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Amal Bio-Energy: Hydrogen production throughout methane pyrolysis from purified biogas of agricultural wastes, for distributed generation

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Hydrogen production throughout methane pyrolysis from purified biogas of agricultural wastes, for distributed generation.

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Abstract:

Current hydrogen production relies heavily on the carbon-intensive steam-methane reforming (SMR) process, while agriculture remains a leading source of potent methane emissions. Addressing this dual challenge, this project introduces a novel prototype for a decentralized, carbon-neutral hydrogen generation system. The process begins with a biodigester that uses agricultural waste to produce biogas, which is then purified to yield biomethane. This biomethane, a renewable source of methane, is subsequently fed into a methane pyrolysis reactor. This method heats the biomethane without combustion, separating it into ultra-clean hydrogen and solid carbon. The entire process, from pyrolysis to hydrogen compression and storage, is designed to be powered by renewable energy, ensuring a zero-emission energy pathway.

By integrating agricultural waste valorization with advanced hydrogen production, this prototype offers a powerful solution to multiple systemic issues. It not only mitigates significant methane emissions from farming but also bypasses the need for fossil fuels in hydrogen generation. This in-situ production model facilitates a distributed energy generation framework, democratizing the energy transition and enabling self-sufficiency in agricultural communities. Ultimately, this project presents a scalable and sustainable approach to producing clean hydrogen, fostering a decarbonized future while turning climate liability into a valuable energy and industrial resource.

Introduction:

Energy has always been fundamental for the development of mankind. From the earliest uses of fire to the most advanced 21st-century technologies, the ability to transform and utilize energy has determined the course of our history. In this context, electrical energy has become the invisible engine that sustains nearly every aspect of modern life.

Although its widespread use didn't truly consolidate until the Industrial Revolution, it was during that same period that the use of fossil fuels (coal, natural gas, oil) became the default method for energy generation, driven by rapid industrial growth.[1] This reliance on fossil fuels puts us in a delicate position, facing an imminent climate crisis. Furthermore, their non-renewable nature makes them extremely inconvenient for societies seeking long-term, sustained development. It's worth remembering that any development model pursuing infinite economic growth with finite resources is destined for collapse.

Our planet is already warming. Today, we're experiencing the hottest summers on record, and at the same time, the coolest ones we'll have for the rest of our lives, which is, without a doubt, terrifying and concerning. As established in the Paris Agreement, to mitigate these effects and keep the temperature increase below 2°C, or, at least the more conservative and achievable goal of 1.5°C, we must achieve net-zero emissions by 2050.[2] The production, distribution, and combustion of fossil fuels are responsible for over 70% of global emissions.[3] Therefore, it's imperative to transition towards cleaner alternatives, such as electrification, biofuels, or hydrogen.

Throughout this text, we're going to review different key concepts that will help us better understand the problem at hand, and finally, we'll ground them in our proposed solution.

Theorical Framework:

1. Hydrogen

Hydrogen is the simplest and most abundant element in the entire universe. However, it's not found naturally in an isolated state on Earth. Instead, it combines with other elements, such as methane (CH4) or water (H2O). Because hydrogen is incredibly light, it wouldn't remain isolated in our atmosphere; it would simply escape into space.

Hydrogen is considered an energy vector because it allows us to store, transport, and supply energy produced from other sources. It's not a primary energy source itself, but rather a carrier that enables the use of energy generated elsewhere.

Currently, hydrogen is a vital raw material globally, used extensively in the production of ammonia (NH3), in oil and refinery processes, and across the food, pharmaceutical, glass, and paper/cardboard manufacturing industries.

Beyond its industrial uses, hydrogen has emerged as a low-carbon alternative fuel option with the potential to decarbonize three critical economic sectors:

1. Transportation
2. Electricity generation
3. Manufacturing processes

The hydrogen consumed in large volumes by individual users is often produced locally and referred to as "captive hydrogen." Conversely, when hydrogen is utilized in industrial settings, it's typically produced centrally and then transported to the point of use, known as "merchant hydrogen,".[4]

In Figure 1, provided by the United States Department of Energy, we can see how a hydrogen economy would work.

