Politecnico di Torino

Master of Science in Petroleum and Mining Engineering
2021/2022
Graduation session: November 2022

Energy transition of Oil and Gas Platforms

Substituting existing power systems of oil and gas platforms through renewable energy later used for hydrogen production and methanation to increase production

Supervisor:
Prof. Mariachiara Zanetti
Co-supervisor:
Andrea Carlino

Presented by:
Mohamad Atoui

Abstract

Oil and gas platforms today are still powered prevalently by fossil fuels, mainly embodied by gas turbines. Power generation is one of the largest contributors to greenhouse gas emissions and global warming. Moreover, oil and gas production operations make up the largest cut of pollution caused by the oil and gas industry. The increase in human population and the economic growth, continuously increase the demand on fossil fuels for energy production, which become more and more scarce with time. Consequently, energy prices with the current world energy mix reality are very volatile, thus rendering access to energy often too costly and insecure. Moreover, price fluctuation is induced by geopolitical discrepancies. A large role in the challenging price of power generation on oil and gas platforms is also played by emission taxes imposed by many authorities around the world. Therefore, it is in everyone's favor to look forward to ecological energy transition initiatives to promote a secure, sustainable and affordable energy future. From this point of view, this paper describes conventional power generation methods currently used on oil and gas platforms, thus proposing plausible alternative methods to exploit renewable energy sources in the environment surrounding the platform. Later, as renewable energy is often attributed to excess energy production, this surplus in energy can be used to produce hydrogen by hydrolysis, which may be either used as a source of energy to power some already existing gas turbines, or even be implemented for methane production along with CO_2 affluent often produced with the gas stream. The methane produced can increase the production rates of the platform, while using renewable energy for the process and reducing the platforms emissions and operation costs with respect to the quantity of gas produced. Finally, this paper covering transition of oil and gas energy production towards renewable energy sources, and methods to exploit them

in efficient ways, on platforms is done in hopes of stimulating this research to promote sustainable and efficient energy production and expand it to a larger scale.

Table of Contents

1.Current Energy Production Scenario

1.Global Energy Mix Picture and Reasons for Energy Transition

Fossil fuels still contribute to a huge share of the energy mix, a cut as high as 80% since decades. (IEA, 2022) Oil, coal and natural gas are still the main sources of energy used to satisfy today's world energy demand. These resources in their turn require energy to be extracted. The energy used to power the operation and production of oil & gas platforms which extract fossil fuels is quite significant, and yet is still produced by burning hydrocarbons which have a great impact on the environment. (S. Oliveira-Pinto, 2019). Switching to more environmentally friendly sources today has become unavoidable. Some energy sources used today are solar, wind, hydro and geothermal energy. However, ocean waves are a quite significant prospect which could play a great part in producing low-impact energy. Wave energy converters (WECs) are the devices used to convert wave energy into a form of energy adaptable to our needs. These devices could be used to replace fossil fuels in powering the O&G platforms. Moreover, introducing them as a new alternative to traditional sources, with economic and environmental privileges, starting from production platforms, could be a way to promote the increase in the share of renewables in meeting today's energy demand. Meanwhile, most of R&D is concerned with solar and wind energy, being mature technologies already in use. Hence, it would be interesting to assess the viability of supplying O&G platforms with the required energy using wave energy systems. (Nizamani, 2021).

According to the International Energy Agency (IEA), the capacity of global oceans is about 93,100 TWh/year. Since providing affordable, reliable and sustainable energy is one of the UN sustainable development goals (United Nations, 2022), it would be advantageous to make use of the energy the oceans can provide in order to strive towards these goals. In addition, it is necessary to remember that fossil fuel combustion is the main source of greenhouse gas emissions, of which carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx) and methane (CH4). CO2 being a great contributor to the increase in the environment's temperature, mostly produced by electricity and heat generation activities. (M. Ragazzi, 2017) Global energy consumption and CO2 emissions were compared by the International Energy Agency (IEA) between the first quarter of 2019 and that of 2020. According to the reports, the world's demand for energy produced from coal and oil has decreased in Q1 of 2020 relative to Q1 in 2019 due to the restricted displacement and economic activity during the rise of the Coronavirus pandemic, a trend coherent to that of the CO2 emissions. This means that CO2 levels in the environment can be reduced by decreasing the use of fossil fuels for energy production. (IEA, 2020)

Another important aspect to introduce is energy security, best defined as having a stable access to energy in a continuous, sustainable and affordable manner. (OSCE - Organization for Security and Co-operation in Europe, s.d.) With decreasing fossil fuel reserves, and increasing demand for energy, competition on resources will continue increasing, thus causing conflicts and instability in fossil fuel prices. This instability leads to complications in countries dependent on the supply of hydrocarbons for their energy mix. For instance, thermal power accounted to around 67% of China's electric power generation in the year 2021. (China Energy Portal, 2022) Moreover, China is highly dependent on imports – mainly from Russia, Africa and the middle east. (Tata, 2017) (Jaghory, 2022) Consequently, China might also find itself obliged to accelerate its transition towards renewable energy alternatives. (Nizamani, 2021) Moreover, India's dependency on oil reached about 84% of its energy demand in 2019. (The Economic Times | Industry, 2019) Thus it is also susceptible to fluctuations in economical stability with the ups and downs of fossil fuel prices. Finally, the EU's dependency rate on imports to satisfy its energy needs has reached more than half to nearly two thirds, with Russia being the main supplier of energy commodities between 2010 and 2020. (Eurostat, 2022)

Fossil fuel prices vary also as a result of economic and geopolitical discrepancies. A disruption of gas supply to EU markets has occurred in 2006 and 2009 due to disputes between Russia and Ukraine, which had a great impact on the socio-economic situation. (Siddi, 2016) Today, the war in Ukraine has generated sharp spikes in energy prices amid disruptions in Russian gas supply. (Adolfsen, Kuik, Lis, & Schuler, 2022) On the contrary, under favorable conditions, the energy supply from renewable resources would always be available. (Nizamani, 2021) Price of non-renewables will continue increasing as demand increases and fossil fuel supply diminishes. Meanwhile, the bulk cost of renewables consists of the building the infrastructure and its maintenance, which allows to have an infinite quantity of energy at a sustainable price. (Shahzad, 2015) Whilst one can claim that the required expenditures for collecting and consuming renewable energy are rather abundant, it is important to state that the advancement of the technology used for producing energy from renewable sources will gradually reduce its price. As may be noticed in the case of solar photovoltaic (SPV) technique used for generating electricity, whose cost has been reduced from 300$ to 4.5$ per watt between 1954 and 2007. Furthermore, as renewable energy sources can be harvested on a domestic level, it may be a way of shifting from fossil fuel resources and produce energy in a self-sufficient manner in order to reduce susceptibility to fuel price fluctuations. (Liming, 2009)

1.2 Conventional Energy Demand and Efficiency of Oil Platforms

The energy demand of oil and gas platforms highly depends on the well size and activities performed: extraction, processing, support and maintenance or storage. The platforms indicated by Y. K. Tiong et al in their study require 10-50MW for its electrical energy production, where the feasibility study itself is performed on a 10MW platform. (Tiong, Zahari, Wong, & Dol, 2015) On the other hand, the consumption of an offshore oil platform on the Norwegian Continental Shelf (NCS)varies between 10MW reaching hundreds of MW. The excess energy produced may be used to power several platforms or supply onshore electricity grids. (He, et al., 2013) Ardal, et al., have studied platform demands in the range of 40MW including into their study the various energy consuming components of a Norwegian platform with a 45MW load. (Årdal, Sharifabadi, Bergvoll, & Berge, 2014). A. Zhang, et al., stated that platform facilities are characterized by a peak power demand of 44 MW. (Zhang, Zhang, Qadrdan, W. Yang, & Wu, 2019) Korpas et al, states that the energy consumption varies between 20 MW to 35 MW. (Korpås, Warland, He, & Tande, 2012) Nguyen et al., performed studies on 4 platforms where the power demand varies between 5.5MW and 30MW. As per heating power, the demand goes from nearly null to more than 10MW (Nguyen, Voldsund, Breuhaus, & Elmegaard, 2016) Oliveira-Pinto, state that conventional platforms use diesel or natural gas to produce energy. They estimate that the energy demand of offshore platforms is fulfilled by 50% NG 50% diesel. (S. Oliveira-Pinto, 2019) On the contrary, Zhang et al. have found co-firing plants which can be fed with NG, diesel and hydrogen. (Zhang, Zhang, Qadrdan, W. Yang, & Wu, 2019) The last to be kept in mind as a potential source in order to feed existing plants with a cleaner fuel. Nizamani et al., used an energy demand of 10-50MW as minimum and maximum values for the evaluation of wave energy resources in oil and gas platforms in offshore Malaysia (SCS). The electricity produced by Wave Energy Converters (WECs) is estimated and taken into consideration to determine the best offshore environment for wave energy development. Consequently, a feasibility study is performed in order to assess whether the energy produced meets the demand of the platforms. (Nizamani, 2021)

Oil and gas operators have typically two choices to power their platforms: either produce energy autonomously using gas turbines (GTs) that feed the generators or acquire energy from the shore, when possible, by subsea cables. While it might seem reasonable to use the gas produced on the platform as a source of energy for the turbine functioning, yet in most cases it is not the most economically favorable solution. Gas turbines are basically jet engines that absorb heat from a hot gas produced by the combustion of natural gas or fuel oil. The thermal power is converted to shaft power which drives the generators to produce electric energy. Electric energy production through this scenario includes combustion, gas compression, heat transfer and spinning, processes which require an equipment that doesn't only consume lots of combustibles, but also necessitates for significant operation and maintenance cost. GTs used are prevalently simple-cycle due to weight and space limitations of platforms. Simple-cycle GTs present low efficiency characteristics, especially when functioning below fuel capacity, a case often present on platforms for redundancy reasons. Most optimistic efficiency values of a GT used for electricity generation is around 25 to 30 percent. While considering the ideal conversion of natural gas to electricity of 10.8kwh/m^3, the real energy produced is 3kWh accompanied by 2kg of CO_2. Thus, it may be estimated that a platform with 100MW of operational capacity releases over 500,000 tons of CO_2 per year in addition to harmful emissions such as nitrogen oxides, which damages the equipment, environment and human health. (Chokhawala, 2008) (Nguyen, Voldsund, Breuhaus, & Elmegaard, 2016) (Svendsen, 2022) A clear consequence of powering platforms by combustibles is their carbon footprint. For instance, in Norway oil and gas extraction activities have accounted for about 25% of its total emissions into air in 2021. (Statistisk Sentralbyrå, 2021) The Norwegian government is one of many others that introduced regulations to limit emissions, by imposing CO_2 and NO_x taxes on the corresponding emissions in 1991 and 2007 respectively. (Norwegian Ministry of Petroleum and Energy, 2012) In addition, the gas turbines alone are responsible for 80% of the CO_2 and NO_x emissions. (He, et al., 2013) These policies aim towards encouraging the reduction of emissions. Thus, it is in the interest of operators to reduce their emissions by rendering platforms more efficient or searching for alternative methods to produce energy. Increasing the platforms' efficiency includes waste heat recovery, as well as electrification in order to make use of onshore electricity grids. However, alternative forms of energy may be captivating due to them being attributed to extremely low emissions, thus reducing costs due to cutting emission taxes, in addition to other economical drivers to be discussed below. (Zhang, Zhang, Qadrdan, W. Yang, & Wu, 2019) (Forbes-Cable, 2019)

In order to reduce a rig's energy consumption, it is opportune to consider the highly consuming equipment and processes in operation on the platform. Hoisting and fluid circulation system are the two activities most widely responsible for power consumption during their operating times. Other rig components such as the rotary system, well monitoring and control equipment have a much lower contribution to the power demand. Energy consumption on offshore platforms involves a range of operations, some of which are:

- Pumping system to extract hydrocarbons and reinject water.
- Heating to separate hydrocarbons based on boiling points in separators
- Enhanced oil recovery by gas reinjection
- Compression and pumping for oil and gas transportation through pipelines to treatment facilities

- Heat and electricity generation for on-site activities and living personnel compartment (Tawiah, Marfo, & Benah, 2016)

