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Space grade Biomethane production for Themis reusable stage demonstrator

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Abstract
The article presents the trade-off for the production of the space grade methane required for space and non-space users in French Guiana and especially the mid-term project of Themis reusable stage demonstrator. The users specifications and required process elements are described, alternative technologies presented and traded with respect to environmental, cost, operations and technical complexity aspects allowing to define the preliminary strategy to be adopted by CNES in aim to create the whole methane based circular economy branch in French Guiana.

1. Context

During the last decade numerous projects of methane/oxygen space engines have been undertaken in the world. The trade-offs that were performed indicated the advantages of those propellants with regards to the existing state of art of LOX/LH2 or LOX/kerosene engines, such as simpler propulsion systems leading to production and exploitation cost reduction, better reliability and improved safety. One of the elements of that trade-off concerns the industrial and technological maturity of propellants production means which impact cost performance and environmental issues.

There are many exogenous factors impacting the availability of both methane itself and its possible sources, not limited just the technical aspects of production but also including logistic of providing the propellant in French Guiana and

Up to now, 3 families of launchers were exploited in French Guiana Space Center: Ariane 5, Vega and Soyuz. The approaching first flight of Ariane 6 and Vega C will mark the turning point as Ariane 5 exploitation approaches its end.

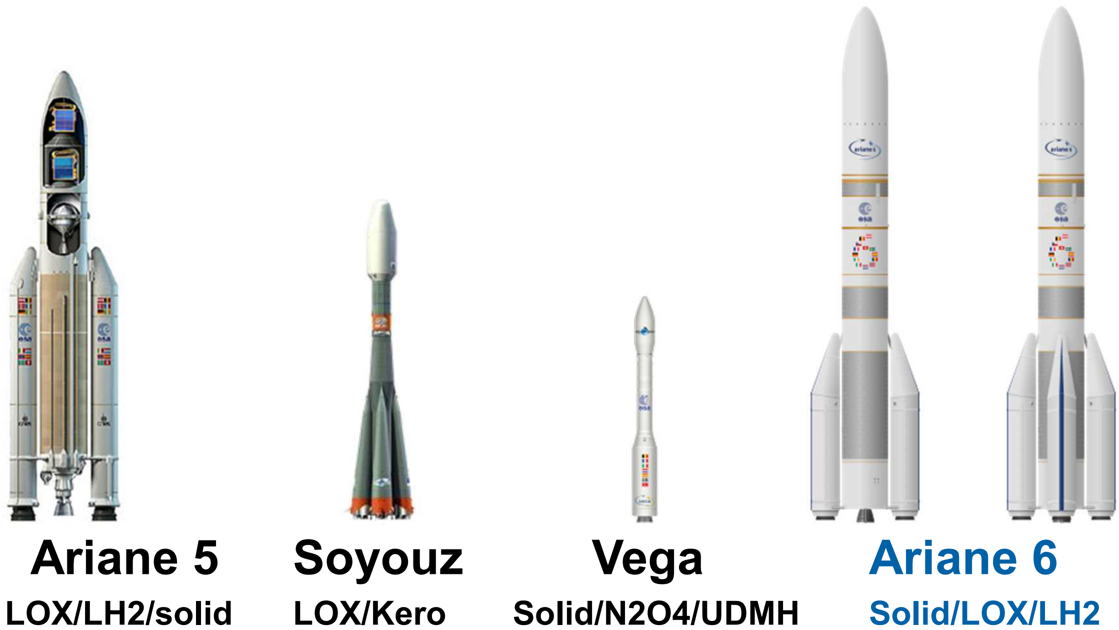

Figure 1: Launchers in Guiana Space Center

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The future launchers architecture (heavy or small launchers) will give priority to mono-propellant configuration which will exclude or strongly limit some of past propellant architectures. Current reference of solid/liquid launchers such as Ariane 5 will strive towards two extreme evolutions:

- Solid launchers, like planned Vega Evolution that will streamline the simplicity of stacked solid stages operations and smaller LOX/LCH4 stage for precise orbital operations. It also allows to abandon certain of toxic propellants used up to now, such as UDMH, Hydrazine derivatives.
- All liquid launchers striving to develop the reusability capability: That is a follow up of Themis demonstrator described in [1]