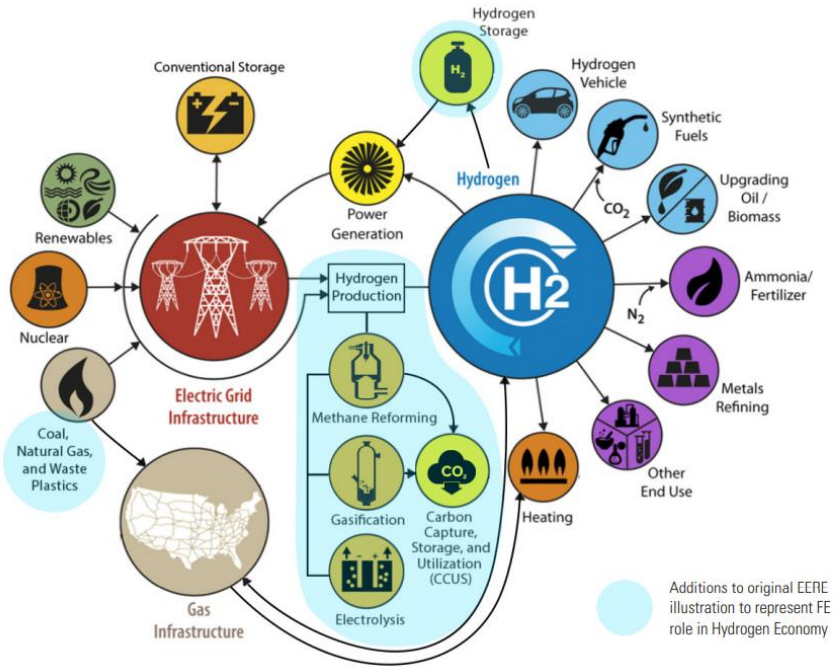


Fig 1. Diagram of a "Hydrogen Economy" Source: adapted from reference[5] (DOE Public Access).

As of today, globally, we generate more than 75 million tons of pure hydrogen per year, with an additional 45 million tons of gaseous mixture.[5] The primary method for producing hydrogen is through natural gas, and the resulting product is denominated as "gray hydrogen." This isn't a new development; the technology is quite mature and has been implemented for several decades. The problem with producing gray hydrogen is that it releases CO2 into the atmosphere as a byproduct. On average, "gray" hydrogen releases between 9 and 10 kg of CO2 for every kg of hydrogen produced. Furthermore, natural gas must be treated to eliminate any remaining sulfur and chlorine, meaning the extraction and treatment of natural gas adds another 1.5 kg to 2 kg of CO_2.[6]

It's worth noting that most hydrogen currently produced is for industrial uses (merchant hydrogen), meaning it's centrally produced. One strategy involves the centralized production of low-emission hydrogen, through "blue hydrogen," where the carbon dioxide byproduct is captured and stored underground.

2. Current Hydrogen Production Methods

2.1) Gray Hydrogen

The primary method for global hydrogen production has been natural gas reforming, accounting for approximately 75% of the 75 million tons of hydrogen generated annually. This process consumes around 205 billion cubic meters of natural gas, which is equivalent to 6% of the global consumption of this resource, and generates over 700 million tons of CO_2 per year.[7] Leading companies in the industrial hydrogen sector (merchant hydrogen) include Air Liquide, Linde/Praxair, and Air Products.

Currently, about 99% of the world's hydrogen is produced from hydrocarbons, mainly natural gas, coal, and oil, through highly energy-intensive processes. Of this total, approximately 75% comes from natural gas via techniques like steam methane reforming (SMR), leading to an annual production of close to 70 million tons of hydrogen. This specific process consumes roughly 205 billion cubic meters of natural gas.

In 2018, hydrogen production was responsible for around **800 million tons of CO_2**, representing over 2% of global emissions (IEA, 2020).[8]

However, by 2023, this metric increase to 920 million tons, according to the International Energy Agency's (IEA) Global Hydrogen Review 2024, which is equivalent to nearly 1 gigaton (billion tons) of CO_2 emitted annually.[9]

Most of these emissions stem from the use of natural gas without carbon capture technologies (two-thirds of the total), with an additional nearly 20% coming from coal without abatement (meaning without applying technologies that reduce or contain the generated emissions, allowing all CO_2 to be released directly into the atmosphere).[9]

2.2) Blue Hydrogen

When natural gas reforming is combined with Carbon Capture, Utilization, and Storage (CCUS) technologies, the hydrogen produced is called blue hydrogen. The two primary technologies for obtaining blue hydrogen are Steam Methane Reforming (SMR) with carbon capture and Auto-Thermal Reforming (ATR), also with carbon capture. Munera (2018)[10] points out that:

> The limitations on fossil fuel consumption are imposed by environmental considerations rather than their availability. New extraction techniques mean that proven reserves are rising, even if vast novel sources, such as methane hydrates, are ignored. Using Carbon Capture and Storage (CCS) to curtail the environmental impact of fossil fuel consumption is controversial and cannot be implemented as rapidly as required.