The energy demand of these activities is usually satisfied by 20-30m^3 of diesel per day depending on the operations carried out on the platform on diesel-powered rigs. In comparison with a diesel car, based on a study by Zhang et al. on the real-world consumption of light-duty vehicles in China, where 16 diesel cars consumed on average 6.6l/100km, a rig consumes in one day what is equivalent to what a diesel car consumes to travel 300,000-450,000 km, i.e., in one to two lifetimes. (Zhang, et al., 2014) To reduce the consumption of a rig, it is important to efficiently plan drilling operations, thus reducing both environmental and economical burdens. An efficient drilling process, requires less fuel per drilled distance, thus consuming less energy and consequently causing less noxious emissions. For instance, automated mud-mixing techniques, as those applied in the Valhall complex, in the North Sea, reduce probability of mixing inaccuracy, exposure to harmful chemicals and excessive emissions caused by human error. (Gunnerod, Serra, Palacios-Ticas, & Kvarne, 2009) Moreover, diligent planning of drilling activities by engineers and logistic operators can save up on time required for drilling and resulting in a more efficient process. Introducing remote-controlled rotating and hoisting systems, together with casing-running operations carried out by a top-drive, contributes to speeding-up operations, by reducing transition time between casing-running and cementing, thus increasing the overall efficiency. (Cummins, 2011) Moreover, a reliability-centered maintenance (RCM) approach, which is a process focused at improving the consistency of assets to prevent their failure, has proven to reduce rig down-time, enhance safety, and in the case of Ensco has shown a 63% return on investment. (Liou, 2012) The drilling rig design is also important. Well-planned working and living compartments decrease the demand for heating and cooling and are especially required in harsh climate conditions where heating requirements are more significant. Hull shape and topside design of drilling rigs creates wind drag, which can lead to significant energy savings when reduced in the design phase. A great factor influencing a rig's energy expenditure is determined by the way a rig is positioned. Moored platforms require much less power than dynamically positioned (DP) ones, because engines continuously consume energy to keep the rig in place. ABB, a British fabricator of power and automated machinery, have developed the *Azipod* propulsion complex, a podded azimuth thruster design, which involves a variable speed electric motor, driving a fixed propellor immersed outside the ship, which eliminates the need for any gears or shafts between the motor and the thruster. This system reduces 10-20% of the energy demand when compared to conventional azimuth mechanical thruster options. (Langley, 2011) The heave compensation system chosen also has an influence on the platform's energy consumption. Implementing active heave drawworks (AHD), a fully electric system, has different energy requirements compared to cylindrical rig option or crown mounted compensator (CMC), because these heave compensation techniques depend on different compositions of hydraulic and electric appliances. Hydraulic systems triumph over their electric counterparts, in terms of power-to-size ratio and their energy storing capacity. Hydraulic machinery is lighter and less cumbersome than electrically driven apparatuses. Gas accumulators used in hydraulic designs store energy which allows them to continue operating even in power failure scenarios. On the other hand, hydraulic systems necessitate a weighty hydraulic power unit (HPU) of considerable size, which provides power supply to the equipment, as well as being highly dependent on the environment's temperature. Implementation of hydraulic power systems can be complicated especially on floating platforms. Hydraulic fluid properties are affected by temperature, which is a drawback when opting for this design. Moreover, efficiency of an electric system ranges between 85-90%, compared to 70% in hydraulic equivalents. This difference in efficiency makes electric systems more attractive in case of high-power requirements. Moreover, electric systems allow more precise momentarily control of torque and velocity, in addition to eliminating the risk of hydraulic fluid leaks, therefore reducing environmental hazards. However, a limitation of the electrically operated process is the requirement for energy storage usually obtained through batteries of significant weight and size. (Tapjan & Kverneland, 2010)

A CMC system uses a standard derrick and draw works with a hydraulically compensated system above the derrick. This system imposes a minimal load on the structure yet has limited heaving capabilities. At top weight conditions it may affect the platform stability and limit the load capacity on the rig. Finally, the CMC has a much lower energy consumption when operating in harsh environments compared to other heaving alternatives.

A cylindrical rig design substitutes the derrick with a mast and the draw works with hydraulic cylinders. This composition lowers the center of mass of the rig and reduces its weight. The heave compensation capacity is limited by the configuration of the compensating cylinder. Even though a cylindrical heaving design requires a large hydraulic power unit, the positioning of the HPU below the rig floor contributes to an enhanced stability by taking down the center of gravity. The use of several cylinders and wires ensures redundancy for failure scenarios. Moreover, the use of cylinders instead of draw works contributes to the reduction of sound pollution.

The AHD design also includes the use of a standard derrick with the draw works being fully electronically managed for heave compensation. A compensation accuracy of less than 2% for the draw works can be secured using AC motors. The regenerative power due to braking may be reintroduced into the rig to be consumed by other devices to reduce losses. Just as the cylindrical design, the AHD solution has a lower center of gravity than the CMC counterpart, yet a lower weight with respect to both other options. Heave compensation is not limited compared to the other designs. The main drawback of the AHD is use of draw works driven by AC motors, which may be noisy in restricted work environments.

Energy production flexibility may be enhanced on platforms by implementing power optimization systems and applying a power load approach. The task in this case would be running the generators at their right optimal load rather than running all generators simultaneously in low efficiency conditions. To allow this, a variety of engines with different power outputs (dimensions) must be used. Otherwise, operating most generators at optimal load, with one or two generators on variable load may be useful. A simple electric power allocation may reduce the recurrence of power outages by reducing the number of dependent systems and crossover links. Reducing the overall equipment, and increasing the efficiency of each unit, when possible, reduces operation and maintenance costs, as well as reducing the spatial burden of the components on the rig. Finally, heat recovery techniques utilized to recuperate heat from exhaust fluids can be used to diminish heat generation by steam, thermal oil or electrical methods. (Ipieca, 2013)

As Russia invaded Ukraine, the world energy picture is changing before our eyes at a pace which once has been unimaginable. Russia’s fossil fuel exports to Europe have been limited due to changes in geopolitical scenarios and policies, steeper than the decrease foreseen as a result of climate policies and net zero commitments. This disruption in addition to the increase in fossil fuel prices is acting as a drive to the use of renewables which can be a more reliable and stable choice. Moreover, it is important to note that a larger share of renewables has been linked to lower electricity prices. (IEA, 2022) For this reason, in the light of conflicts, price instabilities and net zero commitments to mitigate climate change consequences by adhering to net zero commitments, it is in our interest to contribute to this transition streaming towards a more secure, sustainable, affordable and secure energy future.

2. Alternatives for producing this energy

2.1 Various Methods Present to Date

As mentioned earlier, platforms tend to lean on gas turbines for an independent electricity production. These turbines in platform domains are only up to 30% efficient in optimistic scenarios due to implications of single cycle operations, compared to efficiency in conventional combined cycle power stations. (Gu, Li, & Haces-Fernandez, 2021) (Årdal, Undeland, & Sharifabadi, 2012) (Kolstad, Årdal, Sharifabadi, & Undeland, 2014) (Kolstad, Rygg, Sharifabadi, & Undeland, 2013) As a step towards making energy more affordable, sustainable and secure, performing continuous studies on how to maximize the efficiency and reduce the emissions of power generation on oil and gas platforms is a way to promote and favor the commercialization of these techniques, paving the way for energy transition.

Wind energy is a valid energy source, which has already proven to be a potential method in providing platforms with their demand. Norway has already declared successful efforts of utilizing floating offshore wind turbines to satisfy platforms in the Gullfaks and Snorre oil fields. (Legorburu, Johnson, & Kerr, 2018) The feedback provided was the fruitful supply of 35% of the energy required by 5 platforms, as well as the reduction of CO_2 emissions by 200,000 tons/year. (Izquierdo-Pérez, et al., 2020) In addition, reducing the weight of equipment on platforms by replacing conventional turbines provides more space for safe and stable activities by allowing to reduce the operation and maintenance cost and frequency. (Watson, et al., 2019) Solar energy on the other hand is also an actively studied field for oil and gas platforms especially combined with wind or wave energy in order to provide redundancy to the platform energy demand, where two sources combined have proven to be efficient by covering up for each other, solar energy giving less net production than wind (Oliveira-Pinto, Rosa-Santos, & Taveira-Pinto, 2020) (Tiong, Zahari, Wong, & Dol, 2015)

While as stated by Nizamani et al., renewable energy still requires large capital costs, its price has been decreasing with time. In addition, it shows to be more domesticable, hence proving to be a way towards energy security by reducing susceptibility to price fluctuations. Renewable energy sources that may be used on oil and gas platforms are solar, wind and wave energy. This study presents in detail the exploitation of wave energy used to replace gradually the conventional methods powering the current operating platforms. Ocean waves show to be a very promising asset and abundant source of energy, which is harvested and converted into electric energy by wave energy converters (WECs). (Nizamani, 2021)

2.2 Wave Energy

2.2.1Wave Energy Converters

WECs convert mechanical energy provided by water waves, that in their turn induce the relative motion of the unit, thus producing electric energy. Yet, energy is not produced if the WEC oscillates up and down at the free surface of the ocean. The device must be attached in a way to form a lever, that will allow WE conversion into a new form of energy.

The lever is connected to a dashpot, also known as damper, a mechanical device which impedes motion due to viscous friction, thus converting mechanical energy into heat. (Pecher & Kofoed, 2017)

WECs consist of:

1. Hydrodynamic system that captures wave energy
2. PTO that converts energy into electricity
3. A reaction subsystem to hold the WEC in position
4. A control subsystem that controls and monitors the WEC (Pecher & Kofoed, 2017)

The first wave devices are considered a humble wave resource on the coastline.

Coastal sites show some advantages over deep water locations due to the following reasons:

1. Easier to assemble the system, thus reducing the installation costs.
2. WEC is fixed to the seabed, which renders it more stable, thus providing more solid opportunities of energy extraction
3. Electricity distribution costs are reduced due to expenses of deep seabed cables being avoided
4. Maintenance costs less because the site is more accessible (Nizamani, 2021)

Due to their wide variety, WECs can be classified into different categories

First, they can be classified based on their location: onshore, nearshore or offshore. Nearshore devices, usually fixed to the seabed, are located at a depth where the seabed influences the wave motion. On the other hand, offshore devices, usually floating, are located at a depth where the seabed doesn’t interfere with the waves. (Pecher & Kofoed, 2017) Offshore offers the highest quantity of energy because in that case no energy is lost due to friction between waves and the sea bottom. (Waters, 2008) However, due to the same reason, offshore plants are required to withstand higher loads and extreme weather conditions. (Mwasilu & Jung, 2019)

Second, WECs can be classified according to their functioning mechanism (hydrodynamic subsystem) as follows: oscillating water columns (OWC), wave activated bodies or overtopping devices. (Aderinto & Li, 2019)

OWCs employ columns of water where the movement of the ocean in the column produces wave activated bodies, also called oscillating bodies, which absorb energy directly from the ocean, this motion is later converted to electric energy. Wave activated bodies can be described as point absorbers, where a heaving buoy (moved by the waves) is connected to an electric generator. Overtopping devices include a ramp which forces the water into a tank. Further, the water leaving the tank will spin a turbine to produce electricity. (Waters, 2008)

Different kinds of WECs are designed based on the locations and their respective climate conditions. Based on the numbers presented by Nizamani et al., it can be deduced that the wave nature affects the dimension, weight and number of turbines which on one hand affect the material cost and complexity of the system's implementation, and on another hand the subsequent power production of the system. (Nizamani, 2021)

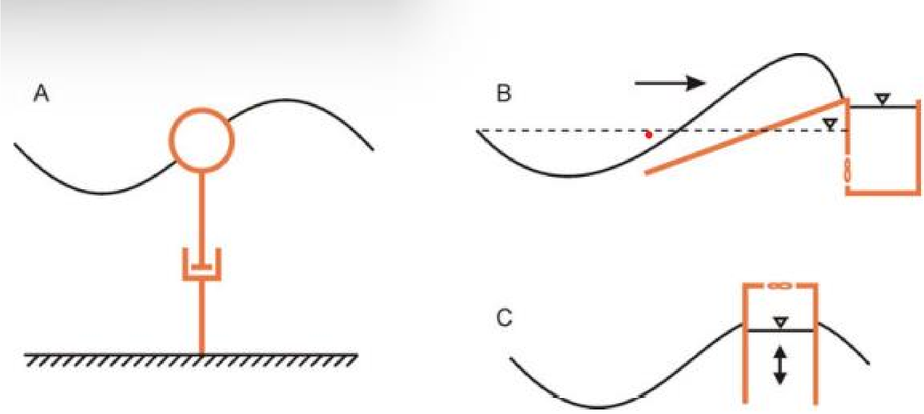
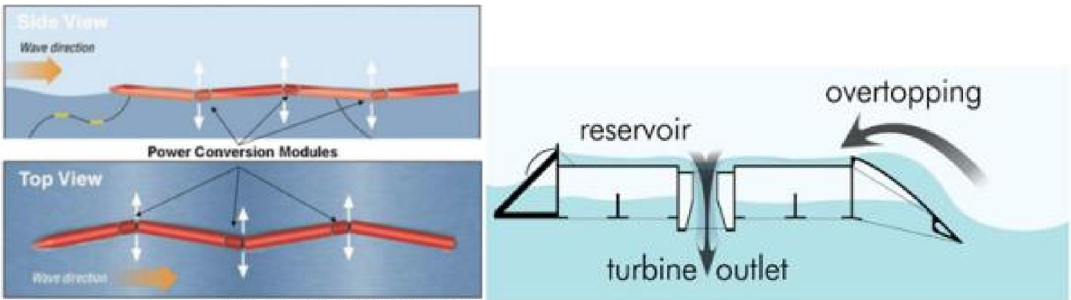


Fig.1 General categories of wave energy converters. A – Wave activated bodies. B – Overtopping devices. C – Oscillating water columns. (Waters, 2008)

Several types of WECs have been tested and implemented during the past 2 decades.

1) **Pelamis:** consists of 4 segments that move perpendicular to the direction of the waves; thus, it is considered a wave activated body. It utilizes a PTO which transmits the hydraulic power created by the motion of the WEC, thus generating electric energy. The prototype was tested in 2006, which lead to the establishment of the first commercial wave form of Agucadoura on the northern Portugal coast. Life cycle assessment was conducted by Thomson et al. in order to assess the environmental impact of the first generation Pelamis P1, including all the necessary connections, throughout its lifecycle. (Poullikkas, 2014) (Thomson, Chick, & Harrison, 2019)
2) **Wave Dragon:** The wave dragon is an overtopping device, where the water fills the reservoirs using ramps, and then spins the turbines to produce power while leaving through the outlet. (Poullikkas, 2014) (Kofoed, Frigaard, & Kramer, 2006)
3) **Aquabuoy:** A small dimension WEC designed by Finavera Renewables to collect offshore wave energy. The instrument consists of a buoy connected to a long tube referred to as the acceleration tube. The buoy oscillates as the wave passes; the kinetic energy transmitted from the wave to the tube compresses a fluid which then spins a turbine generator to produce energy. (Poullikkas, 2014) (Weinstein, Fredrikson, Parks, & Nielsen, 2004)



© Pelamis Wave Power

© Wave Dragon

The figures from left to right represent the Pelamis and Wave Dragon concepts respectively.