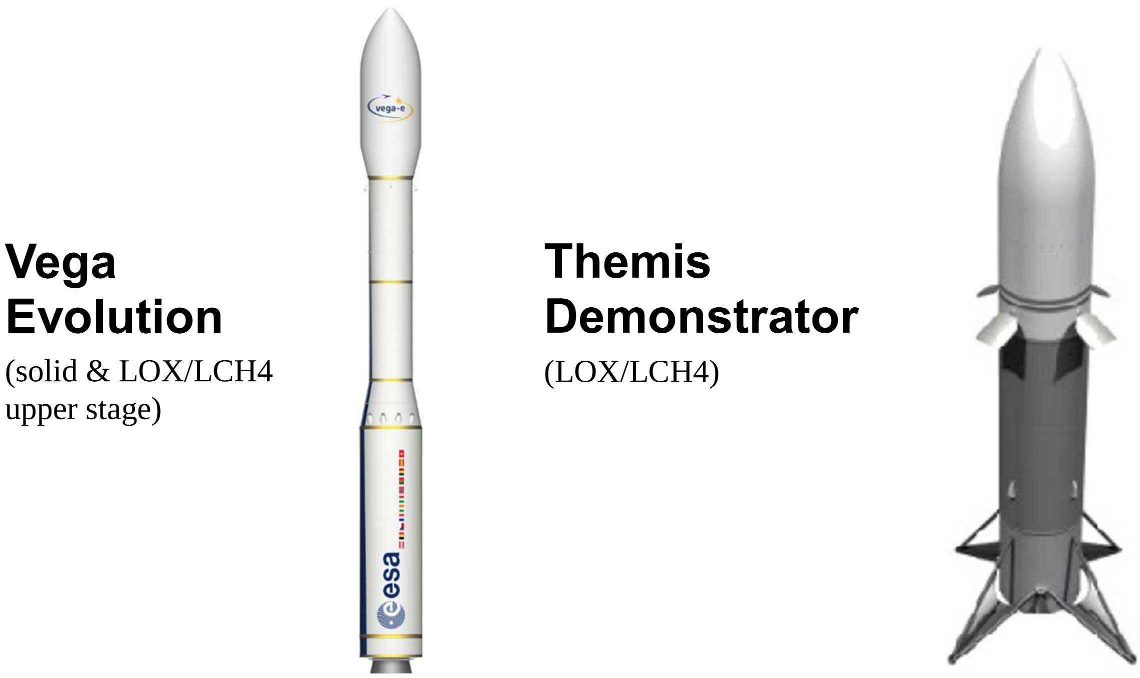

Figure 2: Planned LCH4/LOX launchers in CSG

Both of those families consider the cryogenic methane as the reference configuration for future propulsion since it allows a higher storage temperature than hydrogen, it is closer to the one of liquid oxygen and therefore allows to limit design and operational costs. However, classical methane production processes highlight a strong environmental impact due to the exploitation of a fossil energy. Moreover, with fossil methane hypothesis, Natural Gas needed to produce methane has to be imported while no NG network is available in French Guiana.
These issues have led to analyze the opportunity of implementing a local biomethane production source.

Historically that pre-project takes place since 2016 with different partners:

- 2017: ENGIE study about CH4 for future launchers identifying scenarios relying on fossil methane commercial supply leads to a low production cost (OPEX) but with strong impacts on environmental criteria: it demonstrated the interest of looking for local sourcing in French Guiana.
- 2018: Decision to initiate two feasibility studies about bio methane production scenario with ENEA Consulting and AIR LIQUIDE associated to ANTEA. The two companies proposed a solution based on anaerobic digestion from an input mix of waste and energy cultures.
- 2019: Call for tender for the implementation of a preliminary project of bio methane unit dedicated to THEMIS demonstrator in French Guiana. Two partners are selected: NASKEO for anaerobic digestion and AIR LIQUIDE for purification/liquefaction. CNES was also supported by ENEA consulting for environmental expertise and SIMA-PECAT for local agronomy expertise in French Guiana.
- 2020: End of preliminary project
- 2021: Beginning of phase B (pre-development) anaerobic digestion unit called BIFROST (Bio-Fuel for Rocket Operations in Space Transportation)

In 2022 the BIFROST Definition Key Point was held and confirmed interest of the project. Formal call for tender will be launched before the end of 2022. Other solutions than the one presented in the pre-project will also be able to answer to that call.

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2. Requirements of the target users

There are several target users for methane which have variable requirements in terms of quality, quantity, availability of the propellants.

2.1 Propellant quality

The project aims to provide the compact installation that is able to provide the methane propellant for a prospective, reusable launcher, passing through the first step in form of Themis demonstrator reusable stage [1]. It aims to perform this production with a stringent availability of propellant that is compatible with important launch rate up to 10 launches per year and to provide the propellant with the quality level that is compatible with the space propulsion system (« Grade A MIL-PRF-32207 ») as depicted below:

Table 1: LCH4 quality requirements

LCH4 quality requirements	Grade A MIL-PRF-32207
Purity (CH4), %Vol, min	98.7
Ethane (C2H6), ppmV, max	5,000
Propane (C3H8), ppmV, max	3,000
Total Sulphur volatile, ppmV, max	1
Nitrogen, ppmV, max	5,000
Carbon Dioxide, ppmV, max	125
Water, ppmV, max	1

2.2 Launch manifest and rate

The growth potential of methane production capacity is required for subsequent bigger launch systems which will have the propellant needs corresponding to the high launch rate exploitation of systems both reusable or not going from less than 4 launch campaigns in 2025 up to 5 to 10 launch campaigns in 2030 potentially for at least two different launcher families including Themis demonstrator and subsequent space launcher, Maia as well as Vega Evolution and derivatives. Other microlaunchers appearance cannot be ruled out following the appearance of numerous startups such as Sirius Space Services [4].

The subsequent projection of launch manifest and time periods between two launches for further years serves to dimension the logistics of methane provision up to the launch pad.

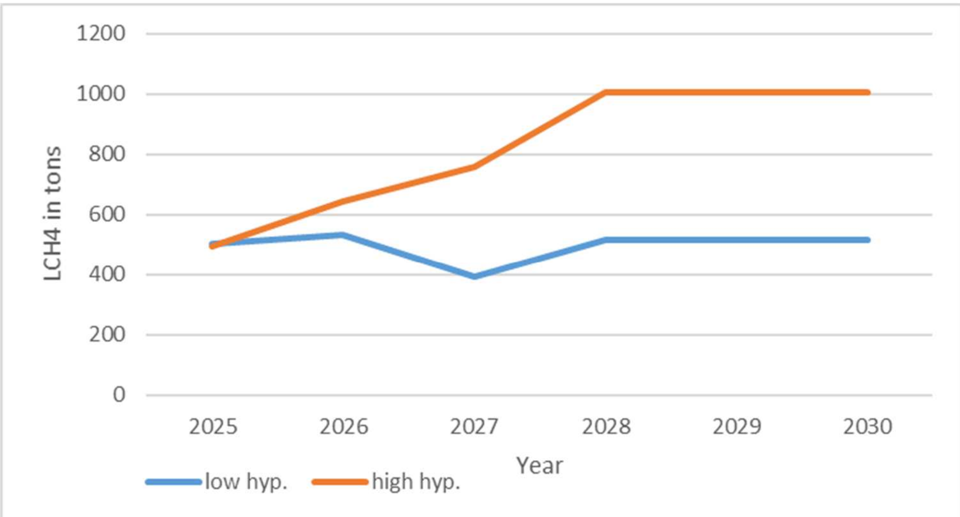

Figure 3: LCH4 yearly quantity requirements

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Whatever is the actual solution chosen for production of methane the storage part of the logistic process is mandatory on Launch Complex site. The discontinuity in the product consumption by the launch campaigns adds the difficulty for the providers of methane: by its nature, the launcher consumption is a punctual event consuming important quantities, with important margins to account for the delayed chronologies (above two times of net launcher propellant need). It is inevitable taking into account the exogenous aspects of launch manifest construction (impact of other launchers families not using methane, such as Ariane 6, anomalies on different parts of the launch system (payload satellite, launcher, ground segment…). Thus the storage tanks and associated process need to be implemented in parallel of the methane sourcing organization in such a way that the product could be available on time for future launch campaigns of Themis and other launchers foreseen starting from 2025.

