references** Park et al. (2002), Wilshusen et al. (2004), Felske et al. (2005), Haubrichs and Widmann (2006), Powelson et al. (2006), Dever et al. (2011), ACUMEN (2015), Entsorga (see below), Kjeldsen and Scheutz (2016)
Technology providers (not an exhaustive list)	Entsorga: geCO2 (http://www.entsorga.it/ENG/tecnologie/emissions/geco2.php)

BIOCOVERS	
Technique	Biocover
Types	Full surface, biowindows, bioactive interception trench
Gas collection	Passive
Process type	Biological
Description	**Full surface biocover (FSB)** The whole landfill area is covered with a homogeneous layer of bioactive coarse materials (such as a coarse soil or compost) underlain by a gas distribution layer of gravel. Gas is loaded passively to the biocover. **Biowindow system (BWS)** A system incorporating the presence of an existing, low permeable soil cover. Areas of the existing cover are replaced by gas-permeable, bioactive materials (such as a coarse soil or compost) underlain by a gas distribution layer of gravel. Gas is loaded passively to the biowindows. **Bioactive intercepting trench (BIT-PO)** A system consisting of a deep trench surrounding the perimeter of a landfill to collect and oxidise methane in landfill gas migrating horizontally from the landfill. The trench may be filled with gas-distributing materials at the bottom and bioactive materials on top. Gas is routed passively to the trench.
Advantages	Can be applied to landfills that do not have a gas collection system installed
Disadvantages	Only works as a passive system, resulting in less gas flow control Requires active monitoring and maintenance that incurs operational costs
Operational range and parameters	For other specifications and notes, refer to biofilter specifications above
References	**Known full-scale operational sites** Amstetten Austria Pausendorf Austria Oberaich Austria Fakse (12/660/1b) Denmark **Data references** Kjeldsen and Scheutz (2016)
Technology providers	Not applicable

Appendix B: Technique selection flowcharts

|Flowchart Key|

Flowchart elements

Technique category

🟨 Heat and power generation technique

🟧 Thermal oxidation technique

🟩 Biological oxidation technique

Decision pathways

Primary technique decision pathway
●——————▶

Secondary technique decision pathway
● · · — · · — · · ▶

Decision points

Technology decision point
?

Declining gas flow and quality decision point
◆

Technology decision considerations

Active/Passive gas collection

Active gas collection

Ø Passive gas collection

Grid connection and utilisation

⚡ High capacity grid connection

Distributed power

🔥 Combined Heat and Power (CHP)