2.2.2Technical parameters

An assessment of wave power potential is performed by Nizamani et al. on Different types of WEC design, in different wave environments, in order to understand the power generating capacity of these devices, and their corresponding feasibility limitations, to estimate the amount of natural gas which can be saved, thus reducing operation costs and emissions.

The rated power of the Pelamis P2, Wave Dragon and Aquabuoy are 750kW, 7000kW and 250kW respectively. The capacity factor is the percentage of electric power generated to the rated power of the WEC. This parameter is normalized for each location studied to the maximum capacity factor out of all locations, just as the mean wave power potential and depth, in order to calculate the WEC Location Suitability index (WLS). WECs also have technical limitations, where each of them has a minimum depth constraint which varies between 25-50m for the 3 WEC models studied. Efficiency parameters of the system are taken into consideration to estimate the energy production of a potential wave farm. The factor f_m estimates the machinery efficiency, as it is the ratio between the power absorbed by the WEC to the mechanical power at the Power Take-Off (PTO) component. The f_e parameter evaluates the efficiency of the conversion from mechanical to electrical energy. Finally, f_t estimates the efficiency of transmitting the electricity produced to the required position in a stable and useful manner. Based on in-depth performance studies of the three previously listed WECs in the various locations, the location with the highest wave potential along with its corresponding suitable WEC, the Pelamis P2, were considered. The power demand of the platform was taken ranging from a minimum of 10 MW to a maximum of 50MW. The pelamis P2 in the best location at its optimal operating conditions provided 91.37kW. Meaning that, one Pelamis P2 device may only supply 0.18-0.91% of the platforms demand which is unsatisfactory.

Therefore, an analysis of implementing 10, 50 and 100 units is performed. (Nizamani, 2021) In environmental terms, the benefits of the project are estimated based on the potential quantity of hydrocarbons substituted when wave energy contributes to the energy supply. It is supposed that 1000ft^3 of natural gas may produce 99 kWh. (Statista Research Department, 2016) In other terms, 1kWh of electricity requires 0.286m^3 of natural gas to be produced. This means that each Pelamis P2 unit may save up to 230000m^3 of natural gas per year, thus avoiding the emission of 160 tons of CO and 700 tons of NO_x per year. (USEPA, 2020) In economic terms, installing 100 Pelamis P2 units combined will satisfy 14.1-70.3% of the platform's demand. These values correspond to saving up to 17600000m^3 of natural gas and reducing emissions by almost 12000 tons of CO and 54000 tons of NO_x. (Nizamani, 2021)

2.3 Solar Energy

Solar energy has already been studied for offshore applications whether to satisfy the energy demand of offshore activities for which it is difficult to obtain energy from land, or due to the scarcity of habitable land, environmental regard and protection of fragile ecosystems. Offshore activities which require power include ocean energy harness equipment, fishing activities, ocean mining, trade, transportation and finally oil and gas platforms studied in this paper. Until today, most of these activities rely on fuel carried along the path to satisfy their power demand. Moreover, in many of these activities long term offshore operations and accidental incidents fuel shortages may be a great threat to the system's functioning and the personnel's survival. In such cases, an autonomous system may be a critical response to the problem. Most of these activities can be alimented with the low grade yet abundant energy provided by natural renewable resources to be collected in the ocean. Trapani and Millar in

2013 introduced a photovoltaic offshore model for a land scarcity dilemma in on the Maltese islands.

Solar energy is continuously gaining more approval due to its environmental benefits, maneuverability, compactness of installation, independency, domestic and industrial usage possibility and little maintenance requirement. (Kumar, Shrivastava, & Untawale, 2015)

The sun is made up of hot plasma merged with magnetic fields. Energy is released by the nuclear fusion of hydrogen nuclei into helium. The surface temperature achieved by the sun is 5762K. (Kreith & Kreider, 1978) The sun's total energy production is $3.8\text{x}10^{20}$MW, of which only a small portion of $1.7\text{x}10^{14}$kW reaches the earth. Nonetheless, the global energy demand in 2004 amounted for only 30 minutes of the sun's energy reaching earth in a year. Complete absorption of solar radiation is impossible due to absorption by the atmosphere, diffraction and scattering. A solar constant is known as the solar radiation that the sun provides per unit area, which is directly exposed to perpendicular sunlight rays, equivalent to 1.368kW/m^2. (Kalogirou, 2004) Based on today's energy demand, around 1 hour of sunlight radiation is enough to satisfy the global energy demand in ideal terms. Solar energy harvesting techniques are classified into two main types: Solar Thermal and Solar Photovoltaic (PV). The thermal process uses solar energy for thermal requisition such as heating internal environments, water heating and desalination. On the other hand, Photovoltaic methodology converts solar energy into electricity without the need for an engine. It is important to note that Thermal solar systems provide low grade energy, and are thus better used for heating applications, while PV provide high grade energy which loses value when degraded and thus is better used in the electric form. (Ghaffour, Goosen, Mahmoudi, & Bundschuh, 2014) Solar energy exploitation in the ocean has many benefits on a technical, social and commercial level. Some of the advantages are:

- Nature cooling by air and seawater in ocean environments provides higher PV efficiency
- No need for water supply for panel cleaning
- Facilitated modeling and scaling from microwatt to megawatt.
- Reduction of water evaporation and algae growth by covering the water surface
- Buoyancy may be used to simplify the structure design
- Environmental benefits due to low emissions
- Availability of space for panel implementation near sites with high demand

Drawbacks:

- Excessive corrosiveness and scaling due to seawater
- Robust design requirement in harsh climate conditions
- Intervention in marine ecosystems and damage to biodiversity
- Lack of policies to encourage the development

Solar Photovoltaic Design

The greatest advantage of photovoltaic systems lies its dimensions, which allows it to produce as little as microwatts to as much as megawatts of power. Its structure is vigorous, uncomplicated and requires little maintenance. Conventional PV conversion efficiency ranges from 15% to 20%. However, in the 1960s and 1970s the energy generated by PV systems in their lifetime was less than the energy required for their production. Today, the panel recovers its energy construction requirements in 2 to 4 years, with 30 years of estimated lifetime. (apani Kim, 2013)

In the light of the nuclear catastrophe that occurred in 2011 in Japan, a 15-meter tsunami led to the destruction of nuclear reactors due to disruption in power supply required for cooling. Four reactors with a capacity of 2719MW became unfunctional. (WNA, 2014) In order to recover the lost energy previously provided by the nuclear power plant, the Japanese government instantly decided to implement a program which promotes the use of renewable energy. The Feed-in-Tariff program local companies are required to buy renewable energy at a price fixed by the government for 20 years. In 2012, Japan reached an incredibly high 7000MW quota by PV system installation and aimed to install 5300MW in 2013. On the long term, Japan set a goal of 28GW by 2020 and 53GW by 2030, looking forward to supply 10% of domestic energy needs by solar power. A 70MW Kagoshima Nanatsujima solar power plant, the largest solar power plant in Japan constructed in record breaking 14 months, is composed of 290,000 PV cells, which are enough to satisfy the demand of 22,000 households and reduce emissions of 25,000t per year. (Power Technology, 2014)

Fig. 4 Existing floating PV applications

2.4 Wind Energy

Power of wind is used for electricity generation, domestic usage, small-scale industrial activities, in-farm housing and flour windmills ever since ancient times. Studies have been performed on the on the viability of offshore wind power, tackling wing dynamic properties and their impact on power generation. When choosing the location to install an offshore wind turbine, a vital parameter ‘Capacity Ratio’ is considered. It is the ratio of the average output power to the maximum power in a given time interval. Optimistically, this ratio is around 45% for an ideal performance, while it usually fluctuates around 20%-35%. Offshore wind turbines are more consistent and productive due to the abundance of sea breezes. (Pinson, Giebel, & Clausen, 2013) Wind Velocity increases while going away from the shore, thus increasing the potential electric power production, however it renders construction plans and offshore grid cabling more difficult. Floating foundations have shown to be a good solution in some cases. Moreover, larger hub heights, and greater rotor diameters are required to capture higher and faster winds. Rated power of the wind is calculated by the following formula:

P_{rated}= Ar x PD x η

Where Ar is the swept are of the rotor, PD is the power density of the wind and η is efficiency of the used turbine indicated by the producer. Power density is proportional to density of the air and the speed of wind cubed. Research by Y. K. Tiong et al. (2015) took wind speed data from SHELL Sabah Water Platform area provided by Sarawak SHELL Bhd. A SIEMENS-SWT-4.0-120 was selected due to its low minimum required wind speed and a potential rated power as high as 4MW at 13m/s optimal wind speed. Considering the average climate conditions of the chosen location, the wind turbine implemented in the study shows a promising rated power of 495 kW.

Based on the results mentioned above, wind turbines can be installed together with solar panels to form arrays able to provide sufficient power to the oil and gas platform. The integration of the two systems is a great consideration, due to the alternating power outputs produced by these 2 systems due to seasonal changes in weather conditions. The PV solar panel contributes most to power generation in summer periods when wind power is at its lowest and vice versa during winter season. (Zahari & Dol, 2014) (Tiong, Zahari, Wong, & Dol, 2015)

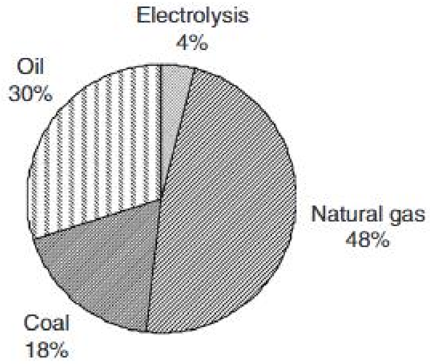
3. Excess Renewable Energy

3.1 Usual excess energy solutions

Climate change, air pollution and the need for secure energy are among the main reasons which push us towards the use of renewables to raise the Renewable Portfolio Standard (RPS). (California Energy Commission, 2018) RPS is a standard imposed by the state, which stabilizes the percentage of electricity sold that must come from renewable resources, introduced to reduce greenhouse gas emissions and promote more efficient energy production. For instance, an RPS of 80% means that 80% of electric energy consumption must be satisfied by renewable sources such as wind and solar energy. (National Conference of State Legislatures, 2021) In case of electricity grids, the variability of renewable energy sources causes incompatibility between the temporal portrait of renewable electricity production and the corresponding demand. Occasionally, power generated may exceed the electric load, thus generating energy which cannot be used. This phenomenon compels renewable energy producers to adopt curtailment measures i.e., deliberately reduce production below capacity in order to balance generation and load. (Georgilakis, 2008) For instance, during lockdown caused by COVID-19 pandemic in UK, energy demand has drastically dropped in a very short time. This led to excess energy production from renewables and consequently surges in unused energy thus causing disruptions in power supply. Certainly, Britain is not the only one to face this problem as other countries which integrated renewables into their energy mix have reported that such occurrences pose problems to their energy supply. (Relph, 2019) China in 2013 revealed 10.74% of its wind energy curtailed. (Bird, et al., 2016) In the United States wind energy curtailment has reached up to 4% in most regions where it occurred. (Bird, Cochran, & Wang, 2014) Electric energy when generated, must be consumed right away, in order to secure balance between demand and supply. Consequently, electric grids are always at a risk of surges, unless this excess is stored or diverged to other uses. Maintaining demand and supply in equilibrium is a difficult task, especially with abrupt changes such as the one caused by the coronavirus pandemic. However, the dilemma of excess renewable energy is not a new one and several solutions already exist, which is crucial for optimizing the use of renewable energy sources in order to obtain the maximum of their environmental benefits. One solution, as stated by Jim Watson, professor and research director at the University College London’s Institute for Sustainable Resources, is pump storage. This technique includes hydro stations which pump water to elevated heights when electricity demand is low and then use it to generate electricity when the demand rises. (Relph, 2019) Forrest and Shafer (2016) in their study on a 50% renewable energy grid have showed that pumped hydropower storage is the most economical solution in reducing greenhouse gas emissions per ton, followed by compressed air and battery storage. Compressed air being a technique where the excess energy is used to feed compressors in order to compress air initially at atmospheric pressure, which will then be decompressed when demand rises. However, this option is clearly not viable on offshore oil and gas platforms. Another common solution is battery storage, which may be an attractive option for electricity grids in order to fight against sudden surges in demand on hourly basis. Nonetheless, this technique is not viable enough for seasonal scenarios. In addition, even though battery storage may seem attractive for domestic or urban uses, it is quite difficult to apply it on platform scale due to weight and size limitations of the platforms. Moreover, another solution is widening electricity grids in order to exploit the energy by selling it to more destinations. This recourse is already being studied and has been mentioned in literature. Finally, a very stimulating alternative is the use of hydrogen as a method for energy storage. Hydrogen in fact can power cars and interestingly may be also used to power some existing gas turbines. This means that hydrogen might be an attractive path for oil and gas operators where they can use renewable resources, thus reducing their emissions and the corresponding taxes, in a cost-efficient manner. A great portion of hydrogen is still produced from natural gas today, meaning that it still contributes to pollutant emissions. However, in this research, hydrolysis of sea water is proposed to produce hydrogen on platforms. Hydrogen may be produced by electrolysis of sea water, where the electric energy provided in this case would ideally be a form of renewable energy produced on the platform. In this case, hydrogen would be produced in an ecofriendly manner, without having to exploit more hydrocarbons, as the initial aim of the research is its mitigation. Further, the hydrogen produced, considering that it can’t be stored or burned on the platform itself to power the equipment, can be rather fed to a methanator, in order to produce renewable methane, thus increasing the production of the site without adding to its environmental impact. Nevertheless, it is important to note that renewable methane requires electrolysis to produce hydrogen, and then the addition of CO2, which often constitutes a part of the production fluids. Moreover, the implementation of a methanator is required.

