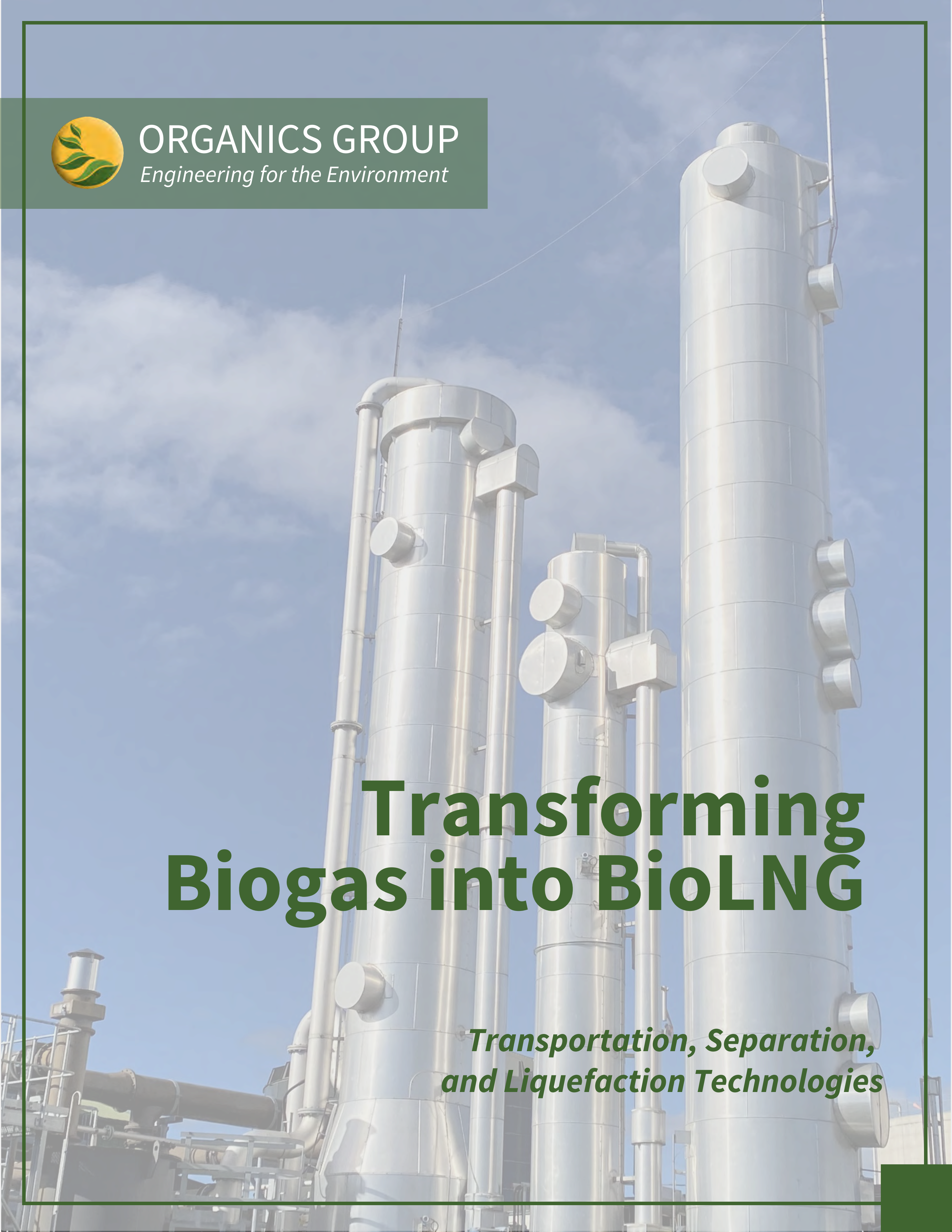

ORGANICS GROUP

Engineering for the Environment

Transforming Biogas into BioLNG

Transportation, Separation, and Liquefaction Technologies

EXECUTIVE SUMMARY

There is a great deal of interest in using biogas as a fuel away from the point of production. As a renewable energy, it will help with environmental sustainability, as well as introducing potential economic benefits. Having decided to consider transporting biomethane offsite, the next issue is to determine how best this may be accomplished.