2.3 Other space users

The other space users of methane could be Orbital applications providers, such as Exploration Company [5], that plans to perform the long haul missions to the moon and in-orbit servicing using an orbital module capable of cryogenic LOX/LCH4 propulsion.

There is also an opportunity to reform the methane into “blue hydrogen”, that could be used by LOX/LH2 launchers such as Ariane 6 instead of currently used “grey hydrogen” produced from methanol reforming. Typically [10] demonstrates that the environmental impact of obtaining LH2 from biomethane is competitive with respect to other means, such as electrolysis with different technologies, while the financial cost is comparable with those technologies.

2.4 Non space users

The methane/ bio natural gas economy must be created in French Guiana to perpetuate its existence locally, independently from the erratic nature of space launch manifests, which might not be sufficient to create a sustainable business. Typically Themis demonstrator campaign will be limited in time (2025-2027). The other actors might face the development uncertainties delaying the entry in exploitation and ramp up of launch rate of their systems. Therefore methane sourcing business plan must take into account further possibilities of use:

- Beyond space applications the peripheral applications, such as energy cogeneration up to several MWh/year. The resulting energy could be used to improve the energy mix of Guiana Space Center with respect to its HVAC (heating, ventilation and air-conditioning) and industrial equipment needs or injected in French Guiana energy grid
- Commercial use of produced methane to address current local needs in French Guiana (bioGNL vehicles – public transportation and individual needs, household bottled gas)
- Fostering the emergency of local industry that would use methane for fabric, plastic and fertilizers production.
- Production of hydrogen by methane vapor-reforming.

2.5 CNES requirements

As a part of its environmental policy the CNES itself expects that the sourcing circuits of methane will provide the maximal independence from importation to French Guiana. The local production will be encouraged to diminish the environmental impacts and maximize the positive social and economic impacts on French Guiana. It is a project that is supposed to provide activity for local businesses, such as farmers or companies of waste treatment.

3. State of art in methane production

The state of art of methane production technologies shows the relative diversity of methods and raw materials required to obtain the final product, as it is demonstrated in subsequent sections. The basic process includes the following steps:

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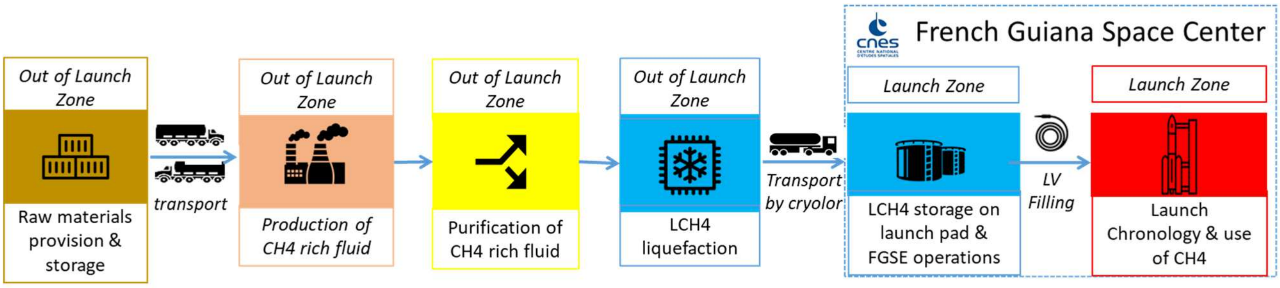

Figure 4: general concept of space grade LCH4 lifecycle

The comparison of that schema to currently used propellants, such as LH2 by methanol reforming were described in [2] and [3]. As the choice of methane is considered as a reference the subsequent chapters concern only methane production.

3.1 Importation of fossil LNG methane or biomethane from Europe

Initially that scenario seemed as the "natural" way of dealing with propellant problem, since it is the closest scenario to already existing methanol logistics [2]. The Fig. 5 illustrates one of the possible processes for the production of LCH4 from LNG (Liquefied Natural Gas) imported from Trinidad and Tobago. LNG must be transported by road and sea to the plant close to the launch site for transformation into LCH4.

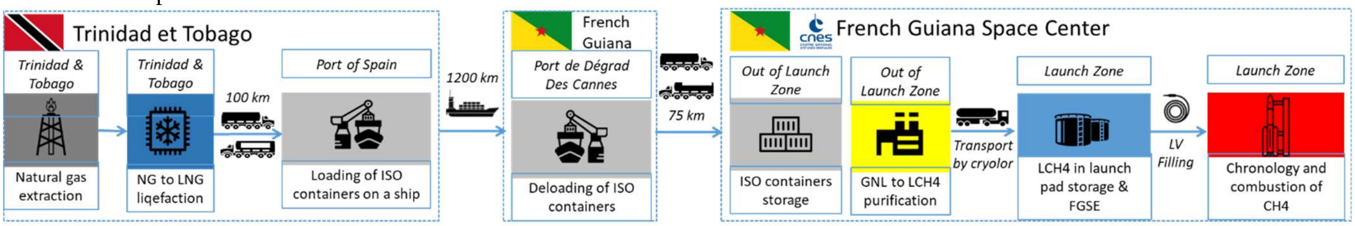

Figure 5: « gray » LCH4 production process from GNL

Alternative schemes to the one presented above have been analyzed from a legislative and safety point of view to have a comparative evaluation on the cost of obtaining LCH4. Typically, we have assessed the interest of setting up a gas pipeline between the port of Dégrad des Cannes (near Cayenne) and the launch site or even transporting the LNG by low-draft boat to the port of Pariacabo in Kourou (port not suitable for large container ships). These variants impact both the distances to be traveled (+75km for Dégrad des Cannes versus 20km for Pariacabo) with the various means of transport envisaged and the traffic on the RN1 national road in French Guiana.

They can also lead to regulatory maintenance requirements in the case of a gas pipeline or to the need for additional facilities if the LNG has to be gasified to transport it by gas pipeline and re-liquefy it on site. If using the Port of Pariacabo, consideration should also be given to the need to develop and maintain an entire dedicated transmission line and its offloading facilities. The financial costs of these alternative solutions have proven to be highly prohibitive (up to three times more than the reference scenario) and regulatory constraints must be added to them.