Technical performance

⚙ Established technology

Emerging technology

Uncertain technical performance

Monitoring and measurement

Costs and revenue

£ Variable or elevated capital costs

£ Variable or elevated operating costs

Revenue generation

Environmental performance

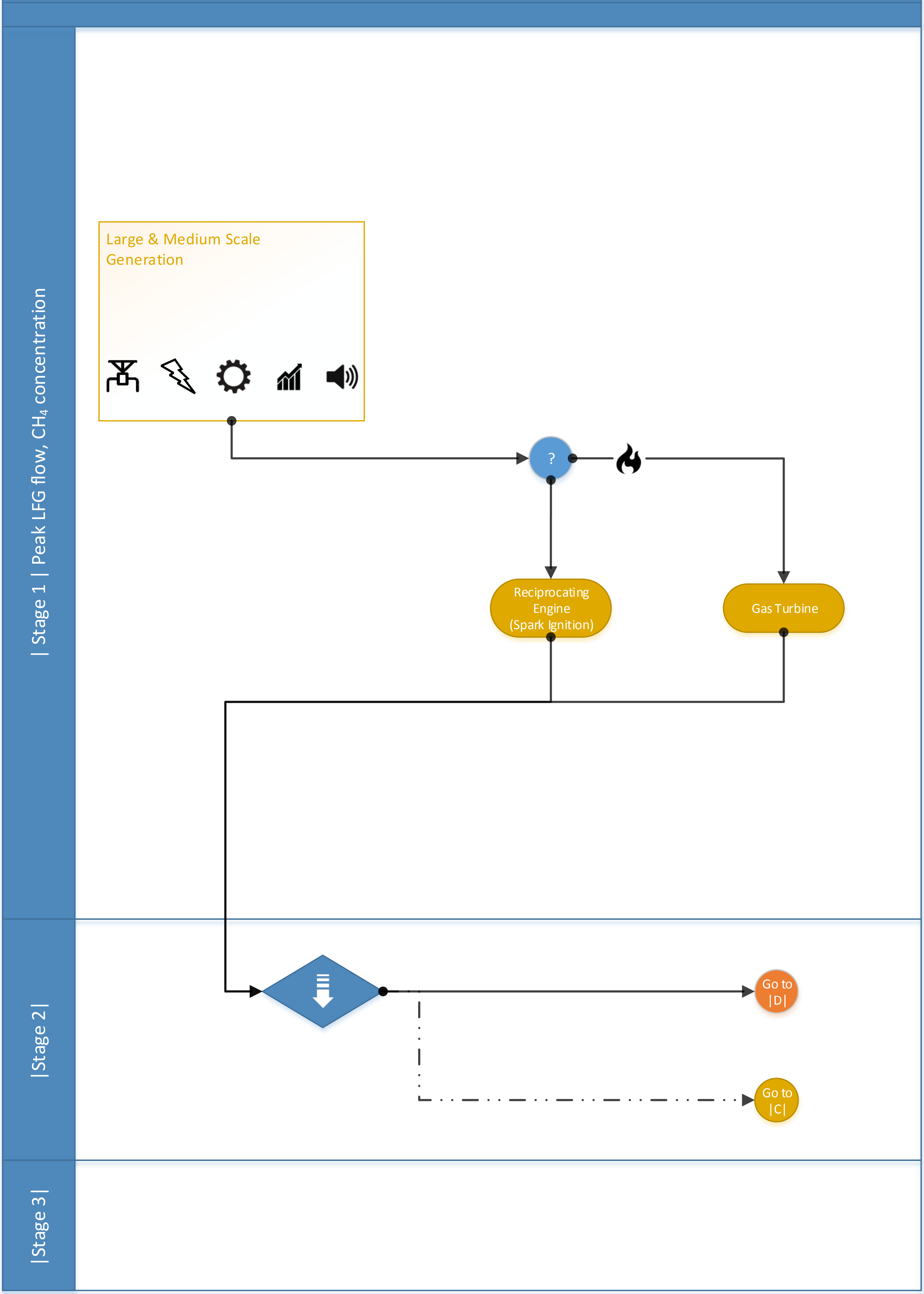
Air quality

🔊 Noise nuisance