In an urban environment the choice of using liquid gas or compressed gas transport is relatively straightforward. It is a function of vehicle miles versus capital and operating costs. In remote locations, where roads may be unsurfaced and often impassible due to rain, the decision becomes more complex. The question of maximum size of road transport vehicles, for example, will become more pertinent. A full-length cryogenic trailer carrying 16 tonnes of liquid gas may make economic sense but if it regularly becomes bogged down on plantation roads, the economic calculus will fail.

It is a simple fact that the locations where biomethane can be produced in large quantities in Indonesia are often well away from a surfaced road network. This leads to the conclusion that smaller trailers and trucks would be preferable, also possessing a reinforced chassis. Trailers built for surfaced roads often sacrifice chassis-strength for weight savings, to facilitate carrying more payload.

There are no hard and fast rules concerning liquid versus compressed gas transport. Using liquid will reduce vehicle miles by around 60%, but liquid gas production equipment costs will generally be greater

A rule of thumb sometimes used is that over 200 km liquid would be more economical. The quality of the road network will impact that assessment.

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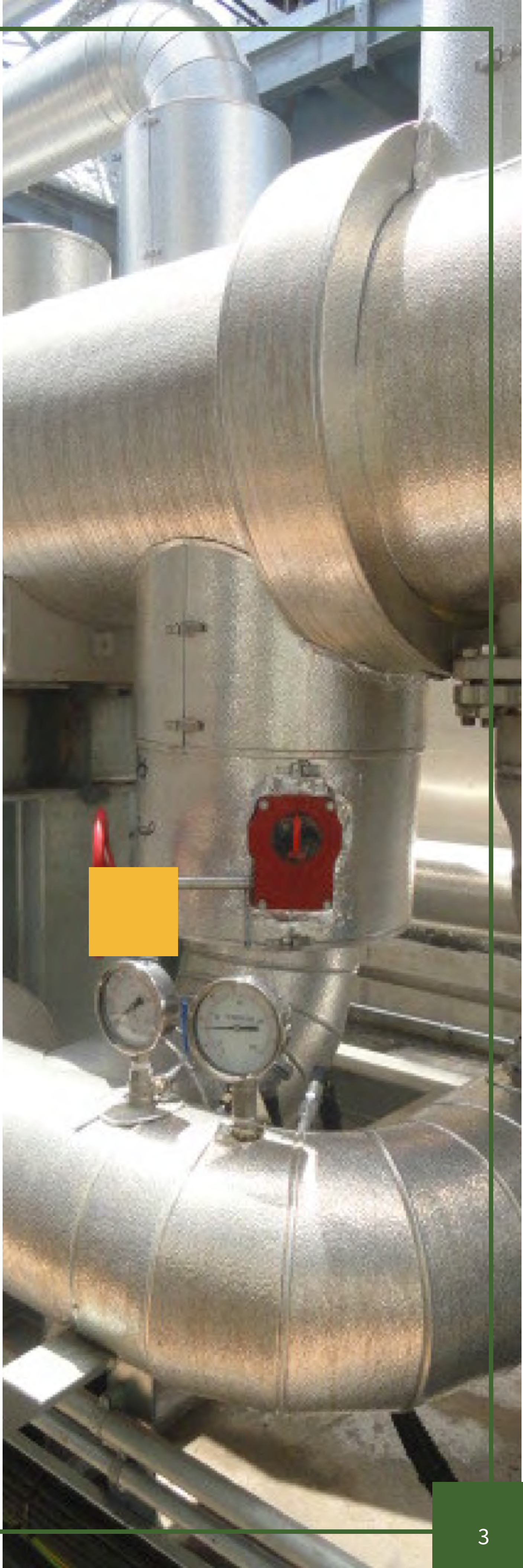


BioLNG vs BioCNG

Choosing between liquid bio-methane, referred to here as BioLNG, and compressed bio-methane, referred to as BioCNG, for storage and transport is an important decision for producers of biogas wishing to transport their gas by road. Some factors which need to be taken into account are:

1. Economic Viability: While a full-length cryogenic trailer carrying 16 tonnes of liquid gas might seem economically sensible, it becomes impractical if it frequently gets stuck on difficult plantation roads.