All of those scenarios have the disadvantage of targeting a segment of the LNG market that is not very attractive to industrial players. The quantity of propellant (which can reach a maximum of a few thousand tons/year depending on the launch rate) seems too high to be easily satisfied by the retail market (standard ISO-containers) but not enough to justify the implementation place of a dedicated shipping line using an LNG carrier. The other problem is the geopolitical impact of Russian war against Ukraine (and other potential conflicts) on the cost and availability of the LNG, showing that the political factors tend to impact heavily the availability of the LNG.

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Figure 6: Standard ISO container for LNG transport (12,2m x 2,4m x 2,6m ~18 tons of LNG) versus Cryolor tank

Another analyzed alternative was the production of bio LCH4 in Europe (already planned on a small scale for the testing of LCH4 engines, such as Prometheus) and its transport to Guyana. It appears that the transport distances are as great as for methanol currently used for LH2 production for Ariane 5 and that the quantities of propellant to be supplied in the case of industrial exploitation of launchers are several times greater than the needs for engine testing. Also it is not so easy to acquire the bio methane in sufficient quantity, as there is an important competition from other local European users (transportation, energy production, industry) for the same raw material. The ecological impacts of LNG or even biomethane solution are not considered as a viable way of securing the whole need of LCH4.

Still the capacity to import the additional methane, if needed, might be necessary in the beginning of the exploitation of the launch systems (typically for Themis demonstration) as a risk reduction measure with respect to eventual planning problems of local production: While financially and ecologically inefficient that might be the only backup solution. In that case the purification and liquefaction processes must be assured by methane provider and in French Guiana only the quality of the LCH4 will be verified and the propellant will be stocked both in ISO and fixed storages.

3.2 Anaerobic digestion

Anaerobic digestion is a process of converting the organic matter in methane and digestate. It includes a sequence of processes by which microorganisms break down biodegradable material in the absence of oxygen. It is considered since the whole process can be performed locally in French Guiana with available resources and it is already a very mature technology of biogas production.

The digestion process begins with bacterial hydrolysis of the input materials. Insoluble organic polymers, such as carbohydrates, are broken down to soluble derivatives that become available for other bacteria. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids. In acetogenesis, bacteria convert these resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide amongst other compounds. Finally, methanogens convert these products to methane and carbon dioxide.

Two main technologies of performing anaerobic digestion in aim to obtain the biogas were considered:

- Liquid process: The materials are continuously incorporated daily into a digester heated by means of tubes fixed to the walls inside the structure. The biogas tank is surmounted by a biogas storage membrane.
- Batch dry process : The waste is incorporated in "batches" in turn into each of the digesters, where it ferments for several weeks without additional addition of raw materials. It is made up of several garages in parallel, emptied and filled one by one at regular intervals.

The term "continuous" or "batch" is used to distinguish processes in which the material is introduced continuously into the digestion process (this is the case of the continuous dry process and the liquid process) from those where the material is introduced by batch. In any case, the bacteria involved in the anaerobic digestion process require stable conditions to produce biogas, and the production of biogas is therefore relatively smooth, even on units in the discontinuous dry process. The thermal conditions in French Guiana are positive for the process increasing the output of the reactor.

One of the issues linked with anaerobic digestion is the time of ramp up/down of the process: it takes up to 3 months after initial mix is introduced to the digestion reactor to obtain good quality biogaz. Manure is used to start up the process and other entry organic elements are gradually added to the digestion tank. The system has some inertia, strengthened by the fact that bacteria are present in the mix and that the temperatures in French Guiana are elevated

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and facilitate the maintenance of needed temperature of 37 deg. C for anaerobic digestion. It allows to stop the exploitation for several days even in case of maintenance. The need to re-perform the ramp-up of 3 months appears only if the installation stopped working during several weeks.

In the tradeoff it was evaluated that it is preferable to use a single site close (less than 20km) to the space base instead of several sites closer to the input sources. That aspect is directly linked with the availability of terrain for installation of the facility and needed plantations. It limits and localizes the traffic that is expected to be generated by the transport of obtained LCH4 to the space base.

In the end the following schema depicts the general overview of the planned installation of roughly 300m x 200m. It includes digestator reactor, the maturation tank, rain water tank, the dedicated areas for storage of input materials (energetic plants, green waste, used oils (HAU), manure…) and output digestate, while the resulting biogas is sent to the purification and liquefaction facility. The final liquid methane is recovered in the Cryolor (mobile tank) and sent to the fixed storage present in the space launch complex.

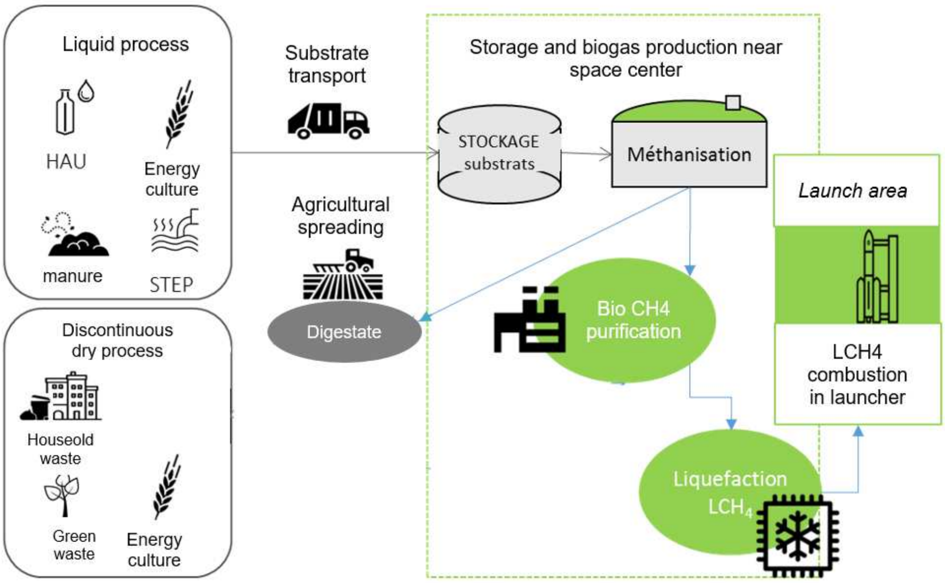

Figure 7: General process of LCH4 production by anaerobic digestion

In more detail the specific security and safety systems are needed : heater, unit for oils hygienisation and torch for neutralization of biogas leaks, the separator to extract to dry digestate from liquid digestate. Also the site perimeter needs to be protected with fencing and operated by employees which need a building for rest.