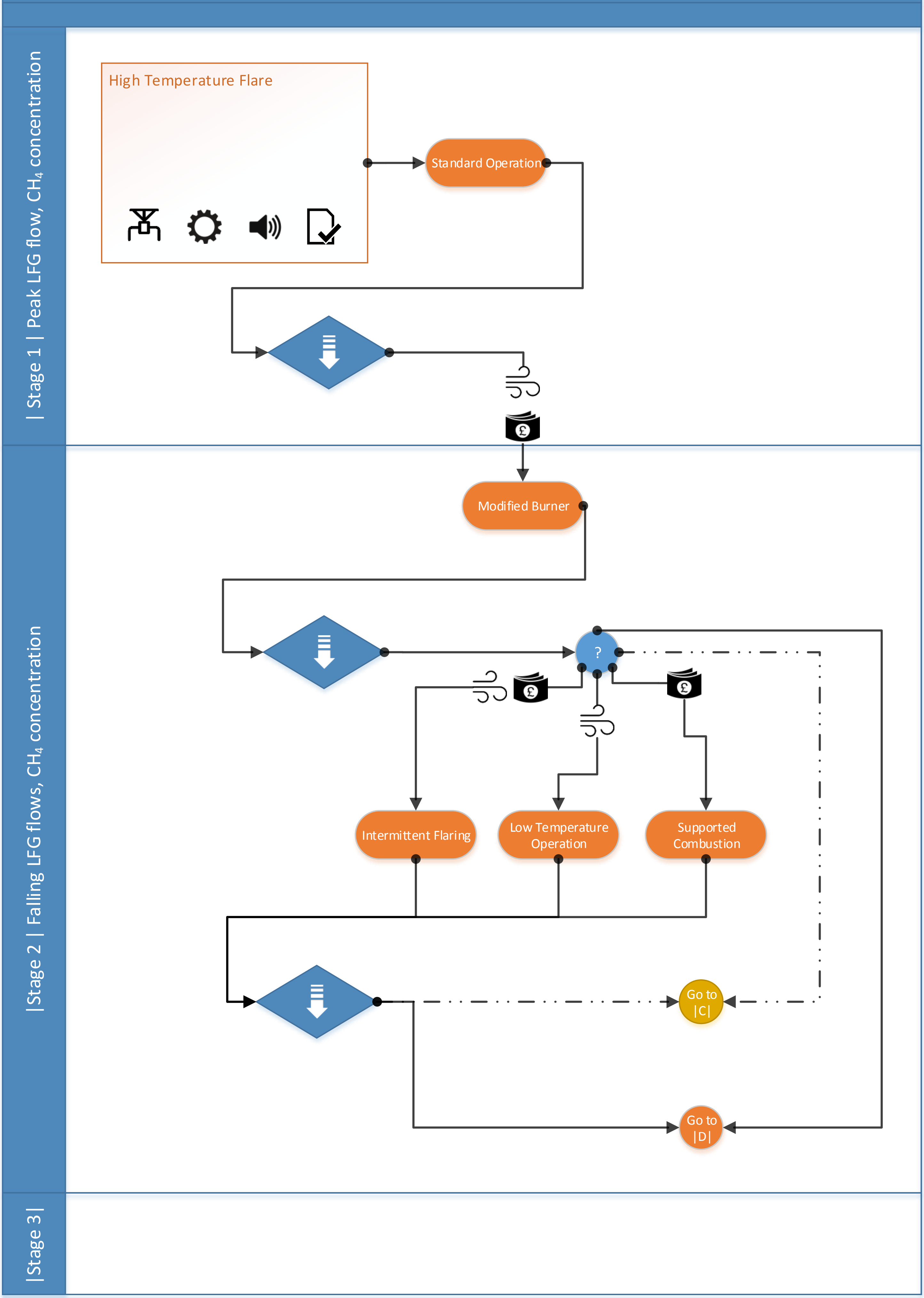
Odour nuisance

✓ Regulatory requirement

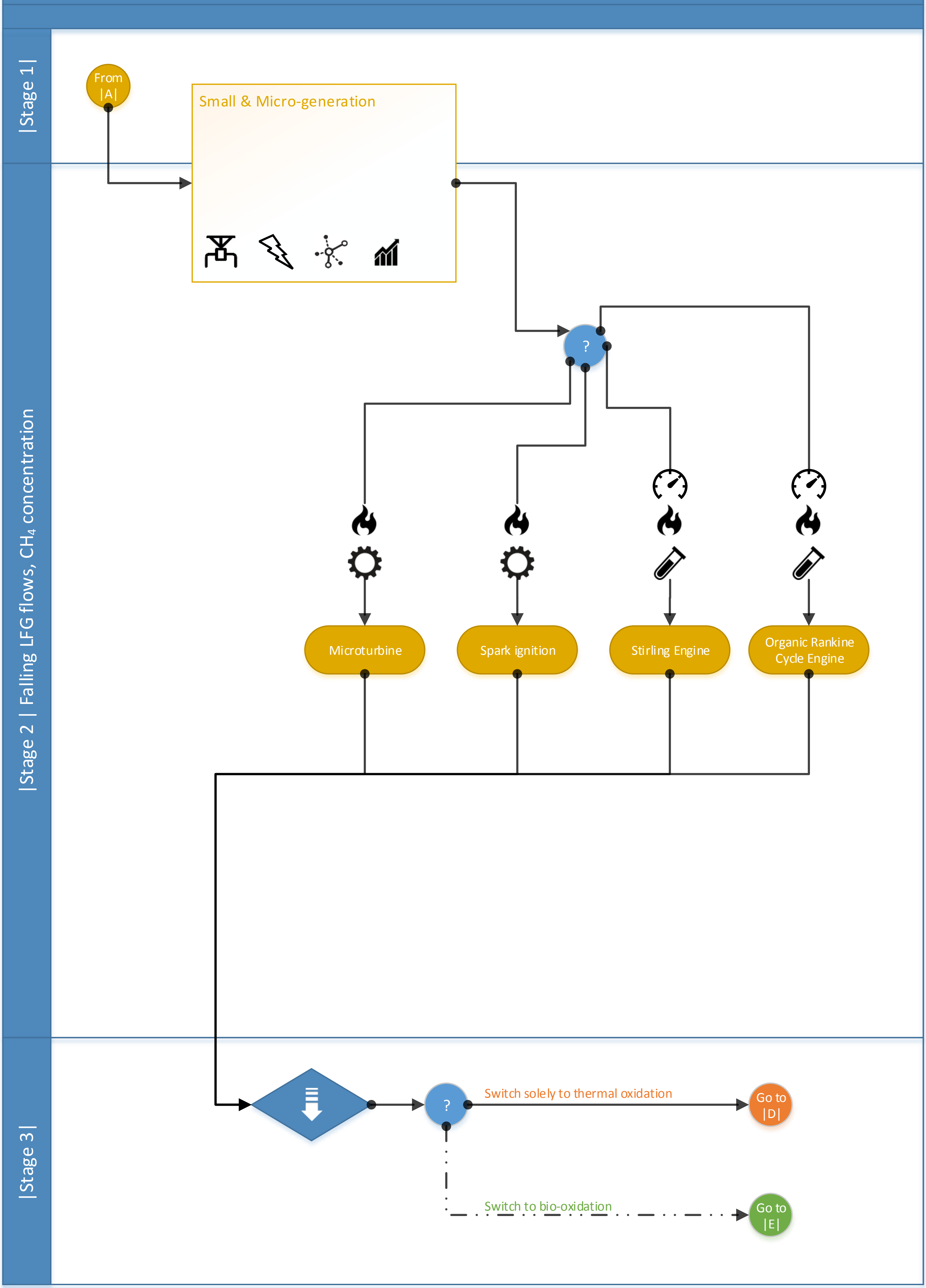
Flowchart |A| Large Scale Generation