2. Volume Efficiency: Liquid methane has a higher energy density by volume than compressed methane. BioLNG occupies about 40% of the volume of BioCNG making BioLNG a superior choice for applications where storage space is limited, such as in marine shipping or long-haul trucking.

3. Transportation Costs: The reduced volume of BioLNG translates to fewer trips needed for the same amount of methane.

4. End-Use Applications: BioLNG may be preferred for industrial applications requiring large, continuous volumes of methane once re-gasified. Conversely, BioCNG is often more suitable where compression and dispensing infrastructure is already established, for shorter distances, or for lighter-duty vehicles and urban settings with frequent fuelling stations.

5. Boil-off Issues: BioCNG can be a better choice for long-term storage due to reduced boil-off issues compared to BioLNG. A BioLNG storage vessel can lose as much as 1% per day, meaning it could be entirely depleted after about three months

Rule of Thumb

While there are no rigid rules, a common guideline suggests that BioLNG may be more economical for distances over 200 km, though the quality of the road network will significantly impact this assessment. The production equipment costs for liquid gas are generally higher, but the reduced vehicle miles (around 60%) can offset this.

BIOGAS SEPARATION

The production of biomethane from biogas involves the primary requirement of removing carbon dioxide and hydrogen sulphide from biogas. Occasionally it will also be necessary to remove oxygen and nitrogen, where these cannot be controlled upstream.

The main separation technologies employed globally include:

- Water scrubbing
- Chemical absorption
- Pressure swing adsorption (PSA)
- Membrane separation
- Cryogenic separation
- Various combinations of the above processes

No single "best" solution exists; the optimal technology choice is driven by the specific circumstances of each situation.

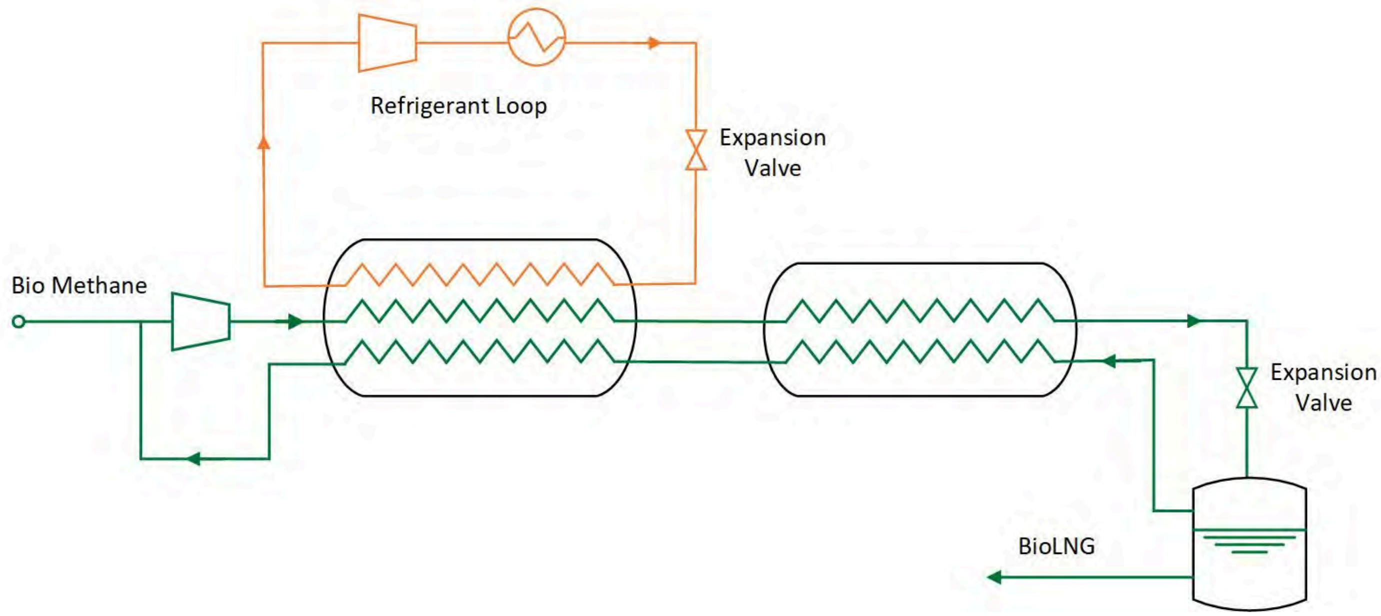
Common Ancillary Processes
Most biogas separation systems incorporate certain common elements:

Bioscrubbers: These are used for hydrogen sulphide removal and offer relatively low capital and operating costs. A properly operated bioscrubber can reliably reduce hydrogen sulphide to low levels from typical biogas concentrations.

Chillers: Required for biogas dewatering and drying, as biogas is typically saturated with water from its production process.

Carbon Filters: These can act as gas polishing units, removing residual hydrogen sulphide and other trace gases like siloxanes that could negatively impact downstream performance.

LINDE-HAMPSON CYCLE



The Linde-Hampson Cycle is a cryogenic process often used for the liquefaction of gases, particularly gases with very low boiling points such as hydrogen, helium, and neon. What makes it special is its simplicity and effectiveness in achieving very low temperatures.

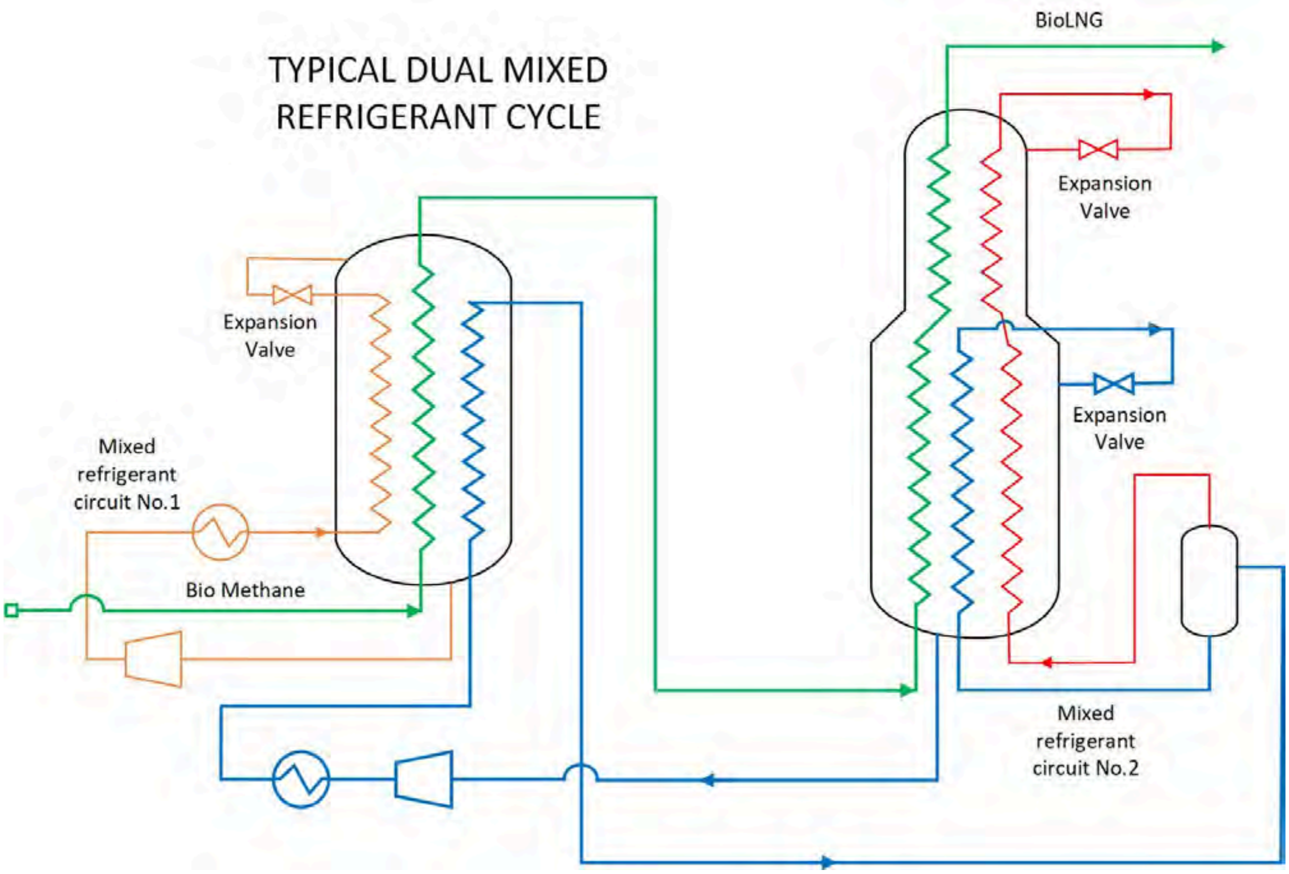
The cycle operates on the principle of isentropic expansion and compression of a gas, followed by heat exchange with a counterflowing stream of the same gas. The stages involved are:

1. **Compression**: The gas is initially compressed to a high pressure, which increases its temperature.
2. **Heat Exchange**: The high-pressure gas then passes through a heat exchanger where it loses heat to a counterflowing stream of the same gas that has already undergone expansion. This cooling process pre-cools the gas before it enters the next stage.
3. **Expansion**: The pre-cooled gas is expanded through a throttling valve or an expansion turbine, causing a significant drop in temperature due to the Joule-Thomson effect. This rapid expansion further cools the gas and creates a liquid.
4. **Recompression**: Expanded and cooled gas which did not liquify returns through the heat exchangers, cooling incoming gas, after which is recompressed, raising its pressure and temperature again.

While the Linde-Hampson Cycle is an effective method for achieving low temperatures and liquefying gases, it does have some drawbacks:

1. **Energy Consumption**: The cycle requires significant energy input for compression and recompression stages.
2. **Complexity at Low Temperatures**: At extremely low temperatures, achieving efficient heat exchange becomes more challenging. Special materials and insulation may be required to prevent energy losses.
3. **Equipment Cost**: The compressors, heat exchangers, and other equipment needed for the Linde-Hampson Cycle can be expensive to purchase, install, and maintain.
4. **Limited Efficiency**: While the Linde-Hampson Cycle is effective for liquefying gases, it may not be the most efficient method for all applications.

MIXED REFRIGERANT CYCLE



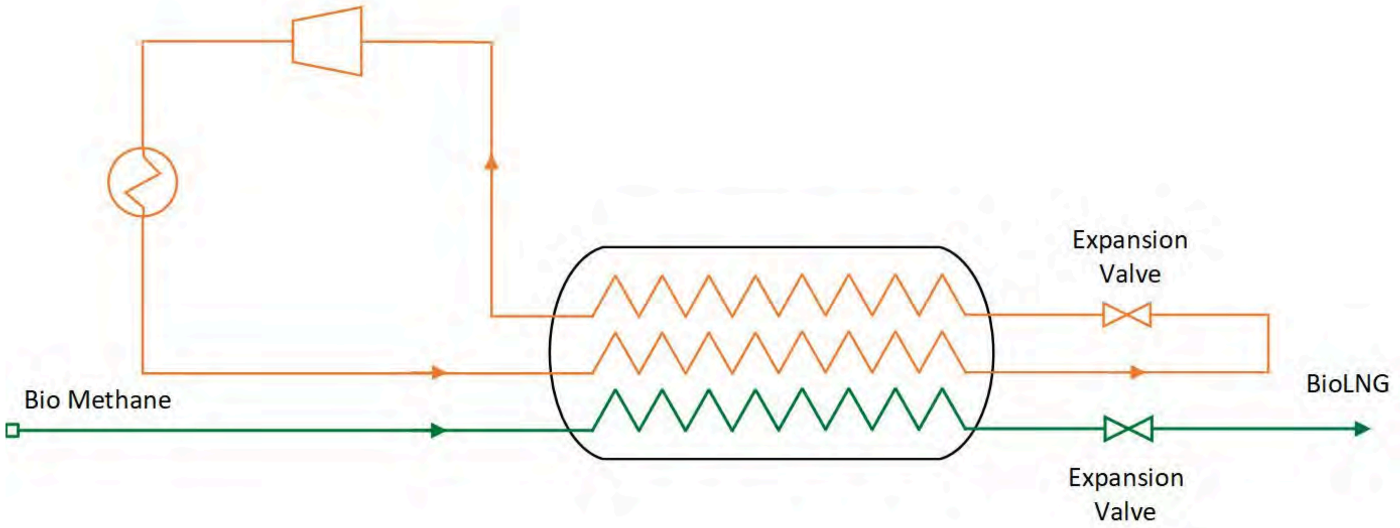
The Mixed Refrigerant Cycle involves a blend of multiple refrigerants circulating through the system to achieve the necessary cooling for liquefaction. What makes the Mixed Refrigerant Cycle special is its ability to optimise the cooling process by utilising the thermodynamic properties of various refrigerants.