Currently, only a few hydrogen production plants are equipped with CCUS systems, and their efficiency hovers between 40% and 60%. This is typically because they only capture CO_2 from syngas-related applications, not from combustion byproducts.[11]

Table 1 provides a summary, based on a literature review[12], of hydrogen production plants with Carbon Capture, Utilization, and Storage (CCUS) technologies, both operational and in the planning phase. In the technology column we are summarizing both Steam Methane Reforming (SMR), Autothermal Reforming (ATR) and . Currently, few facilities have CO_2 capture systems, and generally, capture rates are below 90%. However, several new projects are under development that could increase the adoption of these technologies and improve their efficiency. Even so, it's unlikely that any of these projects will materialize before 2050.

Condition	Plant/Project name	Location	Hydrogen Production ($kN\ m^3\ h^{-1}$)	Technology	CO_2 capture rate (%)
Operating	Air Products Port Arhur	USA	220	SMR	60
	Air Liquide Port Jerome	France	50	SMR	60
	Shell Quest	Canada	210	SMR	50
Announced/Under development	H-Vision	Netherlands	700	ATR	88.
	HyNet	United	100	ATR	97.2
	Acorn	Kingdom	53	ATR	98.7
	H2 Tesside	Scotland	275	TBD[1]	98
	Air products	United	>695	ATR	95
	Alberta	Kingdom	>895	ATR	95
	Air products Louisiana	Canada USA			

Table 1 Hydrogen production plants with CCS (operating and planned). Source: adapted from ref. 12

The supply chain for gray and blue hydrogen faces a critical climate challenge that surpasses even that of CO_2: methane (CH_4) emissions. This gas, which constitutes approximately 95% of natural gas, is released during its extraction, processing, transportation, and distribution. Unlike carbon dioxide, methane has a global warming potential between 30 and 85 times greater over 100-year and 20-year horizons, respectively, making it a potent greenhouse gas. Recent research has evidenced methane emissions throughout the entire natural gas supply chain, which significantly exacerbates the environmental footprint of hydrogen produced from fossil sources.[13]

Emissions attributable to fossil fuels can originate from intentional releases, often due to facility or equipment design (e.g., tanks venting directly to the atmosphere), operational requirements (such as pipeline venting for inspection and maintenance), or for safety reasons (like ventilation systems in coal mines). They can also result from unintentional leaks, whether due to a faulty seal, a leaking valve, or from the incomplete combustion of natural gas (for example, in flares).[13,14]

In the Oil and Gas industry, upstream operations refer to those related to exploration and production.[16] Meanwhile, downstream operations refer to the processes involved in converting Oil and Gas into final products, such as Gasoline, Diesel, or other energy sources like hydrogen.[17]

Upstream operations account for approximately 85% of methane emissions, while gas transportation and other downstream operations are responsible for the remaining 15%. Upstream sources include all emissions derived from production, gathering, and processing, both in onshore and offshore facilities. Most downstream emissions come from gas transportation, including emissions during pipeline transmission and distribution, or in

[1] TBD = To be determinade

the form of liquefied natural gas (LNG) and its regasification. Other downstream sources include storage, refining, and oil transportation.[19]

We can see this more clearly in figure 2.