Dry digestate is stocked in specific area until all anaerobic bacteria die and can be used as fertilizer in the agriculture. The liquid digestate in covered storage tank also contains the anaerobic bacteria and continues to produce the residual biogas. It can be used to seed new batches in empty digestator reactor more effectively than with manure and is recirculated in digester reactor to fluidify the running process bringing more of “fresh” anaerobic bacteria.

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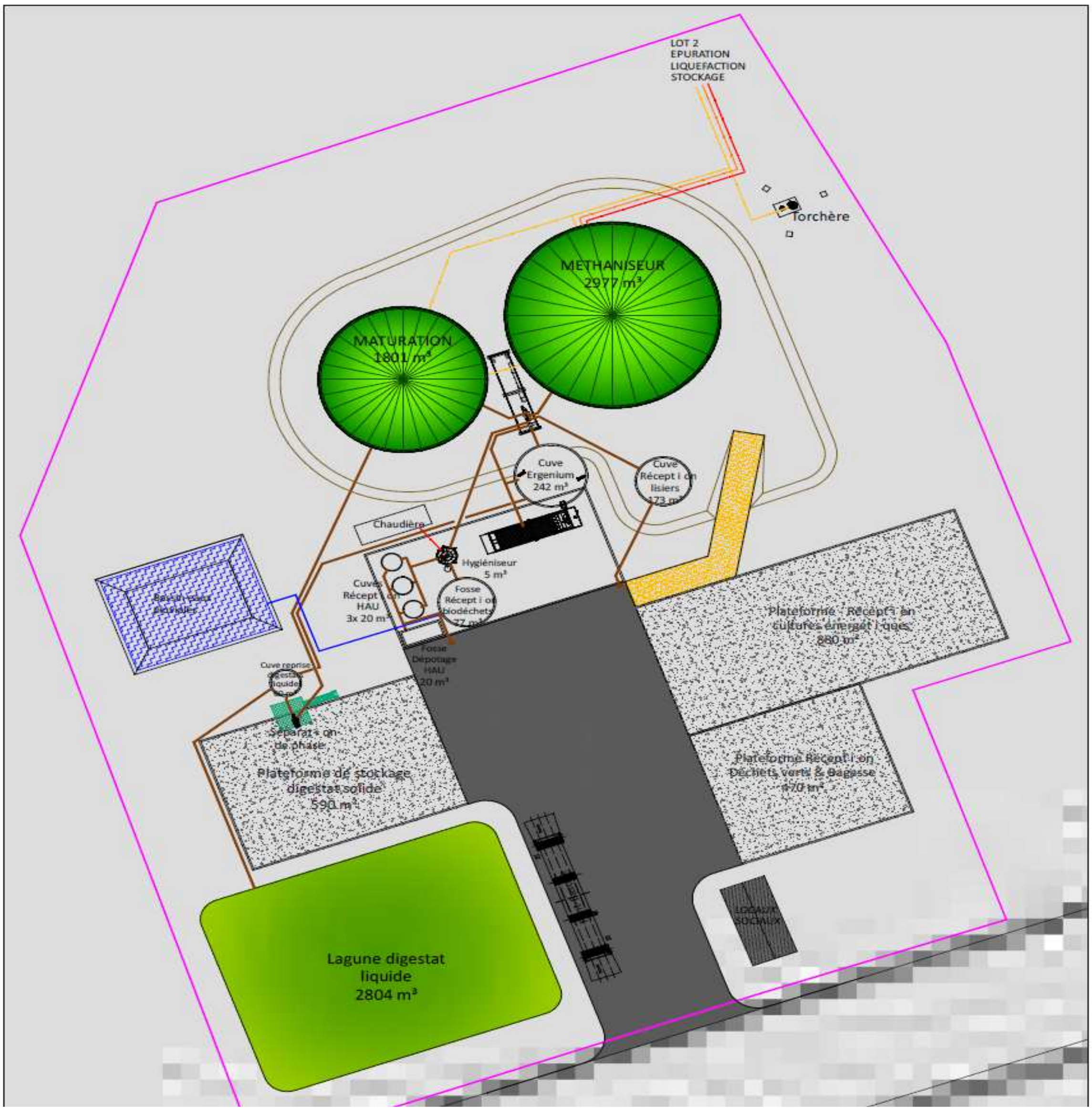

Figure 8: pre-project of anaerobic digestion installation

In terms of production cost the decomposition of organic material is done at 38°C which leads to low energy consumption, especially in French Guiana, where temperature conditions are very linear and close to those conditions (in difference to Europe suffering from seasonal variations). The whole process is more expensive than fossil methane but cheaper than current H2 produced by methanol reforming. Currently the main disadvantage is a strong dependence on the energetic cultures such as sugar cane, however disaffected areas of several hundred hectares were identified close to town Kourou, where such plantations can be done without major impact on the environment. In addition sorting of household waste requested by European and French law [13] represents the opportunity to create the circular economy in French Guiana with respect to the current situation (no sorting: the waste is disposed in landfills or burned).

Anaerobic digestation technology is very mature at industrial level since it can profit from the feedback of more than 600 operational units in France for energy production.