There are many variations of each cryogenic cycle. In the one shown here the biomethane flow is shown in green. The orange line represents the first refrigerant circuit. The blue line represents the second refrigerant circuit and the red line a final refrigerant loop out of the second refrigerant. The biomethane is progressively cooled until be exits as a liquid. Expander valves combined with compressors are used to drive the refrigeration.

The Mixed Refrigerant Cycle has several drawbacks one should be aware of:

1. **Complexity**: MRCs can be complex due to the need to manage multiple refrigerants with different characteristics. This complexity extends to the design, operation, and maintenance of the system.
2. **Higher Initial Cost**: Implementing an MRC typically involves higher initial capital costs compared to simpler refrigeration cycles. The need for multiple refrigerants, additional equipment such as separators and heat exchangers, and more intricate control systems can contribute to increased upfront expenses.
3. **Energy Consumption**: The use of multiple refrigerants may result in higher energy consumption compared to single refrigerant systems.
4. **Maintenance Challenges**: Regular monitoring, inspection, and servicing of multiple components are necessary to ensure optimal performance and reliability.
5. **Potential for Refrigerant Interactions**: Proper selection and management of refrigerant blends are essential to mitigate these risks.

SINGLE MIXED REFRIGERANT CYCLE



The Single Mixed Refrigerant (SMR) Cycle and the Mixed Refrigerant Cycle are both used in natural gas liquefaction processes, but they differ in their approach to refrigeration. The Single Mixed Refrigerant Cycle uses only one mixed refrigerant blend throughout the entire liquefaction process. In contrast the Mixed Refrigerant Cycle involves the use of multiple refrigerants blended together, each serving a specific purpose, operating in different stages of the liquefaction process.

In the Single Mixed Refrigerant Cycle, a mixture of refrigerants is selected based on their individual thermodynamic properties such as boiling points, heat capacities, and thermal conductivities. This blended refrigerant is designed to provide efficient heat exchange and temperature reduction within the cryogenic heat exchangers, optimizing the liquefaction process.