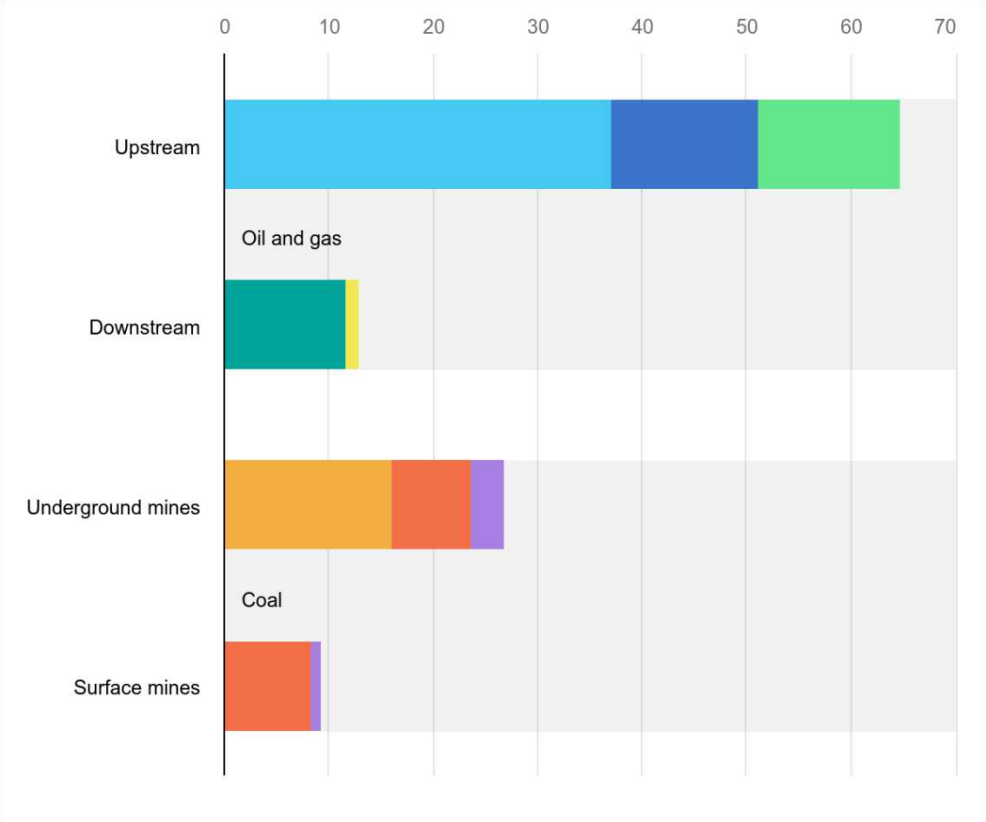


Fig.2. IEA (2025), Methane emissions from fossil fuel operations, 2024, IEA, Paris https://www.iea.org/data-and-statistics/charts/methane-emissions-from-fossil-fuel-operations-2024, Licence: CC BY 4.0

According to the International Energy Agency (IEA), energy production is responsible for 35% of global methane emissions. Natural gas operations were responsible for more than 35 megatons of methane emissions in 2024. [19]

We must also consider that emissions reported by natural gas production plants tend to be much lower than is estimated. An article from the University of Texas at Austin[18] (Bauer et al., 2021) states this:

> Field measurements in North America have identified underestimation in official methane emissions inventories. In the United States, emissions rates as low as 0.3–0.4% have been measured in one shale gas production region. In contrast, some regions in the US as well as several gas exporters like Russia, Algeria or Libya still have methane emission rates around or significantly higher than 2%.

This trend has also been identified by the IEA in the Global Methane Tracker 2024 report[19], where they mention:

> little or no measurement-based data is used to report emissions in most parts of the world – which is an issue since measured emissions tend to be higher than reported emissions. For example, if companies that report emissions to UNEP's Oil & Gas Methane Partnership 2.0 were to be fully representative of the

industry globally, this would imply that global oil and gas methane emissions in 2023 were around 5 Mt, 95% lower than our estimate.

2.3) Green Hydrogen

Another method for hydrogen production is **water electrolysis**. This electrochemical process uses electricity to split water molecules (H2O) into their elemental components: hydrogen gas (H2) and oxygen gas (O2). A key detail of this process is that it takes 9 kg of water to generate 1 kg of hydrogen. The complete reaction is as follows:

$$2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)};$$
$$\Delta H = 285.8 \text{ kJ mol}_{H_2}^{-1}$$

Currently, less than 0.1% of global hydrogen production comes from water electrolysis, and the hydrogen produced is primarily used in markets demanding high purity (such as electronics and polysilicon manufacturing). However, interest in electrolytic hydrogen is growing rapidly due to the reduction in costs for low-GHG renewable electricity from sources like solar and wind.[56]

Nowadays, there are two primary commercial technologies used for water electrolysis: alkaline electrolysis and proton exchange membrane (PEM) systems.