3.2 Hydrogen production Methods

R. Kothari et al. (2008) reported that 96% of hydrogen up until that date has been produced from oil, coal and natural gas through chemical processes. The remaining 4% was produced by electrolysis, yet with the electricity prevalently being produce from fossil fuel sources.



While hydrogen is said to be a clean energy provider, it is in our interest to produce it from renewables while aiming towards reducing greenhouse gas emissions. The main processes used for hydrogen production in decreasing order are as follows:

- Natural gas steam reforming: The most widely used technique, is an endothermic process, with nickel used as catalyst. The higher the hydrogen to oxygen ratio in the feed, the more favored it is for this reaction. Mainly light hydrocarbons are used for this purpose, while heavier HCs are of less interest due to their lower end yield of hydrogen. Finally, huge amounts of steam generated are not required by the system, thus they are either transported or transformed into electric energy through steam turbines before export.

- Partial oxidation of hydrocarbons: Exothermic reaction with oxygen and steam at relatively high pressures, with or without catalyst based on the feed used and the system specifications. This is the second most important method for producing hydrogen, as it may be used for any type of feed, and is therefore used for heavier hydrocarbons, high sulfur feeds and refinery residual oils. A disadvantage of this technique is that it produces carbon monoxide along with carbon dioxide.
- Coal gasification: Shows a similar mechanism relative to the partial oxidation of hydrocarbons. CO, CO2 and H2 are produced in this reaction. CO2 is later removed by washing with ethanamine or potassium hydroxide. Methane is another minor product of this reaction, whose yield might be increased by raising pressure to 1000psi. The average efficiency of the processes studied by R Kothari et al. is 75%. Sulfur oxide production is neglected as it is often nearly null, and sulfur is often removed from the flows.

3.3 Hydrogen from renewable sources

Hydrogen generated from renewable sources is gaining more and more popularity towards becoming an energy carrier in a more sustainable world. As fossil fuels are finite, thus always scarcer and more expensive, and more importantly cause damage to the environment, the world must switch gradually towards hydrogen production from renewable sources such as wind, water and solar energy. Electrolysis is only responsible for greenhouse gas emissions when fossil fuels are used for the system’s power supply.

Thus, using renewable energy to power electrolyzers seems to be the way to go. A renewable energy system such as a photovoltaic, wind, wave or hydropower can all be used to produce electricity. Any of these methods, when combined with an electrolyzer, may produce hydrogen with little to no greenhouse gas emissions.

It is important to study the feasibility of implementing an electrolyzer on an oil and gas platform. This is done by considering the weight, size and electric load of the plant, in addition to the possibility and challenges of using seawater.

The basic functioning of an electrolyzer is described by a cell with H2O flow provided with a low concentration of a compound such as sulfuric acid used to increase conductivity. The other two compartments are the anode and cathode where oxygen and hydrogen are produced respectively, by a source of electricity connected to the platinum electrode placed at the bottom of each compartment. In this study, the source of electricity would be the renewable energy farm described.

4.Biological hydrogen methanation

Biogas is a product of a biologically conveyed process referred to as Anaerobic digestion. Biogas is mainly composed of methane (CH_4) from 50% to 70% and carbon dioxide (CO_2) having a concentration of 30-50%. The respective concentrations of CO_2 and CH_4 in biogas mainly rely on the intrinsic properties of the substrate and the pH of the reaction medium. Apart from these two main products, biogas also contains other minimal amounts of impurities, such as nitrogen of about 0-3%, probably deriving from air contained in the reactants, water vapor (H_2O) of 5-10% or higher at particularly thermophilic conditions originating from medium evaporation, oxygen (O_2) up to 1% which enters along with the substrate or due to leaks. Moreover, other minor impurities are present like hydrogen sulfide

(H_2S) up to 10,000 ppmv, resulting from the reduction of the reactants coming from some waste influents, ammonia (NH_3) resulting from hydrolysis of protein containing substances or urine, hydrocarbons up to 200mg/m3 and siloxanes reaching 41mg/m3 coming from industrial effluents. (Muñoz, Meier, Diaz, & Jeison, 2015) (Petersson & Wellinger, 2009) Besides methane, all other components of biogas are undesired and are treated as impurities. The energy content of pure methane, also defined as Lower Calorific Value (LCV) 50.4MJ/kg or 36MJ/m3 at STP. While biogas with around 60 to 65% of methane has an LCV of around 20-25 MJ/m3 of biogas. Hence, it is clear that the higher the amount of pollutants, the lower the energy content. H_2S and NH_3 in their turn are toxic and highly corrosive gases, which damage the equipment through emission of SO_2 by combustion in case of H_2S. In addition, the presence of siloxane, even in small amounts, causes problems such as sticky residues deriving from silicon oxides which adhere to various system compartments causing defective functioning. (Abatzoglou & Boivin, 2009) At present, different techniques exist for the removal of impurities from biogas to make it more applicable to different uses. The first treatment revolves around "Biogas Cleaning", i.e., the elimination of compounds harmful for health, environment or equipment (such as NH_3, H_2S, Si, Volatile organic compounds (VOCs), siloxanes and CO). Nonetheless, in practical terms H_2S is the only compound being treated, as many current biogas manufacturing systems have a built in H_2S removal compartment, usually based on biological oxidation of H_2S under the action of aerobic sulfate oxidizing bacteria. Another rather important treatment is called "Biogas Upgrading", whose task is to improve the lower calorific value of the biogas, thus rendering it a higher standard fuel. (Sun, et al., 2015) In the case which biogas achieves a purity similar to that of natural gas, the gas produced is then called biomethane. (Kougias, et al., 2017). Presently, natural gas required composition is based on regulations set by the authorities, which exceeds 95% in some cases. However, the European Commission has stabilized regulations to achieve homogenized gas specifications. (Kougias, et al., 2017) It is crucial to bear in mind that during upgrading, the CO_2 content of raw biogas is either eliminated or converted to methane by the reaction with hydrogen. (Kougias, et al., 2017) Numerous upgrading techniques are already implemented; hence a continuously increasing number of biogas plants are arising in Europe. Germany is the leader in this trend, followed by Sweden, UK and other European countries. (Hoyer, Hulteberg, Svensson, Jernberg, & Nörregård, 2016).

Biogas upgrading Technologies

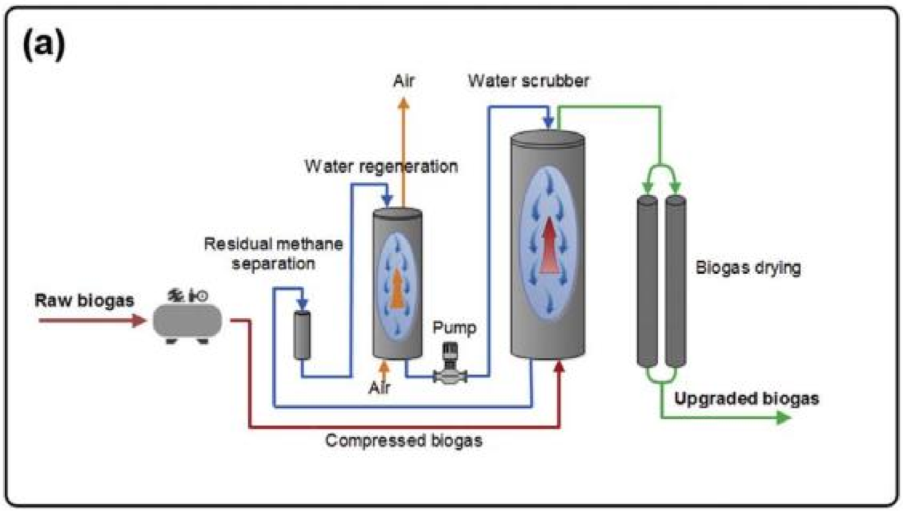
Nowadays, several techniques to separate/convert CO2 from CH4 exist commercially, including absorption, adsorption and membrane separation. In addition, processes involving cryogenic chemical hydrogenation are under study. This study aims to present some of the important techniques and analyze one of them in depth in the scope of oil and gas platforms.

Generally, physicochemical processes can lead to a 96% purity of methane. However, particularly complex thermodynamic and catalytic conditions in terms of temperature, pressure or addition of chemical substances required to achieve an efficient biomethanation.

(Angelidaki, et al., 2018)

Physical absorption using water scrubbing.

Water scrubbing is the most utilized method for cleaning and upgrading biogas. (Thrän, et al., 2014) This process aims at separating CO_2 and H_2S from raw biogas, exploiting their high solubility in water with respect to CH_4 (solubility of CO_2 in water is around 26 times more than that of methane at 25 degrees Celsius based on Henry's law). In this process biogas is pressurized to about 6-10 bar and injected from the bottom of the absorption column, where water flows countercurrent from the top (Bauer, Persson, Hulteberg, & Tamm, 2013). The absorption column is filled with packing material to increase the contact surface and thus mass transfer between gas and liquid. (Ryckebosch, Drouillon, & Vervaeren, 2011) Purified CH4 is released from the top, while water rich in CO2 and H2S is sent to a flush column where its pressure drops, and a part of recovered methane is recirculated into the system. Two techniques are currently available based on the water re-use. Single pass scrubbing is the method applied when treated sewage wastewater is used. Regenerative absorption technique is implemented to allow the recirculation of water after passing through a desorption column where it depressurized by air stripping to remove CO2 and H2S. In case of high H2S concentrations steam or inert gas is used during depressurization to prevent sulfur formation which may lead to technical problems. (Ryckebosch, Drouillon, & Vervaeren, 2011) Regeneration processes are performed due to huge amounts of water required; where for each 1000Nm3/h of biogas, around 180 to 200m3/h of water flow is introduced based on the thermodynamic conditions. (Bauer, Persson, Hulteberg, & Tamm, 2013) After this process, up to 99% purity of methane can be achieved. (Sun, et al., 2015)



Physical absorption using organic solvents.

This method is similar to water scrubbing in process terms yet uses organic solvents consisting of methanol and dimethyl ethers of polyethylene glycol, of which several commercial products are present. The advantage of these products is their high solubility of CO2, up to 3 times more than the solubility in water, which allows the use of less liquid volumes and therefore smaller dimensions of the components. However, this solubility is also the main drawback since it makes the organic solvents difficult to regenerate. Moreover, the selectivity of Selexol (a popular brand solvent used for the process) is much higher towards H2S with respect to CO2, thus high temperatures are required to remove CO2. (Persson, 2003) In this case, in order to reduce energy consumption H2S must be removed prior to the absorption process. The final product in this case may reach up to 98% purity. (Bauer, Persson, Hulteberg, & Tamm, 2013)

Chemical Absorption using amine solutions

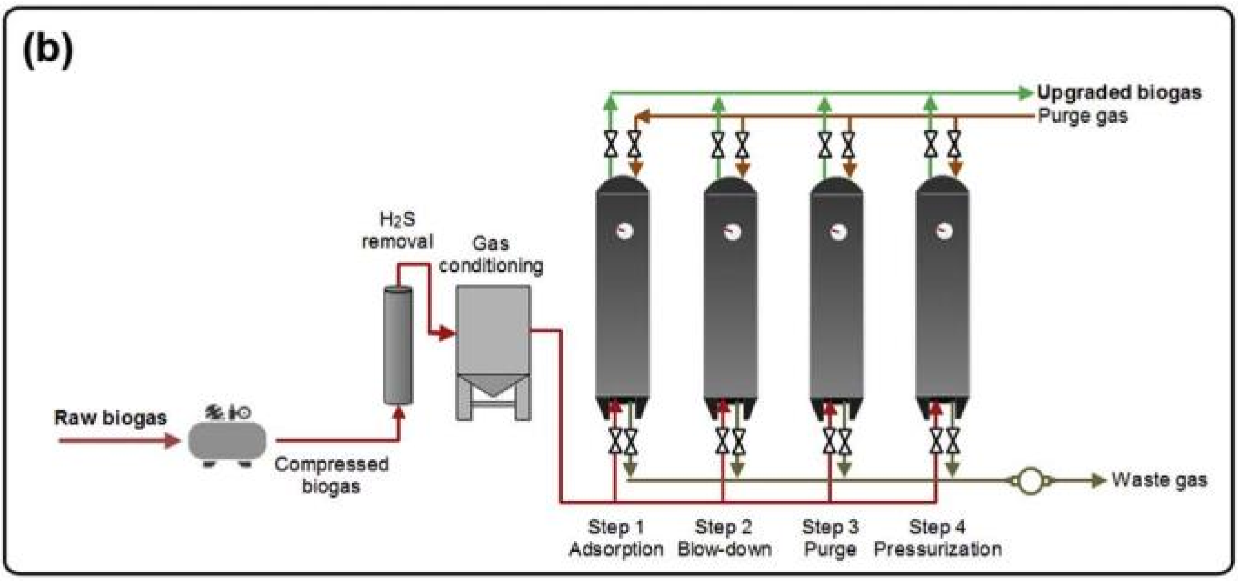
Chemical scrubbers utilize aqueous amine solutions to bind the CO2 molecules which must be removed. An advantage of the system is that it may also completely remove H2S. Absorber and scrubber unit are the main compartments of an amine scrubbing system. Biogas at a pressure of 1-2 bars flows upwards through the absorption column, encountering the amine solution flowing to the bottom, which allows an exothermic chemical reaction to take place, where CO2 is bound to the amine. Further, the amine rich in CO2 and H2S is sent through a stripping column for regeneration. Stripping occurs at 1.5-3 bars and a temperature of 120-160 degrees Celsius. At such high temperature, the chemical bonds formed earlier tend to break, while allowing the formation of steam to act as a stripping fluid. In addition, some alkaline salts of potassium, sodium or calcium hydroxides may be used to enhance the reactivity of CO2. (Kougias, et al., 2017) (Zhao, Leonhardt, MacConnell, Frear, & Chen,