Four main categories of positive externalities have been identified:

- Agronomic externalities linked to decrease of the use of chemical fertilizers thanks to digestate spreading. The odors are strongly reduced with use of digestate improving the comfort of the local populations.
- Social and economic externalities linked to the development of the sector and agricultural ecosystem. Economic reinforcement will also be obtained by creation of partnership between anaerobic digestation unit and French Guiana agricultural actors

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- Environmental externalities linked to the implementation of a renewable energy and to the capacity of preventing savage methane volatilization. Carbon footprint, resources and water consumption will be positively impacted by the project (anaerobic digestion produces more water than it consumes).
- Energetic externalities: Due to local production of biogas which will contribute to energetic independence and will also reinforce the reliability of this production

3.3 Landfill gas

Landfill gas is a mix of different gases created by the action of microorganisms within a landfill as they decompose organic waste, including for example, food waste and paper waste. Landfill gas is approximately forty to sixty percent methane, with the remainder being mostly carbon dioxide. For that reason it is considered mostly as environmental nuisance to be monitored for its impact on global warming. In the same time it represents the short term opportunity for obtaining methane. The schematic principle of landfill gas exploitation is depicted below:

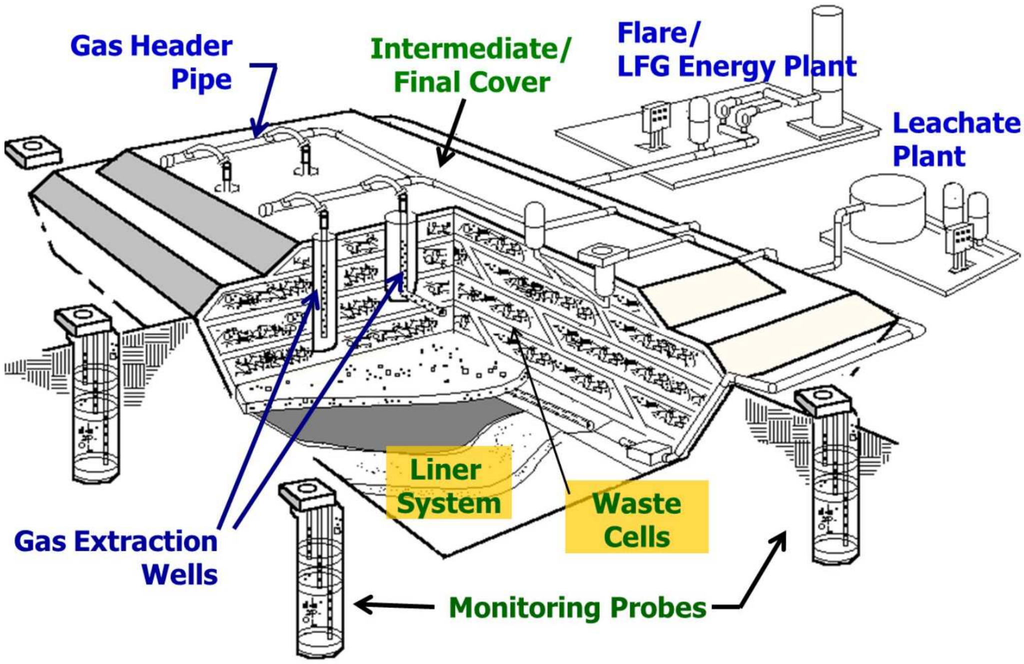

Figure 9: Schematic view of landfill gas exploitation site

Thus the basic process seems “simpler” than a classical anaerobic digestion, since the biogas is recovered from already existing digestate created by concentration of organic material, however the system is passive, its composition is not mastered and it contains important part of non-organic material as the landfill content has not been sorted in any way.

In French Guiana the landfills exist. Those sites offer the possibility to exploit the landfill gas with mid-term perspective at least until the end of 2020s. They provide the biogas in yearly quantities that are compatible with the needs expressed by the users, however more detailed logistics of production does not seem to be compatible with the need of production between two launch chronologies (which can occur in an interval smaller than 2 weeks), what requires an important anticipation in production and storage of CH_4 or concurrent use of backup solutions based on imported LCH_4 or produced by other process.

The long term perspectives for that technology will be reduced by the French law that demands to sort the organic waste from other type of waste starting from 2025 [13], however that is also an opportunity to provide sorted entrant organic material for anaerobic digestion process in the logic of circular economy.

3.4 Digestion of Pontederia crassipes (water hyacinth)

Pontederia crassipes is aquatic plant native to South America (and in French Guiana), naturalized throughout the world, and often invasive outside its native range. The premise of that solution is using that plant could be one of ways to produce the methane out of local resource using local human resources, valorizing abandoned rice plantations for that agricultural activity with respect of environment.

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The tests were performed in Burkina Faso on Anaerobic digestion demonstrating the feasibility of the process [7]. The study was performed by Swiss company Planair [8][9] provides the methane generation capacity of Pontederia crassipes in the framework of methane production in Mali. It concludes on 309 Nm3 of biogas (~60 % CH_4) / ton obtained out of treated organic material (corresponds to around 10 Nm3 CH_4 / t of Pontederia crassipes).
However there is a technological uncertainty concerning the conditions for cultivation of that plant and its optimization. The factor of growth inferior to 20% has been observed in the natural environment that translates to less than 20 g MS/m²/day, leading to 1100 tons of Pontederia crassipes / ha/ year. The TRL of that culture must be improved by research & development tests before undertaking the full scale facility dimensioning and it will not be available before ~2027.

3.5 Digestion of algae

The bibliographic study [12] revealed that algae cultures potentially represent the important added value for the environmental aspects of biogas production. It concerns the potential productivity with respect to conventional agriculture cultures (even by factors higher than 10 times more), ability to capture CO_2, its non-interaction with agricultural food crops, its ability to treat wastewater and finally, not least, its resilience. to epidemics with a rapid self-regeneration cycle (15 days), compared to the agricultural sector. Microalgae can be ten to thirty times more oil productive per unit area of production compared to conventional terrestrial oilseed crops.

Brown or yellow algae (diatoms), resistant and persistent, provide oil and proteins; green algae (Chlorophyceae), dense and invasive in fresh water, are targeted for the production of biofuels, blue algae (Cyanophyceae) can be terrestrial and fix nitrogen from the atmosphere and are used for human consumption; golden algae (Crysophyceae), in fresh water, are less stable and therefore less considered for exploitation. The microalgae have important resistance against bacteria epidemics, which is not the case of more classical plantations.

The tropical climate of French Guiana represents an important contributory factor to the economic yield due to its strong sunshine (algae cultivation all year round) and its heat (gain on drying). The biomass pathway based on macro algae seems to be productive in the tropics (red algae) and a source of CO_2 reduction (brown algae) [11].

However, the turbid waters rich in alluvium constitute the disadvantage because they limit photosynthesis (limitation of the growth of algae). In terms of entry requirements the algae cultures require very important water resources.