Alkaline electrolysis is a well-established technology, in use since the 1920s. Historically, it has been a go-to method for producing hydrogen in industries such as fertilizers and chlorine manufacturing. While very large alkaline electrolyzes were built in the 20th century, most were decommissioned in the 1970s when the steam methane reforming (SMR) process became dominant. Alkaline electrolyzers are attractive for their lower capital costs, mainly because they don't rely on expensive precious metal catalysts.[21]

In contrast, PEM water electrolysis originated in the 1950s and was further developed by companies like General Electric. PEM systems use pure water as the electrolyte, which eliminates the need to handle and recycle corrosive potassium hydroxide. They are highly favored for several key advantages: compact design, high efficiency, rapid response, and dynamic operation that can handle a wide range of loads. Additionally, PEM systems can operate at low temperatures and produce high-purity hydrogen at elevated pressures (30–80 bar), simplifying downstream compression. Recent cost reductions in PEM technology have positioned it as the leading contender for sustainable hydrogen production by 2030.[21]

The cost of producing green hydrogen is significantly influenced by two main factors: the price of low-carbon electricity and the annual operating hours of the electrolyzer, which is determined by the capacity factor of the renewable energy source.

Currently, at typical electricity prices ($40–$70 per MWh) and annual operating hours (4,000–6,000 h per year), green hydrogen is expensive, costing around $5–$7 per kilogram of hydrogen. To achieve the target of low-cost green hydrogen (less than $3 per kgH2), extremely cheap electricity (less than $30 per MWh) and a high-capacity factor (over 80%) would be necessary.[21]

While the electrolysis process itself is emission-free, it's important to be aware of the hidden emissions associated with green hydrogen production. The environmental footprint of an electrolyzer system is not zero; it's a product of the entire lifecycle. Significant emissions can arise from the manufacturing and extraction of components, particularly the precious metal catalysts (like platinum and iridium) used in PEM systems. Similarly, the construction of the renewable energy infrastructure, such as the wind turbines, solar panels, and transmission lines, also contributes to the overall carbon footprint. Evaluating the true "greenness" of hydrogen requires a comprehensive look at these upstream and downstream processes.

In an article published by the Royal Society of Chemistry, the Levelized Cost of Hydrogen (LCOH) was calculated for both blue and green hydrogen, with the findings presented in Figure 3.

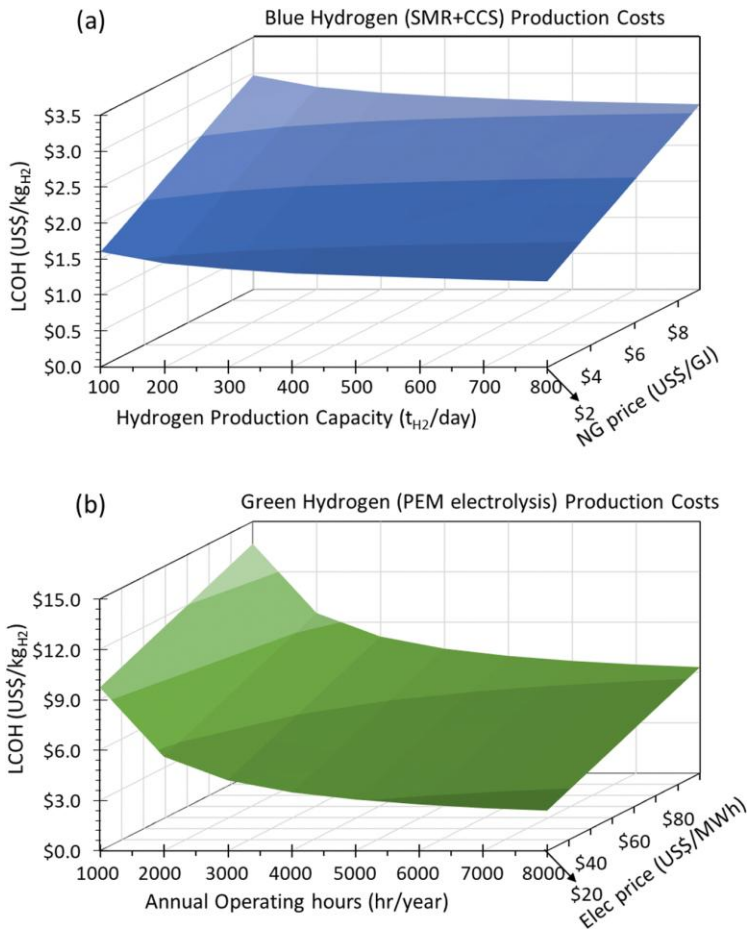


Fig 3. (a) Levelized cost of blue hydrogen ($ per kg$_{H2}$) produced via SMR + CCS as a function of natural gas price ($ per GJ) and plant size (t$_{H2}$ per day). (b) Levelized cost of green hydrogen ($ per kg$_{H2}$) produced via PEM electrolysis as a function of electricity price ($ per MW h) and annual operating hours (hours per year). retrieved from: Moghaddam, A. L., Hejazi, S., Fattahi, M., Kibria, M. G., Thomson, M. J., AlEisad, R., & Khan, M. A. (2025). Methane pyrolysis for hydrogen production: navigating the path to a net zero future. Energy & Environmental Science, 18(X),