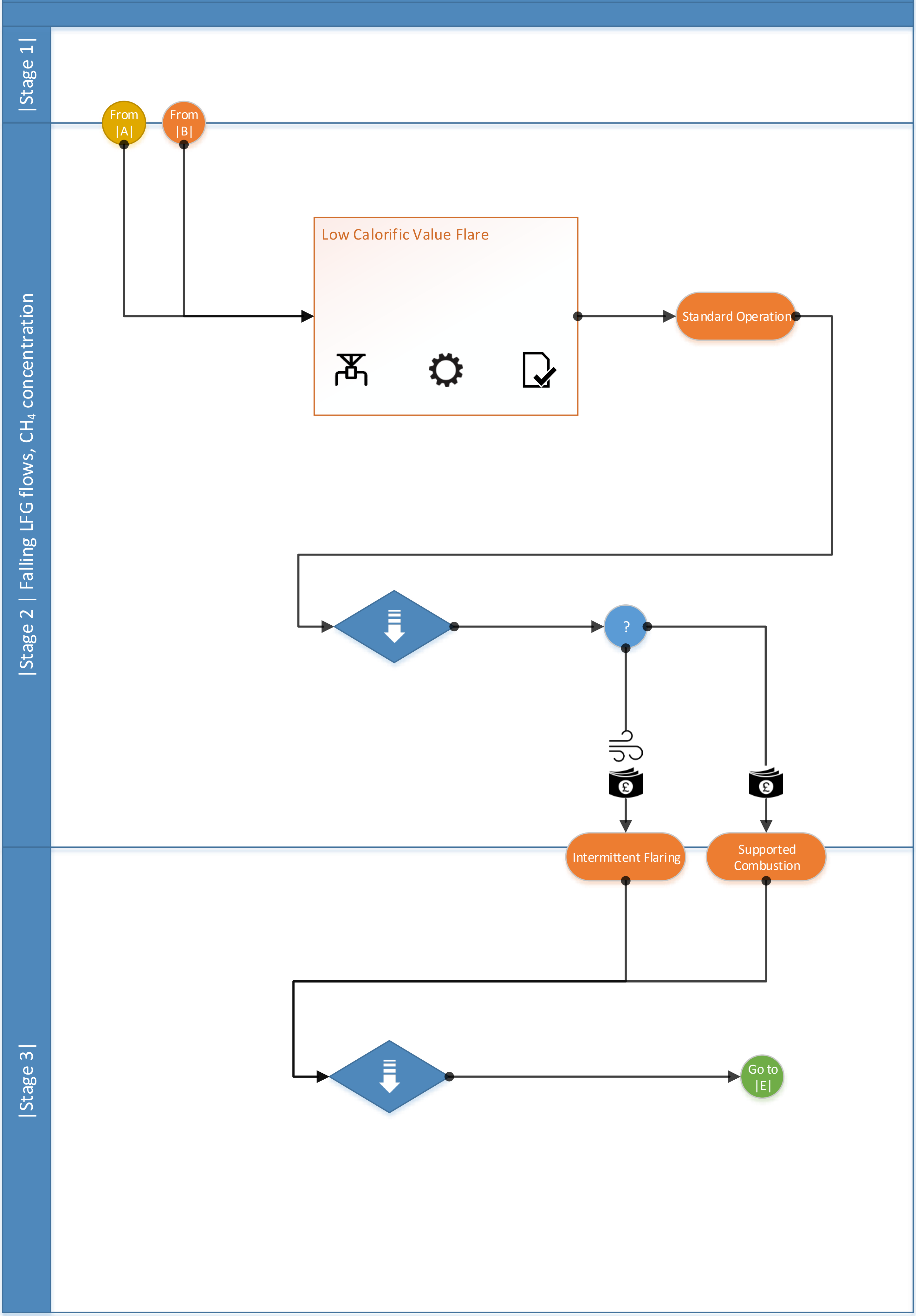
Flowchart |B| High Temperature Flare



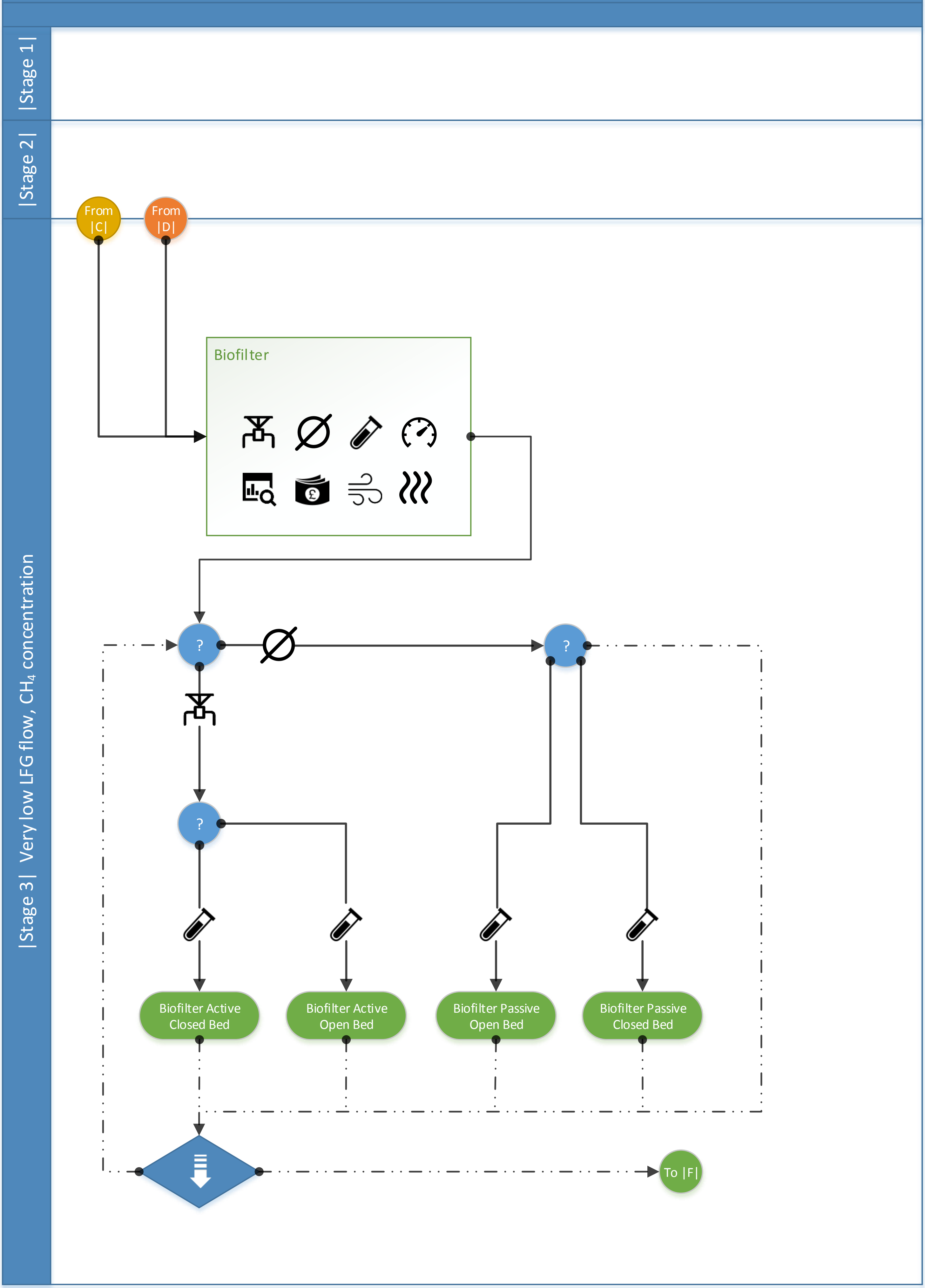
Flowchart |C| Small and micro generation