In addition, at equivalent surface, algae produce less of methane than energetic cultures, such as sorghum or sugar cane: Respectively on average ~100t/ha/year against ~250t/ha/year. Algae cultivation is more complex, more water-intensive, more sensitive to conditions (pH, salt, etc.) also harvesting algae seems less easy than harvesting energetic cultures (digestate difficult to dry for microalgae, important energy cost). For that reason the cultures of algae could be a complementary but not main source of biogas.

There is not enough of economic lessons learned on that technology, since there are no more than 10 facilities using algae in the world and oriented to bio-gas production. The level of maturity of the production by biomass of microalgae (phycoculture) does not allow to engage in large-scale industrialization.

3.6 CH_4 synthesis by electrolysis and reforming / ISRU

Another possible technology of methane production by synthesis is developed notably for Mars exploration missions [15]. In terms of methane production the exothermal reaction of Sabatier is proposed:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (\Delta H = -165.4 \text{ kJ/mol}) \qquad (1)$$

Other potential reactions use CO instead of CO_2:

$$CO + 3H_2 \rightarrow CH_4 + H_2O \qquad (2)$$

The CO_2 could obtained by direct capture in the air (Direct Air Capture), while hydrogen could be obtained from electrolysis. For CO_2 there are several solutions for capture. A lot of studies are done by NASA and other space institutions in aim to develop the ISRU means (In Situ Resource Use) for Mars exploration. Typically the Perseverance rover is equipped with MOXIE experience [15] which produces O_2 by electrolysis of captured CO_2. Other example

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is [6] where the DAC unit, commercialized by the ETH's spinoff Climeworks is described. It applies adsorption desorption cycles to an amine-functionalized sorbent to concurrently extract CO_2 and H_2O from ambient air. Adsorption proceeds at ambient temperature and pressure for 180 min per cycle, desorption at 95 degrees C and 0.1-0.3 bar for 43 min per cycle. The unit can process an air flow of 2,000 m3/h with 5.5 cycles per day, yielding around 8 kg per day of CO_2 with a measured purity of 98% (the remainder being air) and 2040 kg per day of water, depending on relative humidity. The industrial size system would implicate a unit covering a DAC system of 4,500 m2 capturing 100,000 tons of CO_2 per year

The CO_2 capture component is an interesting opportunity for "greening" of other types of methane production, notably involving burning of methane emissions in the torch that produce CO_2 or even more globally for all industrial processes as a compensatory measure with respect to the environment. Also captured and condensed CO_2 could be used in other industrial processes and applications in liquid and solid form.

Another process "greening" opportunity is linked generally with "green hydrogen" projects that foresee to nullify the CO_2 equivalent emissions by implementation of photovoltaic power plants coupled with electrolysis. There are numerous technologies with varying level of maturity. Some of them were presented in [2] and [10] where the important costs of obtained H_2 molecule were established (above 10€/kg of LH_2). There exist also even more advanced projects such as use of microbes, algae [12] for direct production of hydrogen by living organisms.

The relative problem with that solution is inherent to all systems functioning with electrolysis, known from different process for "green H_2" production: it requires huge amounts of energy that require very expensive installations in terms of OPEX and CAPEX (roughly 10 times more expensive than an installation required for the anaerobic digestion described above). That translates into an important cost of obtained methane. Other problem is the low technological maturity of the whole H_2 reforming system to justify the industrial capacity required for launchers exploitation.

3.7 Methane purification, liquefaction and storage

The common part of all above solutions concerns the purification (of H_2O, H_2S, other hydrocarbons, CO_2, N_2, O_2…) and liquefaction processes to be executed by methane provider in its facility. Several purification technologies are described in [2] & [14] including absorption, adsorption, molecular membranes, etc. The technical problem is very similar (limitation of impurities with respect to quality specification), however the composition will vary depending on the origin of initial liquid. Typically the purification of synthetized CH_4 will be simpler than the one obtained from GNL or landfill gas, as no toxic substances are expected. The biogas obtained out of anaerobic digestion is somehow in between those two extremes, but still depends on the homogeneity of raw materials mix and stability of digesting process. Beyond purification of most apparent impurities, such as H_2O, H_2S or other hydrocarbons, the N_2 and O_2 constitute the biggest challenge to satisfy Grade A methane specification as the purification processes require the use of more complex, cryogenic means. Thus the relaxation of the user specification is an expected solution. Releasing some of purity criterions, could have an impact on the qualification logic of launch systems, however there are significant gains on the cost and availability of the propellant by simplification of the purification process. For example regarding Grade A for launch vehicles we expect to proceed to the relaxation of requirements concerning O_2, N_2 and H_2O.
These constraints could be relaxed by studies and margins engine tests taking into account the impacts on the engine such as mix ratio pour O_2, NPSP (propellant inlet total pressure-propellant vapor pressure) for N_2, icing pollution risk for H_2O.

The liquefaction process is a standard in the GNL/cryogenic fluids industry and its choice is defined according to the overall quantity of the liquid (from use of lost liquid nitrogen for cooling for smaller quantities, passing by compression/expansion cycles up to more complex Brayton cycles for very huge, industrial quantities). The methane provider will chose the process for according to the overall business plan taking into account the non-space usages.

For space applications the last step of the LCH_4 life cycle takes place on the Launch Site itself: the methane will be stored there in the fixed horizontal storage tanks between chronologies. That storage will manage its own pressurization by specific fluid panel and degassing losses by burning them in flare. The loading of storage will be possible from Cryolor trucks or standard ISO containers. Considering the amount of propellants to be used it is not foreseen to implement any reliquefaction system, as it would require more complex system (reference being the simplest cooling by lost liquid nitrogen). The reliquefaction system is considered to be less economic and less environmentally efficient than simply neutralizing losses because of required liquid nitrogen production, procurement and increased maintenance needs of the whole system.