2.3) Hydrogen Distribution Methods

At this point, it would be interesting to delve a bit deeper into the differences between Merchant Hydrogen and Captive Hydrogen[20]

- "Merchant" hydrogen—hydrogen generated on site or in a central production facility and sold to a consumer by pipeline, bulk tank, or cylinder truck delivery

Most large hydrogen projects are based on this type of production, which is centralized and requires complex infrastructure.
On the other hand, we have Captive Hydrogen, which is defined as:

- hydrogen produced by the consumer for internal use

2.3.1) Merchant Hydrogen

Merchant hydrogen requires a much more complex infrastructure than the simple installation of a Steam Methane Reforming (SMR) plant. Although it's possible to leverage some of the existing natural gas production and transportation infrastructure, moving towards a hydrogen-based economy involves technical and economic challenges regarding its distribution, storage, and safety. Unlike other fuels, hydrogen exhibits unique properties: extremely high diffusivity, extremely low density in both gaseous and liquid states, and a broad flammability range. These characteristics necessitate specialized equipment, such as stainless-steel pipelines, and significantly increase distribution costs.[1,21]

Furthermore, hydrogen can cause phenomena such as **hydrogen embrittlement** and corrosion, by penetrating the crystalline structure of metals or behaving as an active agent like halogens. This further complicates its large-scale handling. In terms of storage, its low density necessitates either compression to high pressures, cryogenic liquefaction, or the use of technologies like metal hydrides—all technically sophisticated and costly options.[1]

Any analysis concerning the transport and distribution of hydrogen must consider both centralized production at sites remote from the point of use—which can range from large-scale plants to medium-sized facilities for regional markets—as well as "in situ" or "captive" hydrogen production. Centralized molecular hydrogen production necessitates infrastructure for its transport and distribution, as well as intermediate storage capabilities. In contrast, "in situ" generation generally only requires storage at the point of use. On the other hand, in the case of merchant hydrogen, the use of chemical hydrogen carriers involves centralized material fabrication, its shipment to the point of use, and the subsequent management or recycling of the residues generated after hydrogen liberation.

2.3.2) Captive Hydrogen

When considering hydrogen generation plants, a more viable and cost-effective option involves "in situ" projects, which produce hydrogen on a smaller scale, near or at the point of consumption. Projects of this type require significantly less investment as they do not necessitate highly specialized infrastructure for hydrogen storage and transportation.

3) Methane emissions

Methane is responsible for approximately 30% of the increase in global temperatures since the Industrial Revolution, and rapid and sustained reductions in methane emissions are key to limiting short-term global warming and improving air quality.[22]

According to **an article from Yale Environment 360**, a publication of the Yale School of the Environment, methane has reached its highest concentration in the last 3 million years, with a prevalence of 415.39 ppm (parts per million).[23]

Before continuing, we need to understand the concept of radiative forcing. This is, basically, what happens when the energy entering our planet is different from the energy leaving it. This energy travels in the form of radiation; that is, the incoming energy is solar radiation, and the outgoing energy is infrared radiation in the form of heat. Naturally, if more heat enters our atmosphere than leaves it, our planet is going to warm up, as it is doing today. This phenomenon is known as radiative forcing because the energy difference forces climatic changes.[4]

Before the Industrial Era, the radiation Earth received and the radiation it emitted back into space were almost balanced, which maintained a relatively stable average temperature. This is why researchers use a "baseline" year

prior to the start of global industrialization to calculate radiative forcing. For example, the Intergovernmental Panel on Climate Change uses the year 1750 as a reference.[24]
Compared to this baseline, **radiative forcing** allows us to directly measure how recent human activities have altered the planet's climate.[25]

In the following image (fig.4), retrieved from the MIT Climate Portal's "Radiative Forcing" article, we can see this phenomenon explained.