2010) Theoretically, sodium hydroxide is around 50% more efficient in capturing CO2 when compared to mono-ethanolamine. (Yoo, Han, & Wee, 2013) Main drawbacks of this method are the toxicity of the solvent to both humans and environment, great amounts of energy required for regeneration, the cost of the solvents and their continuous loss due to volatility. Hence, alkaline salts are often preferred due to their abundance and cost feasibility. (Yoo, Han, & Wee, 2013). A 99% methane purity can be achieved by this method due to the high selectivity of the chemical reaction, which allows less than 0.1% methane loss. (Angelidaki, et al., 2018)

Pressure swing adsorption (PSA)

This method extracts the various gases from the influent raw biogas due to their affinity to the adsorption material implemented. Adsorbents may be carbon molecular sieves, zeolites, activated carbon and other materials with a high specific area. (Augelletti, Conti, & Annesini, 2017) The pivot of this method is the attraction of gases at high pressure to the surface of the adsorbing material. Thus, when a pressurized gas is introduced, adsorption of the impurities takes place, whereas, at low pressures the gases are released. PSA consists of adsorption, blowdown, purge and pressurization. (Augelletti, Conti, & Annesini, 2017) First, pressurized raw biogas at 4-10 bars is sent through the adsorption column, where CO2, H2S, O2, N2 and H2O are retained by the adsorbent, while methane flows to the top and to be collected by lowering the pressure. In practice, several adsorption vessels are introduced to guarantee continuity. (Bauer, Persson, Hulteberg, & Tamm, 2013) When the adsorption material is saturated, the biogas passes to another vessel. The saturated adsorbent is regenerated by depressurizing the material allowing it to release the gases. The released gas contains a considerable amount of methane and thus must be recycled. (Awe, Zhao, Nzihou, Minh, &

Lyczko, 2017) The adsorption of H2S however is irreversible, thus it must be treated earlier before the adsorption process. (Zhao, Leonhardt, MacConnell, Frear, & Chen, 2010)This technique is attractive due to its low space requirement, cost efficiency as well as safety and ease of operation. (Augelletti, Conti, & Annesini, 2017)Biogas in this case can be upgraded up to 96-98% methane yet losing up to 4% of methane. (Bauer, Persson, Hulteberg, & Tamm, 2013) (Ryckebosch, Drouillon, & Vervaeren, 2011)



Membrane separation

The membrane technique is a valid competitor to the commonplace absorption systems used to upgrade biogas. The fundamental concept of this method is the selective permeability of the membrane versus other gases in this increasing order of permeation as follows: C3H8, CH4, N2, H2S, CO2 and H2O. (Bauer, Persson, Hulteberg, & Tamm, 2013) Depending on the separator specifications, this method may be applied for both dry and wet streams. Gas/gas (dry) procedure required specific membranes, typically polymeric. The polymeric components that show to be compatible with CO2 and CH4 separation are cellulose acetate and polyimide. (Baker, 2012) The permeance of the undesired gases is determined by sorption coefficients and on the characteristics of the used membrane which determine the selectivity towards the different gases. (Baker, 2012) Sorption characteristics of the material are influenced by the condensability of the permeant, which makes larger molecules more condensable compared to smaller ones. Conversely, diffusion coefficient drops as the molecular size rises. When considering both diffusion and sorption criteria, it appears that smaller molecules such as CO2, are more likely to permeate the membrane when compared to CH4 which tends to condense since it is a larger molecule. (Baker, 2012) Thus, in polymer composed membranes the solubility and diffusivity parameters of CO2 are greater compared to CH_4, leading to enhanced permeability. Hence, CH4 will tend to remain at the higher-pressure side of the membrane, while CO2 along with a sizable portion of methane (up to 10-15%) will end up in the lower pressure side. In practical applications, H2S removal is performed prior to the process to avoid corrosive gases reaching the equipment. (Persson, 2003) Later, biogas undergoes compression before being introduced to the membrane-containing compartment. (Bauer, Persson, Hulteberg, & Tamm, 2013) The system's efficiency is highly dependent on the material and typology used for the membrane. Evidently, the better membrane is the one with great permeability difference between methane and CO2 in order to restrict CH4 leakage and secure an efficient process with minimal losses. At present, four chief processes of gas/gas membrane processes are in use. A one stage, a two-stage coupled with a recirculating loop, a two-stage and a three- stage with a sweep biogas stream (Makaruk, Miltner, & Harasek, 2010) Clearly, the single stage process is simple as it contains no circulating components compared to the two-stage operation, which therefore requires less maintenance (Baker, 2012), thus reducing operational expenditure (Angelidaki, et al., 2018) In addition, the two-stage design with sweep, the biogas stream exiting the bottom unit is reintroduced into the top unit after mixing with the influent gas stream in the form of a sweep stream. In the end, the three-stage design also has a sweep gas stream and an additional membrane separator to the two-stage system yet having a low-pressure feed membrane containing both enrichment and stripping sections. In the aforementioned process designs, the resulting methane content is typically 95%, but can reach up to 98% under specific constraints. (Bauer, Persson, Hulteberg, & Tamm, 2013)

The advantage of wet membrane separation is that wet membranes also present absorption characteristics, thus combining the advantages of the solid membrane with the previously mentioned absorption techniques, where gas molecules may be absorbed by the liquid phase after crossing the membrane counter-current with respect to the liquid. The liquid may then be regenerated at elevated temperatures, resulting in the release of CO2, pure enough to be used for other applications. The downside of this technology is its high cost and fragility of membranes which last approximately 5 to 10 years. (Bauer, Persson, Hulteberg, & Tamm, 2013)

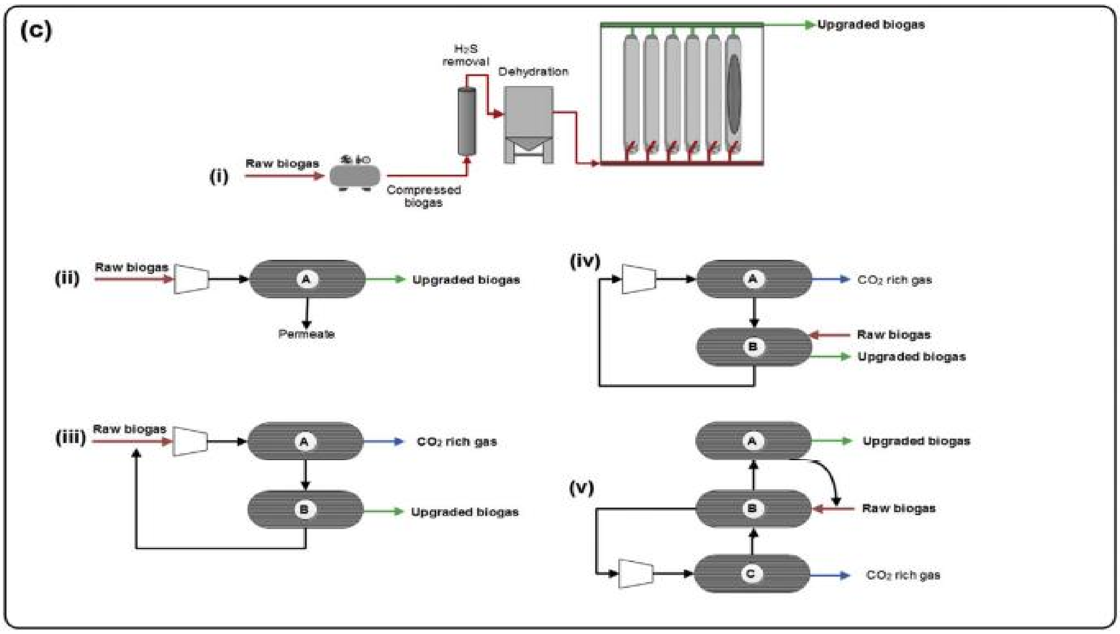


Figure showing the various aforementioned types of membrane processes

Cryogenic separation process

This method is based on the decrease of biogas temperature, liquifying methane to separate it from CO2 and other pollutants (Muñoz, Meier, Diaz, & Jeison, 2015), to achieve a methane up to the quality standards of Liquified Natural Gas (LNG) (Grande & Blom, 2014). Separation is carried out by water removal and compression up to 80 bars, followed by gradual cooling up to -110 degrees Celsius. (Ryckebosch, Drouillon, & Vervaeren, 2011) In this process minor impurities such as H2O, H2S, siloxanes and halogens are removed along with CO2 which is the predominant undesirable component, until methane reaches a purity of more than 97% in this process, however it is still unpopular and understudy (Bauer, Persson, Hulteberg, & Tamm, 2013), due to economic feasibility, methane loss issues and operational problems such as cogging, resulting from an excessive portion of solidified CO2 or other impurities inhibit the expansion of this method. (Bauer, Persson, Hulteberg, & Tamm, 2013) (Muñoz, Meier, Diaz, & Jeison, 2015) (Ryckebosch, Drouillon, & Vervaeren, 2011)

Chemical Hydrogenation of methane

CO2 may be reduced with H2 through a chemical process by applying the Sabatier reaction. In practical applications several catalysts are in use, with Nickel and Ruthenium dominating the industry (Jürgensen, Ehimen, Born, & Holm-Nielsen, 2015) have already been examined at high temperature (300ºC) and pressure (5-20 MPa) (Xia, Cheng, & Murphy, 2016). Due to impressive selectivity, the reaction may completely convert CO2 and H2. (Jürgensen, Ehimen, Born, & Holm-Nielsen, 2014) However, in spite of the attractive efficiency, some disadvantages are still present, such as the negative impact on sustainability due to the presence of catalysts poisons as impurities, which necessitates its frequent substitution. (Gübitz, Bauer, Bochmann, Gronauer, & Weiss, 2015) Another difficulties facing the process are the scarcity of raw material for catalyst manufacturing and great energy consumption during operation. (Angelidaki, et al., 2018)

Biological Renewable methane production

Biological upgrading processes can be distinguished into photosynthetic and chemoautotrophic. The majority of these designs has been experimentally verified and are at the early stages of piloting and commercialization. The greatest benefit of this technique is the conversion of CO2 into a more valuable energy rich outcome at contained costs (atmospheric pressure and relatively low temperature) thus endorsing the concept of sustainability and giving rise to circular economy. (Angelidaki, et al., 2018)

The previously mentioned methods are to be seen not only as ways to upgrade methane, but also methods of CO2 capturing in order to avoid its release into the environment to reduce greenhouse gas emissions, or to convert it into another gas (methane in this case), which is of useful lower calorific value, thus having an attractive energy content. In other words, this technique may be applied to remove a greenhouse gas, converting it into a worthwhile material, using renewable energy sources and respecting the values of a circular economy.

Chemoautotrophic Methanation

This technique relies on the use of hydrogenotrophic methanogens, i.e., organisms which can metabolize hydrogen as a source of energy, by reducing CO2 to produce methane according to the following reaction:

- $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Nonetheless, in order to give rise to a sustainable process, the hydrogen used in the process must come from a renewable source. Consequently, the conceptualization of utilizing renewable electricity to electrolyze water for hydrogen production has gained vast consideration, even more so in the case when this energy comes from surplus renewable energy production coming from wind, sun or the ocean which would have been curtailed or lost otherwise. This technique is also valuable for the purpose of storing the excess renewable energy, a recent pioneering application called power to gas (P2G). As explained earlier, solar and wind and ocean energy are methods which need calibration during darkness or when the wind and waves are motionless. Batteries aren't always a convenient solution due to their relatively low storage capacity, elevated cost, toxicity and environmental impact of the materials used and finally the restrictions of size and weight in case of oil and gas platforms. Renewable electricity is used to electrolyze water into H2 and O2, thus producing a clean energy carrier without CO2 emissions in the process. Nonetheless, hydrogen has some drawbacks to be considered before using it in practical applications. Precisely, hydrogen has an immanent downside due to its low volumetric energy, which makes its storage complicated. (Jürgensen, Ehimen, Born, & Holm-Nielsen, Utilization of surplus electricity from wind power for dynamic biogas upgrading: Northern Germany case study, 2014)Moreover, the implementation of hydrogen as a transportation fuel is still the development phase. (Muñoz, Meier, Diaz, & Jeison, 2015).