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4. Solution tradeoff

The comparison of the propellant production chains, associated to the specific situation of French Guiana and its space industry [2], allowed to define the specifications and several preliminary concepts of methane production for future launchers using methane. The following table summarizes the different technologies trade-off (in blue the most positive solution, in red the most negative solution with respect to compared characteristic):

Table 2: methane production trade-off

Characteristic	"Gray" LCH4	Anaerobic digestion	Landfill gas	Pontederia crassipes digestion	Algae digestion	CH4 synthesis
Total process TRL	9	9	9	3	3	3
Technical requirements complexity for CH4-rich fluid acquisition	--- traffic & cost of ISO containers maritime and road transport -- need to buy LCH4 instead of GNL to avoid purification process implementation	++ use of diverse organic raw material, +/- energetic cultures (use of agricultural area, but additional local employment), - traffic & cost of transport of organic material by public roads - specific facility for digestion process	++ existing process for "raw material" provision - specific facility for landfill gas extraction - installation on landfills only	- important water needs - specific facility for digestation process - monoculture, limiting the entry organic material quantity in the process - Pontederia crassipes considered as energetic culture	- important water needs - more difficult to harvest than more standard cultures - specific facility for digestation process - monoculture, limiting the entry organic material quantity in the process	--important water and energy needs -- area surface for solar batteries - complex facilty for both electrolysis and CCS/CCU (CO2 recovery) for reforming process
CH4 Purification	--- Needs to be performed in Europe/provider country or require complete GNL purification process in French Guiana	- Complexity depends on raw material diversity	-- Non mastered raw material composition induces more important impurities	++ Homogeneity of organic material decreases variability in CH4 rich gas composition	++ Homogeneity of organic material decreases variability in CH4 rich gas composition	+++ CH4 synthesis allows to master the conditions that optimally limit the quantity of impurities
CAPEX	- need to implement storage area according to law in port and in CSG for ISO containers	-- digestion facility & LCH4 purification/ liquefaction -- agricultural equipment, culture area	- pre-project necessary for French Guiana specificities - gas extraction facility -- LCH4 purification/ liquefaction	-- R&T activity necessary -- digestion facility & LCH4 purification/ liquefaction -- agricultural equipment, culture area	-- R&T activity necessary -- digestion facility & LCH4 purification/ liquefaction -- agricultural equipment, culture area	--- important R&T activity necessary --- factor 10 on the CAPEX of implementation wrt anaerobic digestation
OPEX	+++ a an existing and very mature branch: the prices of LNG tend to be lower than biogas --- Strong dependence on unstable world market and geopolitics	- installations maintenance - LCH4 transport means	- installations maintenance - LCH4 transport means	- installations maintenance - LCH4 transport means	- installations maintenance - LCH4 transport means	--- installations maintenance - LCH4 transport means
Environmental performance	--- fossil character of propellant & long haul transport	+++ compatible to treat sorted organic waste - need to transport raw organic material	++ local exploitation of landfill gas --- Obsolete in mid-term wrt environment law	++ local implantation: small need of transport + possibility to treat sorted organic waste	++ local implantation: small need of transport + possibility to treat sorted organic waste	+++ the CO2 emissions nullified, rendered negative - water consumption
Timely availability of propellant for Launch Campaigns	+++ availability of smaller quantities on commercial market wo anticipation --- sensitivity to geopolitics (wars) -- Low commercial interest of LNG/biomethane providers	- depends on the availability of entry organic materials, ++ modularity (possible to scale up the facility and use several digestators and multiple organic raw materials)	-- Less versatile than anaerobic digestion (localised and limits in scaling up)	- depends on the availability of entry organic materials – monoculture + supposed high yield of Pontederia crassipes culture (TBC)	- depends on the availability of entry organic materials – monoculture + supposed high yield of algae culture (TBC)	+++ potentially unlimited, since depending only on energy and water availability

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Globally the anaerobic digestion is considered as a favorite solution, as it addresses the actual needs of French Guiana territory in terms of waste treatment, socio-economical improvements by bringing new the industrial activity, work places for local population and provides a potential for really independent sourcing of methane both for Launch Base uses and local needs. It is also very versatile and adaptable to the adverse needs of both space and non-space users.

Following the tradeoff the definitive solution was not completely decided, since it depends on different time scales coupled with the development of target users:

- In short term perspective (up to 2025) the storage area will be foreseen for imported ISO containers with LCH4 to treat potential problems with operational qualification of the target methane production process for the beginning of the exploitation foreseen in 2025. That investment is relatively minor in comparison with the whole project and could be repurposed to other needs following other launch system projects of CNES.
- In midterm perspective (up to the end of 2020s) anaerobic digestion and landfill gas are the solutions justifying the investment for CH4 launchers needs. They have both the advantage to propose overall high technological maturity and realistic planning and cost objectives (qualification in 2025), however the landfill gas solution still needs to be consolidated technically by the preproject study in the specific French Guiana context.
- In long term perspective (after 2030) the anaerobic digestion will be reference that will allow to use sorted organic waste from French Guiana contributing to the circular economy, while landfill gas solution will be rendered obsolete following French and European law. However the composition of entry organic material could be improved according to the developed cultures. The opportunities given by algae or Pontederia crassipes plantations could be seized as opposed to the energetic cultures, if any of those two technologies manages to increase its TRL by research & technology actions.
- Concerning implementation electrolysis and CO2 recovery the main opportunities reside in the possible environmental compensatory measures in the long term. The costs and insufficient technological maturity of methane synthesis on industrial scale by that mean are prohibitive for the short term implementation for Themis demonstrator. In addition CH4 synthesis alone does not solve the waste problem in the same way as anaerobic digestion.

In all cases the purification and liquefaction processes will be executed at the facility of methane provider and not in the Launch Complex. The specific LCH4 storage zone is already foreseen in the CSG Launch Complex. In terms of LCH4 logistics that storage will be regularly filled in with propellant provided by Cryolor or ISO container transports up to its storage capacity dimensioned for a single launch campaign.

5. Conclusions

In conclusion the preliminary results confirm the interest of producing biomethane in French Guiana for the reasons of cost savings, positive environmental and social-economic impacts. Full fossil methane sourcing or transporting it from Europe is not a viable option and the local production will be thus further evaluated because of particular context on the energy markets.

Also the CNES will strive to include that project in the context of French Guiana territorial needs, which will contribute to implement the circular economy. Business plan of this economy will be consolidated with other space and local non-space users' needs.

CNES will be particularly vigilant on the process parts interfaced with space operations including purification, liquefaction and storage of space grade methane. The follow up with detailed concept design and development of the dedicated methane production unit is being organized, while storage unit in Launch Complex will be implemented in parallel to meet the planning objectives of Themis demonstrator project.

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