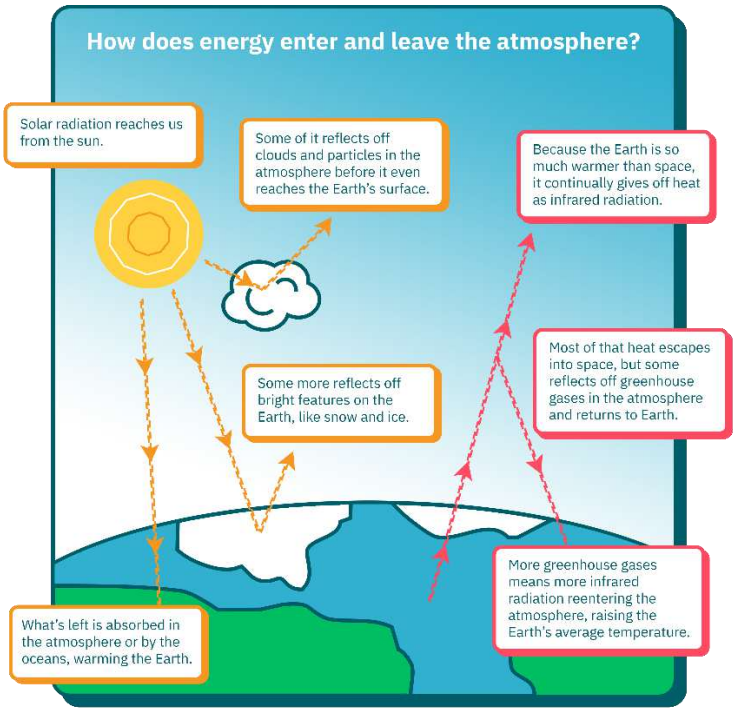


Fig. 4. Source: Timon Studler via Unsplashed. License: Creative Commons Attribution-Noncommercial-Share Alike 4.0 International (CC BY-NC-SA 4.0).

Methane (CH_4) has a considerably greater climate impact than carbon dioxide (CO_2) over a 100-year horizon, with a Global Warming Potential (GWP) of 28, according to the IPCC. Although its anthropogenic emissions represent only about 3% of global carbon emissions by mass, its effect on cumulative radiative forcing since 1750 has been disproportionate: it is estimated to have contributed approximately 0.62 W/m², which is equivalent to about 23% of the total observed increase.[4,25]

If indirect effects such as ozone generation, stratospheric water vapor, and CO_2 are considered, the total radiative forcing attributable to CH_4 rises to about 0.97 W/m². Furthermore, because its atmospheric half-life is relatively short (approximately 9 years), reducing its emissions can quickly be reflected in a decrease in its concentration and, therefore, in its climate impact. For these reasons, methane emission mitigation is recognized as an effective short- and medium-term strategy.[26]

3.1 Methane measurement

There are different Greenhouse Gas (GHG) emission metrics to compare the impact of methane (fugitive) emissions with CO2 emissions and other greenhouse gases. The most prominent is the GWP, or Global Warming Potential. GWP is a measure of how much energy the emission of one ton of a gas will absorb over a given period, relative to the emission of one ton of carbon dioxide (CO2). The higher the GWP, the more a given gas will warm the Earth compared to CO2 over the same period. Generally, 100-year intervals are used to calculate GWP.[27]

3.2) Methane and Agriculture

Agriculture is the anthropogenic activity that generates the most methane emissions. According to a 2017 study by the Royal Society[28], 145 metric tons of CH4 were released into the atmosphere. Taking methane's GWP of 28 into account, this would be equivalent to 4.06 billion tons of CO2.

Figure 5 presents a Climate Watch[29] graph showing the exponential growth of methane emissions between 1990 and 2021. It is observed that agriculture is, by a wide margin, the main source of these emissions. The graph represents methane emissions expressed in tons of carbon dioxide equivalent (CO_2eq).