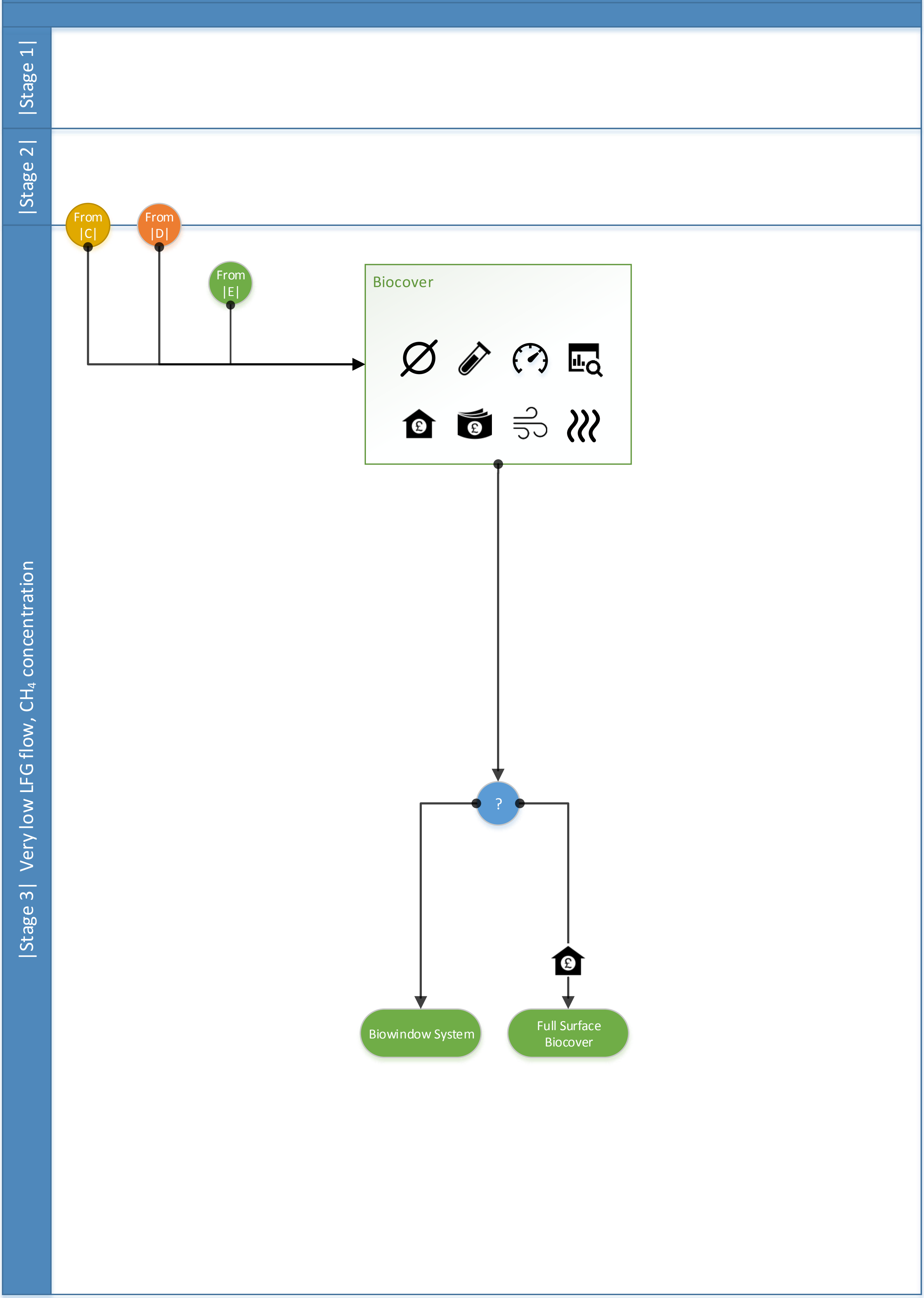
Flowchart |D| Low Calorific Value Flare



Flowchart |E| Biofilter



Flowchart |F| Biocover



Would you like to find out more about us or about your environment?

Then call us on
03708 506 506 (Monday to Friday, 8am to 6pm)

email
enquiries@environment-agency.gov.uk

or visit our website
www.gov.uk/environment-agency

incident hotline 0800 807060 (24 hours)
floodline 0345 988 1188 / 0845 988 1188 (24 hours)

Find out about call charges: www.gov.uk/call-charges