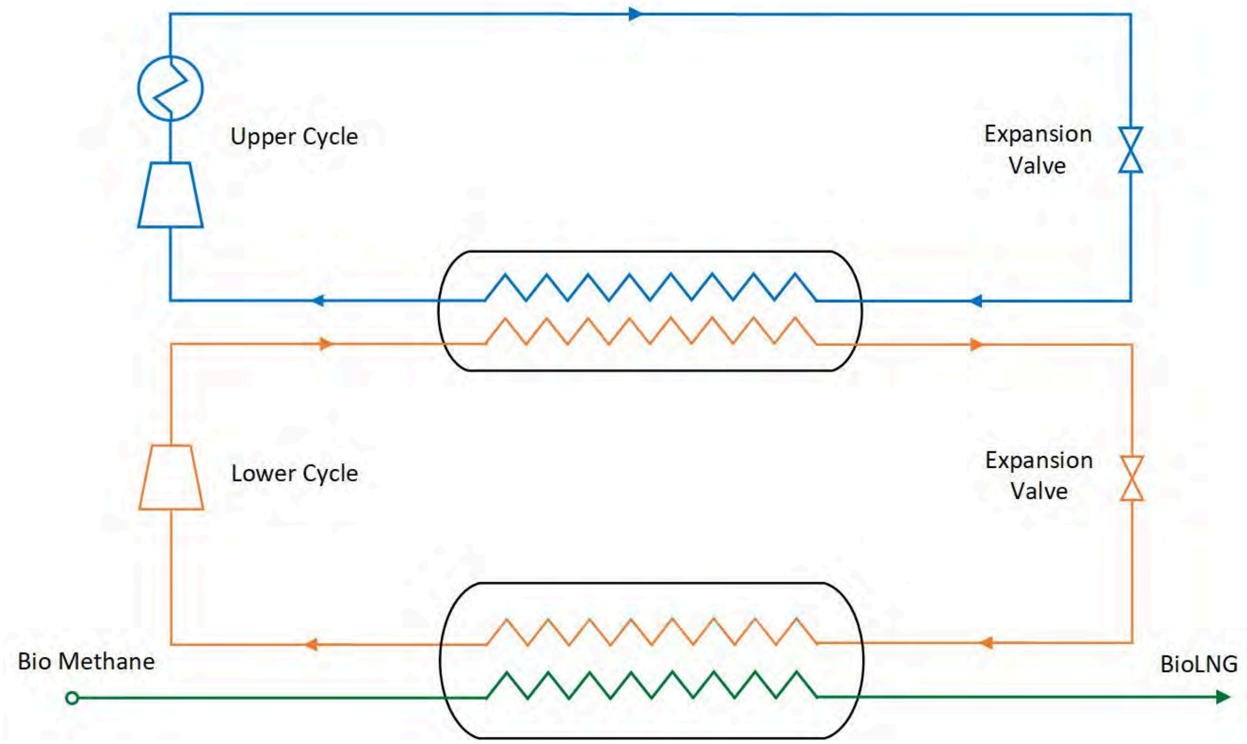
In the cycle shown here, a single refrigerant circuit is used to cool the condenser, with expander valves on both the refrigerant circuit and the biomethane circuit driving the cryogenic cooling.

The SMR cycle's uniqueness lies in its simplicity and efficiency. By utilizing a single mixed refrigerant rather than multiple separate refrigerants or cascading systems, it reduces complexity, equipment footprint, and operational costs. This streamlined approach enhances reliability, reduces maintenance requirements, and improves overall process efficiency.

While the Single Mixed Refrigerant (SMR) Cycle offers several advantages, it also has some drawbacks:

1. **Complex Refrigerant Composition**: Designing the optimal composition of the mixed refrigerant blend can be challenging. The selection and blending of refrigerants must consider their individual properties and interactions to ensure efficient cooling and liquefaction.
2. **Limited Flexibility**: The SMR cycle relies on a single mixed refrigerant blend throughout the liquefaction process. While adjustments can be made to optimize performance, such as changing the composition or circulation rate, the cycle may have limited flexibility compared to other refrigeration methods.
3. **Performance Sensitivity to Composition**: The efficiency and performance of the SMR cycle can be sensitive to changes in the composition of the mixed refrigerant blend. Small variations in the composition or impurities in the refrigerants can affect the cooling capacity and overall process efficiency, requiring careful monitoring and maintenance.

CASCADE CYCLE



The Cascade Refrigeration Cycle involves two (as shown here) or more separate refrigeration cycles operating at different temperature levels, with each cycle utilising its own refrigerant. The first cycle, referred here to as the Lower Cycle, is used to provide cooling to the second cycle. The second cycle, or Upper Cycle, reduces the refrigerant to the temperature required to condense, or liquefy, the biomethane.

In this cycle, refrigerants with different boiling points are used in each stage, allowing for sequential cooling as the refrigerant passes through the stages. The refrigerants are selected based on their compatibility with the desired temperature range and their ability to efficiently absorb and release heat at specific temperature levels.