Hence, blending the P2G technique to convert hydrogen into methane is a very interesting method as it combines renewable energy exploitation with biogas, both being sustainable processes. This procedure is a great potential source to convert renewable electricity into a chemical energy carrier, which can be smoothly introduced into the natural gas framework already in use. Energy content of methane (36MJ/m3) is significantly greater than that of hydrogen (10.88 MJ/m3). (Luo, et al., 2012). Furthermore, this technique uses the existing equipment of biogas facilities, thus making it more economically favorable. Moreover, chemoautotrophic processes do not absorb or or capture CO2 but convert it into methane, thus increasing enormously the energy content of the product. The product may be called windgas or solargas based on the renewable energy source behind electrolysis. (Kougias, et al., 2017). Last but not least, this technique allows to promote a sustainable production of pioneering of pioneering biogas, which permits the production of methane independent of the availability of biomass. This makes the method also interesting for oil and gas platform applications. Three designs can be described to date, in-situ, ex-situ and hybrid methods. (Kougias, et al., 2017) So far, the in-situ and ex-situ techniques have already been experimentally tested, with various literature availability on the topic. However, hybrid design is still requiring more research and experimental work already taking place with a promising potential. (Angelidaki, et al., 2018)

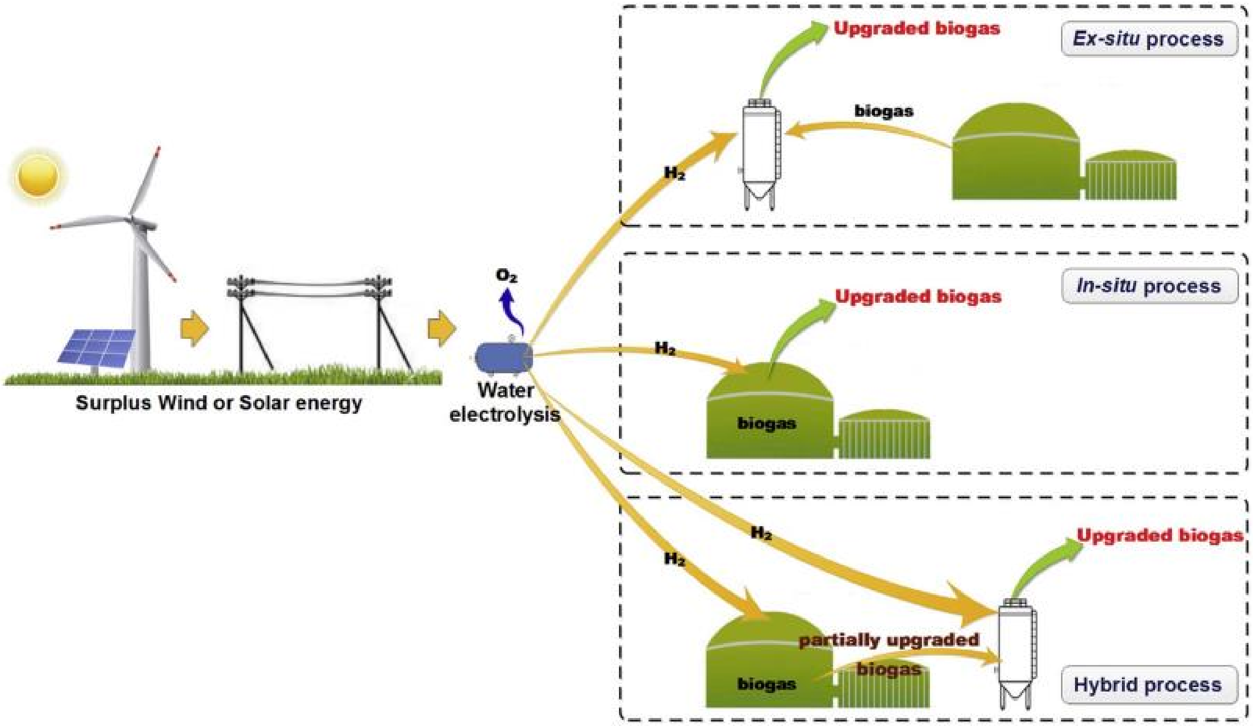


Figure showing 3 chemoautotrophic biomethanation processes: 1)Ex-situ 2)In-situ 3)Hybrid

In-situ Biological Methantion

This method includes the introduction of H2 into a biogas reactor, to be combined with the innate CO2, produced by the anaerobic metabolizer, to finally be converted into methane under the action of autochthonous methanogenic bacteria called archaea. (Kougias, et al., 2017) This method can lead to a methane purity of up to 99% in the case of careful monitoring of the reaction medium. An important obstacle of this technique faces is the rise of pH to levels over 8.5 which hinders the production of methane. The rise in pH is linked with the removal of bicarbonate which is the main buffer substance in the reactor. As CO2 is dissolved in the liquid phase, it produces H+ ion and bicarbonate according to the following chemical equilibrium:

$$H_2O + CO_2 \leftrightarrow H^+ + HCO_3^-$$

Based on Le Chatelier principle, the consumption of CO2 will lead to the decrease in hydrogen ion, thus increasing the alkalinity of the medium. Previous experiments also proved a slight hindering of methane production due to bicarbonate depletion. (Luo, et al., 2012)This proves the previous statement that a pH of 8.5 is the limit for optimal methanogenesis in terms of reaction parameters. (Bassani, Kougias, Treu, & Angelidaki, Biogas Upgrading via Hydrogenotrophic Methanogenesis in Two-Stage Continuous Stirred Tank Reactors at Mesophilic and Thermophilic Conditions, 2015) To resolve this issue, co-digestion with waste with acidic character was suggested to limit the increase in pH. (Luo & Angelidaki, 2013) In detail, it has been proven that manure (fertilizing animal waste) and cheese whey wastewater helped keep the pH at optimal conditions for the complete process duration. Another method suggested to solve this issue was pH control to allow an almost pure biomethane production. (Luo, Wang, & Angelidaki, 2014) Another challenge to be faced is the oxidation of Volatile Fatty Acids (VFA) and alcohols which is only possible if H2 concentration is very limited. (Batstone, et al., 2002) Contrarily, high Hydrogen partial pressure (more than 10 Pa) hinders anaerobic digestion, and favors the augmentation of electron sinks like ethanol, lactate, propionate and butyrate. (Liu & Whitman, 2008) It is said that sudden surges of H2 concentrations are present in the influent, VFA degradation wouldn’t be feasible. (Batstone, et al., 2002) Consequently, the process may lose its functional parameters, leading to fatal worsening due to high acidification by VFA increase. A modern stydy showed that the introduction of H2 at concentrations above the stoichiometric requirement of biomethanation led to augmented quantities of acetate, due to change in the reaction conditions favoring homoacetogenic process, thus limiting methanogenic activity of archaea. (Agneessens, et al., 2017) Nonetheless, longer exposure to hydrogen grows the hydrogenotrophic bacterial presence and makes it immune to this problem. (Reeve, Morgan,

& Nölling, 1997) Another issue to be tackled is solubilizing the hydrogen to allow it to pass from the gas to the liquid phase in order to allow its contact with the bacteria. Solubility of gases in water is generally very low, which hinders mass transfer thus decreasing the reactivity. (Tirunehe & Norddahl, 2016) Therefore, the methods and equipment used for H2 injection, as well as reactor design and gas recirculation trajectories are crucial points for the productivity of in-situ biomethanation. (Bassani, G.Kougias, & Angelidaki, 2016) Batch experiments showed that CO2 concentrations below 12% do not allow proper H2 uptake, (Agneessens, et al., 2017)leading to a methane purity of only 89%. (Mulat, et al., 2016) In continuously fed reactors, Luo & Angelidaki, 2013 utilized hollow fiber membranes to introduce H2 in an anaerobic reaction medium treating manure and cheese whey, were able to reach a 96% purity. (Luo & Angelidaki, 2013) Other processes by Luo et al. in an up-flow anaerobic sludge blanket vessel, with the addition of a membrane in hollow fiber in an external degassing compartment showed a 94% methane content. (Luo, Wang, & Angelidaki, 2014) Nevertheless, since hollow fiber membranes are costly, the use of ceramic sponges was tested to allow the contact between Co2 and H2 to convert them into methane. (Bassani, G.Kougias, & Angelidaki, 2016)

Ex-situ biological methanation

The ex-situ biogas upgrade method is based on CO2 supply from an extrinsic source, along with H2 in an anaerobic vessel initially accommodating pure or enriched hydrogenotrophic organisms, leading to their transformation into methane. (Kougias, et al., 2017) The technique is preferred over the in-situ version for the following reasons:

- Ensures the correct functioning of the standard biogas process since the transformation into methane takes place in a separate reactor

- The biochemical conditions are manageable with less effort due to the absence of organic degradation (primary steps of anaerobic digestion like hydrolysis and acidogenesis are not involved)
- Ex-situ method is a biomass independent process
- Outside sources of CO2 may be used which increases the possibility of the process's applications
- This method allows the supply of power to distant locations from the available grids.

As shown in the comparison performed by Angelidaki et al., the ex-situ method can be adapted to high volumes of feed gases, while keeping a gas retention as low as 1 hour, which reduces the size of the upgrading unit. The efficiency of the process, taken as the purity of the methane content, varies between 79 to 98%, based on the type of the implemented reactor. (Angelidaki, et al., 2018) A technical obstacle of this process is the limited gas-liquid mass transfer, governed by the following equation in the case of H2:

- ➢ $r_t = 22.4k_La\ (H_{2gTh} – H_{2l})$

Where r_t is the gas-liquid mass transfer rate of H_2 in L/ ($L_{reactor}$ .day), 22.4 is the molar volume at STP conditions in L/mol, k_La is the gas transfer coefficient in day^{-1}, H_{2g} is the H_2 concentration in the gas phase in mol/L and H_{2l} represents the H2 dissolved in the liquid phase in mol/L. Hence, it is clear that the H2 gas-liquid mass transfer rate is proportional to k_La, which is reliant on the specifications of process like gas recirculation flow (Guiot, Cimpoia, & Carayon, 2011) (Kougias, et al., 2017), reactor design (Bassani, G.Kougias, & Angelidaki, 2016) (Kougias, et al., 2017), the implemented diffusion apparatus (Bassani, et al., 2017) (Díaz, Pérez, Alfaro, & Fdz-Polanco, 2015) (Luo & Angelidaki, 2013) and stirring potency

(Luo & Angelidaki, 2013). Several sources in literature suggest pioneering ideas to improve the efficiency of biomethanation. A study on the comparison between these techniques has been performed by Angelidaki et al. (2018). It has been proven that temperature is a pivotal parameter in determining the reaction's efficiency. In detail, it has been demonstrated that enriched thermophilic environment resulted in 60% higher H2 and CO2 conversion with respect to mesophilic conditions in a batch experiment. (Luo & Angelidaki, 2012) Another research deduced that raising the temperature from 55ºC to 65ºC renders biomethanation more efficient. (Guneratnam, et al., 2017) However, no matter the temperature setting, the microbial environment needs adaptation time to perform an efficient fermentation of CO2 and H2. For instance, a reaction in a mesophilic medium within a packed-bed reactor with a stagnant culture of hydrogenotrophic organisms for an eight-month period, lead to a 96% yield of methane. (Rachbauer, Voitl, Bochmann, & Fuchs, 2016) The biological methanation productivity obtained is comparable to that of the thermophilic process. (Bassani, et al., 2017)

(Luo & Angelidaki, 2013). Reactor design and the implementation of gas recirculation and/or liquid stirring equipment are also crucial elements in the construction of a biomethanator. Series up flow or bubble vessel reactors have shown to reach 98% methane purities, even without injecting H2 in sophisticated ways using membrane structures. (Kougias, et al., 2017) In addition, packed reactors have shown a superior performance of 98-99% efficiency resulting from the establishment of anaerobic association films (layers) that contribute to biocatalysis leading to better results. (Burkhardt, Koschack, & Busch, 2015) (Savvas, Donnelly, Patterson, Chong, & Esteves, 2017) Lastly, high mixing velocity (Luo & Angelidaki, 2012) or diffusion enhancement equipment able to form bubbles to facilitate the mixing, have shown best reaction kinetics and yield. (Bassani, et al., 2017)

Feasibility of energy discontinuity and electrolysis

The final task of this work is to evaluate the possibility of integrating several of the previously listed systems, including renewable energy converters and electrolyzers on a single platform by assessing some parameters mentioned in literature to understand the feasibility of integrating several low emission systems, from renewable energy, to hydrogen production from a clean source, finally to biological methantion with lower power demand and green hydrogen instead of the grey alternative produced by greenhouse gas emitting processes. Electrolysis requires a high amount of energy of around 4.5-5kWh/m3 of H2 yet it managed to gain prestige among industrial electrolysis systems due to their promising potential derived from potential cost-sustainable energy production. The economic feasibility of electrolyzers is determined by the cost of electric energy, which in its turn is the energy with greatest cost since it is a secondary energy source requiring energy conversion. Electricity producing systems are only 30-40% efficient, hence the efficiency of electrolysis is even lower since it is not an ideally efficient process either. To achieve a favorable electrolysis design, energy use must be optimized to reduce losses. (Nikolic, et al., 2010) Hydrogen is gaining more and more popularity as a clean energy carrier, where the best way to produce it in terms of sustainability would be through electrolysis while exploiting renewable energy sources with a low impact. (Ivy, 2004) (Zeng & Zhang, 2010)

According to statistical data provided by Petroleum Association of Wyoming, in 2018 there were 25,605 producing wells, of which 14,638 were gas wells, with an average production of 298 Mcf/day (thousands of cubic feet) (Petroleum Association of Wyoming, 2019) which is equivalent to around 8438 m3/day. Thus, a comparable methane production by the methanation compartment must be achieved for the process to be of economic interest.