The Cascade Refrigeration Cycle offers improved control over temperature gradients and reduces the risk of refrigerant leakage compared to single-stage systems. The Cascade Refrigeration Cycle, while effective for achieving very low temperatures, has several drawbacks:

1. **Complexity**: Cascade refrigeration systems can be more complex compared to single-stage refrigeration systems. They require multiple separate refrigeration cycles operating at different temperature levels, each with its own compressor, condenser, and evaporator.
2. **Higher Initial Cost**: Implementing a cascade refrigeration system typically involves higher initial capital costs compared to single-stage systems. The need for multiple compressors, heat exchangers, and control systems increases upfront expenses.
3. **Efficiency Challenges**: While cascade systems are effective for achieving very low temperatures, their efficiency can be lower compared to single-stage systems, especially at higher temperature differentials between stages.
4. **Refrigerant Management**: Each refrigerant used in the different stages must be compatible with the temperatures and pressures encountered, and precautions must be taken to prevent cross-contamination or refrigerant leaks.

SIAD Macchine Impianti

SIAD Macchine Impianti contributes to the BioLNG and LNG markets by providing a range of liquefaction plants and services. The company offers three main types of liquefaction plants, categorized by tonnage:

- SMART LIN LNG: Smaller size, producing 1 to 5 tons per day. It is based on nitrogen evaporation from a liquid nitrogen storage tank, offering very low electrical consumption. This technology uses liquid nitrogen at cryogenic temperatures to liquefy feed gas inside a plate-fin heat exchanger within a cold box to increase thermal efficiencies. The layout is skid-mounted, making it very simple.

- SMART DCE LNG: Middle size, based on the direct compression and expansion Linde cycle. Its capacity ranges from 5 to 15 tons per day through a single module, with a turndown between 60% and 100%. Specific electrical consumption is typically in the range of 0.55 to 0.7 kWh per kilogram of LNG produced. The standard LNG output is at 3 bar gauge and approximately -150 degrees Celsius. This cycle, also known as the Joule-Thomson expansion cycle, uses methane or biomethane as the refrigerant fluid, reducing electrical consumption and eliminating the need for an external refrigerant. The process involves three steps: compression, pre-cooling, and liquefaction.

- SMART TB LNG: Larger size, ranging from 10 tons per day up to 600 tons per day, based on the Brayton-Joule cycle.

Scales of application

The BioLNG and LNG industry is typically covered by three plant scales:

Nano-scale: Below 10 tons per day. Common cycles include Linde cycles (SMART DCE) and cryogenic liquid vaporization (SMART LIN).

SMART-LIN has a very low electricity consumption primarily due to the use of liquid nitrogen for methane liquefaction, with the minimal electrical consumption being related to the use of vaporisers.

SMART DCE's electricity consumption is linked to the reciprocating compressor compressing the feed gas. The Linde cycle is similar to SMART DCE. The Stirling cycle, by way of comparison, has a high specific electricity consumption, over 35% higher in kWh/kg compared to the Linde cycle. The Linde cycle also has a lower CAPEX due to fewer machines involved.

Micro-scale: Below 75 tons per day. The Brayton-Joule cycle often finds its best application in terms of specific power consumption for this size.

The Single Mixed Refrigerant cycle has the lowest specific electricity consumption but the highest CAPEX due to multiple hydrocarbon gas circuits.

The Brayton cycle technology offers a lower CAPEX due to its nitrogen cycle, with specific power consumption typically 3% higher than single mixed refrigerant.

The high-pressure Linde cycle is not typically applied at this scale.

Small-scale: Below 500 tons per day. Both the Brayton cycle and mixed refrigerant cycles are well-suited for this scale.

Conclusion

The conversion of biogas into BioLNG presents a viable pathway for utiliaing this renewable energy source more broadly. The decision to transport biomethane as a liquid or compressed gas hinges on a careful assessment of transport distance, road conditions, economic factors, and end-use applications. Furthermore, the selection of appropriate biogas separation technologies and cryogenic liquefaction cycles is paramount. While each liquefaction cycle (Linde-Hampson, Mixed Refrigerant, Cascade, and Single Mixed Refrigerant) offers distinct advantages and drawbacks, the most suitable choice will depend on specific project requirements, economic considerations, and desired operational complexities.

Understanding these nuanced aspects is crucial for optimizing the production and distribution of BioLNG, thereby contributing to a more sustainable energy future.