Moreover, a source of CO2 is required for methanation, which can be either through anaerobic digestion, or from emissions in a flue gas. (Kozak, Köroğlu, Cirik, & Zaimoğlu, 2022) In addition, often oil and gas wells produce CO2 rich hydrocarbon streams, as high as 26.1%. (Nguyen & De Oliveira Junior, 2017) As per methanation, the energy required for the reaction is 0.44kWh/m3 of biogas upgraded. The energy consumption is predominantly consumed by gas recirculation, around 84% of the energy necessary to pass H2 to the liquid phase at an elevated rate. Meanwhile, heat requirements are negligible. (Alfaro, Fdz-Polanco, Fdz-Polanco, & Díaz, 2018)These energy demands are greater than those of the various commercial techniques in use such as pressure-swing adsorption or water scrubbing (Bauer, Persson, Hulteberg, & Tamm, 2013) with energy requirements around 0.2-0.3 kWh/m3 of biogas. However, it should be taken into consideration that 0.35 m3 of biogas are converted per m3 of biogas feed in best case methane yield scenario. Moreover, methane combustion provides 9.95kWh/m3, the energy stored in new CH4 produced would be 3.5kWh/m3 of upgraded biogas. Hence, the energy requirement constitutes around 13% of the energy introduced by the new portion of CH4, which is a clear energetic benefit. From a different point of view, CH4 potential energy grows from 6 to 9.5 kWh/m3 when upgraded. By subtracting the energy demand for the upgrade, there is a 50% gain in potential energy. It is crucial to mention that electrolysis energy demand for H2 production is 7.2 kWh/m3 of biogas, therefore it is profitable to exploit excess energy produced from renewable sources in order to sustain the costs of the methanation. When this excess energy is available, bioconversion is economically favorable. (Alfaro, Fdz-Polanco, Fdz-Polanco, & Díaz, 2018)

Nizamani et al. stated that a farm of 100 Pelamis P2 wave energy converters produced 62GWh/year, an amount of energy satisfactory to electrolyze water enough to produce hydrogen which in its turn produces $8.6x10^{6}$m3 of methane. Surely, this doesn't mean that the energy provided by the WECS was made exclusively for methane production, but to supply the platform with its energy demand; yet this number is stated to show that wave energy if applied on a large scale may provide inherent values for the activities required. Other energy sources mentioned earlier always show comparable values with the power requirements. Finally, it is interesting to look at all these processes as complementary, in order to exploit every possibility to produce the cleanest energy possible while also growing production, leading to a sustainable design contributing to a circular economy. A model called energy hub, analyzed by Svendsen, 2022 who re-introduces this concept of an integrated energy system model. The mentioned model contained apart from the basic platform equipment: batteries, electrolysis and fuel cells, gas turbines and a wind energy farm. (Svendsen, 2022) In the scenario studied by this project work, a platform study would involve a renewable energy hub of 2 or more alternating energy sources, which provide more continuous power supply. Furthermore, this energy when in excess may be implemented to electrolyze water and produce hydrogen. H2 could be a form of energy storage, yet has a low energy capacity, and thus is better coupled with CO2 to produce methane, raising significantly the energy content.

Bibliography

Abatzoglou, N., & Boivin, S. (2009). A review of biogas purification processes. *Biofuels Bioprod. Biorefin., 3*, 42-71.

Aderinto, T., & Li, H. (2019, November). Review on Power Performance and Efficiency of Wave Energy Converters. *Energies, 12*(22), 4329.

Adolfsen, J. F., Kuik, F., Lis, E. M., & Schuler, T. (2022, April). *The impact of the war in Ukraine on euro area energy markets*. Tratto da European Central Bank | Eurosystem: https://www.ecb.europa.eu/pub/economic-bulletin/focus/2022/html/ecb.ebbox202204_01~68ef3c3dc6.en.html

Agneessens, L. M., Ottosen, L. D., Voigt, N. V., Nielsen, J. L., Jonge, N. d., Fischer, C. H., & Kofoed, M. V. (2017). In-situ biogas upgrading with pulse H2 additions: The relevance of methanogen adaption and inorganic carbon level. *Bioresource Technology, 233*, 256-263.

Alfaro, N., Fdz-Polanco, M., Fdz-Polanco, F., & Díaz, I. (2018). Evaluation of process performance, energy consumption and microbiota characterization in a ceramic membrane bioreactor for ex-situ biomethanation of H2 and CO2. *Bioresource Technology, 258*, 142-150.

Angelidaki, I., Treu, L., Tsapekos, P., Luo, G., Campanaro, S., Wenzel, H., & Kougias, P. (2018). Biogas upgrading and utilization: Current status and perspectives. *Biotechnology Advances, 36*, 452-466.

apani Kim, M. D. (2013). Novel offshore application of photovoltaics in comparison to conventional marine renewable energy technologies. *Renewable Energy, 50(C)*, 879-888.

Årdal, A. R., Sharifabadi, K., Bergvoll, Ø., & Berge, a. V. (2014, June). Challenges with Integration and Operation of Offshore Oil & Gas Platforms Connected to an Offshore Wind Power Plant. *2014 Petroleum and Chemical Industry Conference*, 1-9.

Årdal, A. R., Undeland, T., & Sharifabadi, K. (2012). Voltage and Frequency Control in Offshore Wind Turbines Connected to Isolated Oil Platform Power Systems. *Energy Procedia, 24*, 229-236. doi:https://doi.org/10.1016/j.egypro.2012.06.104

Augelletti, R., Conti, M., & Annesini, M. C. (2017). Pressure swing adsorption for biogas upgrading. A new process configuration for the separation of biomethane and carbon dioxide. *Journal of Cleaner Production, 140*, 1390-1398.

Awe, O. W., Zhao, Y., Nzihou, A., Minh, D. P., & Lyczko, N. (2017). A Review of Biogas Utilisation, Purification and Upgrading Technologies. *Waste Biomass Valor, 8*, 267-283.

Baker, R. W. (2012). *Membrane technology and applications.* John Wiley & Sons.

Bassani, I., G.Kougias, P., & Angelidaki, I. (2016, December). In-situ biogas upgrading in thermophilic granular UASB reactor: key factors affecting the hydrogen mass transfer rate. *Bioresource Technology*, 485-491.

Bassani, I., Kougias, P. G., Treu, L., & Angelidaki, I. (2015). Biogas Upgrading via Hydrogenotrophic Methanogenesis in Two-Stage Continuous Stirred Tank Reactors at Mesophilic and Thermophilic Conditions. *Environmental Science Technology, 49*(20), 12585-12593.

Bassani, I., Kougias, P. G., Treu, L., Porté, H., Campanaro, S., & Angelidaki, I. (2017). Optimization of hydrogen dispersion in the thermophilic up-flow reactors for ex-situ biogas upgrading. *Bioresource Technology, 234*, 310-319.

Batstone, D., Keller, J., Angelidaki, I., Kalyuzhnyi, S., S.G. Pavlostathis, A. R., Sanders, W., . . . Vavilin, V. (2002). The IWA Anaerobic Digestion Model No 1 (ADM1). *Water Sci Technol, 45*(10), 65-73.

Bauer, F., Persson, T., Hulteberg, C., & Tamm, D. (2013). Biogas upgrading - technology overview, comparison and perspectives for the future. *Biofuels, Bioproducts and Biorefining, 7*(5), 499-511.

Bird, L., Cochran, J., & Wang, X. (2014). *Wind and Solar Energy Curtailment: Experience and Practices in the United States.* Golden, CO: NREL.

Bird, L., Lew, D., Milligan, M., Carlini, E. M., Estanqueiro, A., Flynn, D., . . . Altiparmakis, A. (2016). Wind and solar energy curtailment: A review of international. *Renewable and Sustainable Energy Reviews*, 577-586.

Burkhardt, M., Koschack, T., & Busch, G. (2015). Biocatalytic methanation of hydrogen and carbon dioxide in an anaerobic three-phase system. *Biresource Technology, 178*, 330-333.

California Energy Commission. (2018). *Clean Energy and Pollution Reduction Act - SB 350.* Sacramento, California: California Energy Commission. Tratto da ca.gov: https://www.energy.ca.gov/rules-and-regulations/energy-suppliers-reporting/clean-energy-and-pollution-reduction-act-sb-350

China Energy Portal. (2022, January 27). *2021 electricity & other energy statistics (preliminary).* Tratto da China Energy portal: https://chinaenergyportal.org/en/2021-electricity-other-energy-statistics-preliminary/

Chokhawala, R. (2008). Powering platforms Connecting oil and gas platforms to mainland power grids. *ABB*.

Cummins, T. (2011, September 21). *Modified cement head cuts rig-up time, risks*. Tratto da Drilling Contractor: https://www.drillingcontractor.org/modified-cement-head-cuts-rig-up-time-risks-10689

Díaz, I., Pérez, C., Alfaro, N., & Fdz-Polanco, F. (2015). A feasibility study on the bioconversion of CO2 and H2 to biomethane by gas sparging through polymeric membranes. *Bioresource Technology, 185*, 246-253.

Díaz, N. A.-P.-P. (s.d.).

Eurostat. (2022, January). *Energy production and Imports*. Tratto da Eurostat: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_production_and_imports#More_than_half_of_EU_energy_needs_are_covered_by_imports

Forbes-Cable, M. (2019, October 29). *Why power oil and gas platforms with renewable energy?* Tratto da Wood Mackenzie: https://www.woodmac.com/news/feature/why-power-oil-and-gas-platforms-with-renewables/

Georgilakis, P. S. (2008). Technical challenges associated with the integration of wind power into power systems. *Renewable and Sustainable Energy Reviews, 13*(3), 852-863.

Ghaffour, N., Goosen, M., Mahmoudi, H., & Bundschuh, J. (2014). Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. *Desalination, 356*, 94-114.

Grande, C. A., & Blom, R. (2014). Cryogenic Adsorption of Methane and Carbon Dioxide on Zeolites 4A and 13X. *Energy & Fuels, 28*(10), 6688-6693.

Gu, C., Li, H., & Haces-Fernandez, F. (2021). *Feasibility of the Potential for Wave and Wind Energy Hybrid Farm to Supply Offshore Oil Platform in Gulf of Mexico.* Houston, Texas: Offshore Technology Conference.

Gübitz, G., Bauer, A., Bochmann, G., Gronauer, A., & Weiss, S. (2015). *Biogas science and technology.* Springer International Publishing.

Guiot, S. R., Cimpoia, R., & Carayon, G. (2011). Potential of Wastewater-Treating Anaerobic Granules for Biomethanation of Synthesis Gas. *Environmental Science and Technology, 45*(5), 2006-2012.

Guneratnam, A. J., Ahern, E., FitzGerald, J. A., Jackson, S. A., Xia, A., Dobson, A. D., & Murphy, J. D. (2017). Study of the performance of a thermophilic biological methanation system. *Bioresource Technology, 225*, 308-315.

Gunnerod, J., Serra, S., Palacios-Ticas, M., & Kvarne, O. (2009, January 17). *Highly automated drilling fluids system improves HSE and efficiency, reduces personnel needs*. Tratto da Drilling Contractor: https://www.drillingcontractor.org/highly-automated-drilling-fluids-system-improves-hse-and-efficiency-reduces-personnel-needs-3170

He, W., Uhlen, K., Hadiya, M., Chen, Z., Shi, G., & del Rio, E. (2013). Case Study of Integrating an Offshore Wind Farm with Offshore Oil and Gas Platforms and with an Onshore Electrical Grid. *Journal of Renewable Energy*. Tratto da https://doi.org/10.1155/2013/607165

Hoyer, K., Hulteberg, C., Svensson, M., Jernberg, J., & Nörregård, Ö. (2016). *Biogas upgrading - Technical Review.* Energiforsk.

IEA. (2020). Global Energy Review 2020. *Global Energy and CO2 Emissions in 2020*.

IEA. (2022). *World Energy Outlook 2022.* Paris: IEA. Tratto da https://www.iea.org/reports/world-energy-outlook-2022

Ipieca. (2013, April 10). *Offshore Drilling Rigs*. Tratto da ipieca: https://www.ipieca.org/resources/energy-efficiency-solutions/units-and-plants-practices/offshore-drilling-rigs/#reference-4

Ivy, J. (2004). *Summary of Electrolytic Hydrogen Production.* US Department of Energy. Golden, Colorado: National Renewable Energy Laboratory.

Izquierdo-Pérez, J., Brentan, B. M., Izquierdo, J., Clausen, N. E., Pegalajar-Jurado, A., & Ebsen, N. (2020). Layout Optimization Process to Minimize the Cost of Energy of an Offshore Floating Hybrid Wind-Wave Farm. *Processes, 8*(2), 139.

Jaghory, D. (2022, February 10). *China Sector Analysis: Energy.* Tratto da GLOBAL X: https://www.globalxetfs.com/content/files/China-Sector-Analysis-Energy.pdf

Jürgensen, L., Ehimen, E. A., Born, J., & Holm-Nielsen, J. B. (2014). Utilization of surplus electricity from wind power for dynamic biogas upgrading: Northern Germany case study. *Biomass and Bioenergy, 14*, 126-132.

Jürgensen, L., Ehimen, E. A., Born, J., & Holm-Nielsen, J. B. (2015). Dynamic biogas upgrading based on the Sabatier process: Thermodynamic and dynamic process simulation. *Bioresource Technology, 178*, 323-329.

Kalogirou, S. (2004). Solar Thermal Collectors and Applications. *Progress in Energy and Combustion Science, 30*, 231-295.

Kofoed, J. P., Frigaard, P., & Kramer, M. (2006). Recent Developments of Wave Energy Utilization in Denmark. *Proceedings of the Workshop on Renewable Ocean Energy Utilization: the 20th annual conference Korean Society of Ocean Engineers*.

Kolstad, M. L., Årdal, A. R., Sharifabadi, K., & Undeland, T. M. (2014). Integrating Offshore Wind Power and Multiple Oil and Gas Platforms to the Onshore Power Grid Using VSC-HVDC Technology. *Marine Technology Society Journal, 48*(2), 31-44. doi:https://doi.org/10.4031/MTSJ.48.2.5

Kolstad, M., Rygg, A., Sharifabadi, K., & Undeland, T. (2013). Grid integration of offshore wind power and multiple oil and gas platforms. *OCEANS* (p. 1-7). Bergen: MTS/IEEE.

Korpås, M., Warland, L., He, W., & Tande, J. O. (2012). A Case-Study on Offshore Wind Power Supply to Oil and Gas Rigs. *Energy Procedia, 24*, 18-26.

Kougias, P. G., Treu, L., Benavente, D. P., Boe, K., Campanaro, S., & Angelidaki, I. (2017). Ex-situ biogas upgrading and enhancement in different reactor systems. *Bioresource Technology*, 429-437.

Kozak, M., Köroğlu, E. O., Cirik, K., & Zaimoğlu, Z. (2022). Evaluation of ex-situ hydrogen biomethanation at mesophilic and thermophilic temperatures. *International Journal of hydrogen energy, 47*(34), 15434-15441.

Kreith, F., & Kreider, J. (1978). *Principles of Solar Engineering.* Hemisphere, Washington DC, USA: McGraw-Hill.

Kumar, V., Shrivastava, R., & Untawale, S. (2015). Solar Energy: Review of Potential Green & Clean Energy for Coastal and Offshore Applications. *Aquatic Procedia, 4*, 473-480. Tratto da https://doi.org/10.1016/j.aqpro.2015.02.062.

Langley, D. (2011, September 21). *Shedding light on electrical simplicity*. Tratto da Drilling Contractor: https://www.drillingcontractor.org/shedding-light-on-electrical-simplicity-10672

Legorburu, I., Johnson, K., & Kerr, S. A. (2018). Multi-use maritime platforms - North Sea oil and offshore wind: Opportunity and risk. *Ocean & Coastal Management, 160*, 75-85.

Liming, H. (2009, June). Financing rural renewable energy: A comparison between China and India. *Renewable and Sustainable Energy Reviews, Elsevier, 13*, 1096-1103.

Liou, J. (2012, May 7). *Reliability-centered maintenance program reduces downtime, results in 63% ROI*. Tratto da Drilling Contractor: https://www.drillingcontractor.org/reliability-centered-maintenance-program-reduces-downtime-results-in-63-roi-16152

Liu, Y., & Whitman, W. B. (2008). Metabolic, Phylogenetic, and Ecological Diversity of the Methanogenic Archaea. *Annals of the New York Academy of Sciences, 1125*, 171-189.

Luo, G., & Angelidaki, I. (2012). Integrated biogas upgrading and hydrogen utilization in an anaerobic reactor containing enriched hydrogenotrophic methanogenic culture. *Biotechnology and Bioengineering, 109*(11), 2729-2736.

Luo, G., & Angelidaki, I. (2013). Co-digestion of manure and whey for in situ biogas upgrading by the addition of H2: process performance and microbial insights. *Applied Microbiology and Biotechnology, 97*, 1373-1381.

Luo, G., Johansson, S., Boe, K., Xie, L., Zhou, Q., & Angelidaki, I. (2012). Simultaneous hydrogen utilization and in situ biogas upgrading in an anaerobic reactor. *Biotechnology and Bioengineering, 109*(4), 1088-1094.

Luo, G., Wang, W., & Angelidaki, I. (2014). A new degassing membrane coupled upflow anaerobic sludge blanket (UASB) reactor to achieve in-situ biogas upgrading and recovery of dissolved CH4 from the anaerobic effluent. *Applied Energy, 132*, 536-542.

M. Ragazzi, G. I. (2017). Assessment of environmental impact from renewable and non-renewable energy sources. *International Journal of Energy Production of Management, 2*(1), 8-16.

Makaruk, A., Miltner, M., & Harasek, M. (2010). Membrane biogas upgrading processes for the production of natural gas substitute. *Sep. Purif. Technol.*, 83-92.

Mulat, D. G., Mosbæk, F., Ward, A. J., Polag, D., Greule, M., Keppler, F., . . . Feilberg, A. (2016). Exogenous addition of H2 for an in situ biogas upgrading through biological reduction of carbon dioxide into methane. *Waste Management, 68*, 146-156.

Muñoz, R., Meier, L., Diaz, I., & Jeison, D. (2015). A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading. *Rev Environ Sci Biotechnol*, 727-759.

Mwasilu, F., & Jung, J. (2019). Potential for power generation from ocean wave renewable energy source: a comprehensive review on state-of-the-art technology and future prospects. *IET Renewable Power Generation, 13*, 363-375. doi:https://doi.org/10.1049/iet-rpg.2018.5456

National Conference of State Legislatures. (2021, August 13). *State Renewable Portfolio Standards and Goals*. Tratto da National Conference of State Legislatures: https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

Nguyen, T.-V., & De Oliveira Junior, S. (2017). System evaluation of offshore platforms with gas liquefaction processes. *Energy, 144*.

Nguyen, T.-V., Voldsund, M., Breuhaus, P., & Elmegaard, B. (2016). Energy efficiency measures for offshore oil and gas platforms. *Energy, 117*, 325-340.

Nikolic, V. M., Tasic, G. S., Maksic, A. D., Saponjic, D. P., Miulovic, S. M., & Kaninski, M. P. (2010). Raising efficiency of hydrogen generation from alkaline water electrolysis – Energy saving. *International Journal of Hydrogen Energy*, 12369-12373.

Nizamani, Z. (2021, August). Renewable Wave Energy Potential for Sustainable Offshore Oil Platforms. *IEEE Access, 9*, p. 116973-116993.

Norwegian Ministry of Petroleum and Energy. (2012). *Facts 2012 - The Norwegian Petroleum Sector.* Oslo, Norway: Norwegian Petroleum Directorate.

Oliveira-Pinto, S., Rosa-Santos, P., & Taveira-Pinto, F. (2020). Assessment of the potential of combining wave and solar energy resources to power supply worldwide offshore oil and gas platforms. *Energy Conversion and Management, 223*(113299).

OSCE - Organization for Security and Co-operation in Europe. (s.d.). *Energy Security*. Tratto da OSCE: https://www.osce.org/oceea/446236

Pecher, A., & Kofoed, J. P. (2017). *Handbook of Ocean Wave Energy.* Aalburg: Springer.

Persson, M. (2003). Evaluation of upgrading techniques for biogas. *Report SGC*.

Petersson, A., & Wellinger, A. (2009). Biogas upgrading technologies–developments and innovations. *IEA Bioenergy 20.*

Petroleum Association of Wyoming. (2019). *Oil and Gas Facts & Figures*. Tratto da Petroleum As: https://pawyo.org/2019-facts-figures/

Pinson, P., Giebel, G., & Clausen, N. (2013). Renewable Energy Resources – Onshore/Offshore Wind Energy. *Reference Module in Earth Systems and Environmental Sciences, 3*, 53-64.

Poullikkas, A. (2014). Technology prospects of wave power systems. *Electronic Journal of Energy & Environment*, 47-69.

Power Technology. (2014, October 14). *Kagoshima Nanatsujima Mega Solar Power Plant, Japan*. Tratto da Power Technology: ttp://www.power-technology.com

Rachbauer, L., Voitl, G., Bochmann, G., & Fuchs, W. (2016). Biological biogas upgrading capacity of a hydrogenotrophic community in a trickle-bed reactor. *Applied Energy, 180*, 483-490.

Reeve, J. N., Morgan, R. M., & Nölling, J. (1997). Environmental and molecular regulation of methanogenesis. *Water Science and Technology, 36*(6-7), 1-6.

Reiter, G., & Lindorfer, J. (2015). Global warming potential of hydrogen and methane production from renewable electricity via power-to-gas technology. *Int J Life Cycle Assess, 20*, 477-489.

Relph, N. K. (2019, August 19). What Do We Do With Too Much Renewable Energy? *Sierra*.

Ryckebosch, E., Drouillon, M., & Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. *Biomass and Bioenergy, 35*(5), 1633-1645.

S. Oliveira-Pinto, P. R.-S.-P. (2019). Electricity Supply to offshore oil and gas platforms from renewable ocean wave energy: Overview and case study analysis. *Energy Conversion and Management*, 556-569.

Savvas, S., Donnelly, J., Patterson, T., Chong, Z. S., & Esteves, S. R. (2017). Biological methanation of CO2 in a novel biofilm plug-flow reactor: A high rate and low parasitic energy process. *Applied Energy, 202*, 238-247.

Shahzad, U. (2015). The Need for Renewable Energy Sources. *International Journal of Information Technology and Electrical Engineering, 4*, 16-19.

Siddi, M. (2016). The EU's Energy Union: A Sustainable Path to Energy Security? *The International Spectator, 51*(1), 131-144.

Statista Research Department. (2016). *Electricity Generation Per Unit of Fuel Used United States.* Hamburg, Germany: Statista.

Statistisk Sentralbyrå. (2021, June 8). *Emissions to air*. Tratto da Statistisk Sentralbyrå: https://www.ssb.no/en/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft

Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., & Yu, X. (2015). Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation. *Renewable and Sustainable Energy Reviews, 51*, 521-532.

Svendsen, H. G. (2022). *Optimised operation of low-emission offshore oil and.* Trondheim, Norway: SINTEF Energy Research .

Tapjan, R., & Kverneland, H. (2010, September 8). *Hydraulic vs electrical rig designs: pros and cons on floater heave compensation systems*. Tratto da Drilling Contractor: https://www.drillingcontractor.org/hydraulic-vs-electrical-rig-designs-pros-and-cons-on-floater-heave-compensation-systems-6843

Tata, S. (2017, January 14). *Deconstructing CHina's Energy Security Strategy*. Tratto da The Diplomat: https://thediplomat.com/2017/01/deconstructing-chinas-energy-security-strategy/

Tawiah, S., Marfo, S. A., & Benah, D. J. (2016). *Solar Power for Sustainable Offshore Petroleum Exploration and Production in Africa.* Nairobi, Kenya: SPE/AAPG Africa Energy and Technology Conference.

The Economic Times | Industry. (2019, May 05). *India's oil import dependence jumps to 84 per cent*. Tratto da The Economic Times: https://economictimes.indiatimes.com/industry/energy/oil-gas/indias-oil-import-dependence-jumps-to-84-pc/articleshow/69183923.cms

Thomson, R. C., Chick, J. P., & Harrison, G. P. (2019). An LCA of the Pelamis wave energy converter. *The International Journal of Life Cycle Assessment, 54*, 51-63.

Thrän, D., Billig, E., Persson, T., Svensson, M., Daniel-Gromke, J., Ponitka, J., & Seiffert, M. (2014, September). Biomethane—Status and Factors Affecting Market Development and Trade. *IEA Task 40 and Task 37 Joint Study*.

Tiong, Y. K., Zahari, M. A., Wong, S. F., & Dol, S. S. (2015). The Feasibility of Wind and Solar Energy Application for Oil and Gas Offshore Platform. *IOP Conference Series: Materials Science and Engineering, 78*. Tratto da https://iopscience.iop.org/article/10.1088/1757-899X/78/1/012042/pdf

Tirunehe, G., & Norddahl, B. (2016). The influence of polymeric membrane gas spargers on hydrodynamics and mass transfer in bubble column bioreactors. *Bioprocess and Biosystems Engineering, 39*, 613-626.

United Nations. (2022). *Sustainable Development Goals*. Tratto da United Nations: https://www.un.org/sustainabledevelopment/energy/

USEPA. (2020). *Stationary Internal Combustion Sources* (5th ed., Vol. 1). Washington, DC, USA: United States Environmental Protection Agency.

Waters, R. (2008). Energy from ocean waves: Full scale experimental verification of a Wave Energy Converter. (U. University, A cura di) *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, 580*.

Watson, S., Moro, A., Reis, V., Baniotopoulos, C., Barth, S., Bartoli, G., & Croce, A. (2019). Future emerging technologies in the wind power sector: A European perspective. *Renewable and sustainable energy reviews, 113*(109270).

Weinstein, A., Fredrikson, G., Parks, M., & Nielsen, K. (2004). AquaBuOY - the offshore wave energy converter numerical modeling and optimization. *Oceans '04 MTS/IEEE Techno-Ocean '04 (IEEE Cat. No.04CH37600), 4*, 1854-1859.

WNA. (2014, October 14). Tratto da World Nuclear Association: http://www.world-nuclear.org/

Xia, A., Cheng, J., & Murphy, J. D. (2016). Innovation in biological production and upgrading of methane and hydrogen for use as gaseous transport biofuel. *Biotechnology Advances, 34*(5), 451-472.

Yoo, M., Han, S.-J., & Wee, J.-H. (2013). Carbon dioxide capture capacity of sodium hydroxide aqueous solution. *Journal of Environmental Management, 114*, 512-519.

Zahari, M. A., & Dol, S. S. (2014). Application of Vortex Induced Vibration Energy Generation Technologies to the Offshore Oil and Gas Platform: The Preliminary Study. *World Academy of Science, Engineering and Technology, Open Science Index 91, International Journal of Aerospace and Mechanical Engineering, 8*, 1321-1324.

Zeng, K., & Zhang, D. (2010). Recent progress in alkaline water electrolysis for hydrogen production and applications. *Progress in Energy and Combustion Science; an international review journal, 36*, 307-326.

Zhang, A., Zhang, H., Qadrdan, M., W. Yang, X. J., & Wu, a. J. (2019). Optimal Planning of Integrated Energy Systems for Offshore Oil Extraction and Processing Platforms. *Energies, 12*, 756.

Zhang, S., Wu, Y., Liu, H., Ruikun, H. P., Zhou, Y., Fu, L., & Hao, J. (2014). Rea-world fuel consumption and CO2 (carbon dioxide) emissions by driving conditions for light-duty passenger vehicles in china. *Energy*, 247-257.

Zhao, Q., Leonhardt, E., MacConnell, C., Frear, C., & Chen, S. (2010). *Purification technologies for biogas generated by anaerobic digestion. Compressed Biomethane.* CSANR.

Zhongyang, L., & Agraniotis, M. (2017). *Low-Rank Coals for Power Generation, Fuels and Chemical Production.* Woodhead Publishing.