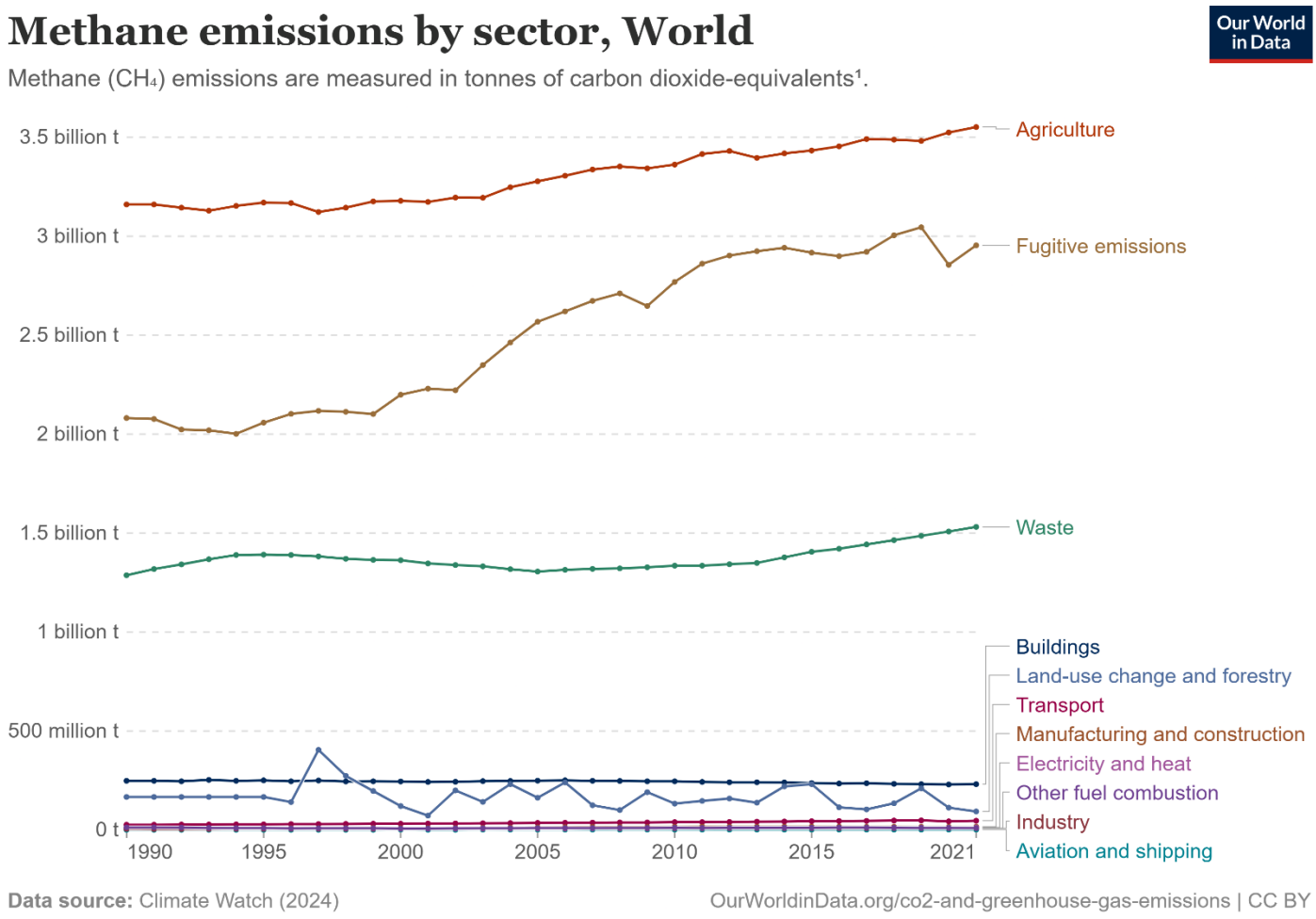


Fig 5. Source: Climate Watch (2024), adaptado de Our World in Data. Disponible en: https://ourworldindata.org/co2-and-greenhouse-gas-emissions. Licencia: CC BY.

According to the FAO (Food and Agriculture Organization), one of the primary sources of methane emissions is manure management.[30]

Methane produced from organic animal waste is a microbial anaerobic process and primarily occurs when the waste is stored (manure management). Smaller quantities of methane are also produced when this waste is directly deposited on the soil.[30]

Globally, it is estimated that livestock manure management (ruminants and non-ruminants) generate 2.52 gigatons of CO_2 equivalent, with manure storage, particularly in liquid form where anaerobic conditions are maintained, being the primary source of emissions.[31] Ruminant manure contributed 2.3 Gt of CO2 equivalents, while swine contributed 0.2 Gt of CO2 equivalents. Manure management alone accounts for an annual generation

of 17.5 million metric tons of CH4. In the United States, the Environmental Protection Agency (EPA) estimates CH4 emissions from manure to be between 470 and 523 Megatons of CO2 equivalent per year. In the European Union, that figure stands at 44 Mt CO2eq.[32]

Figure 6 presents a map illustrating the global density and distribution of livestock.[33]

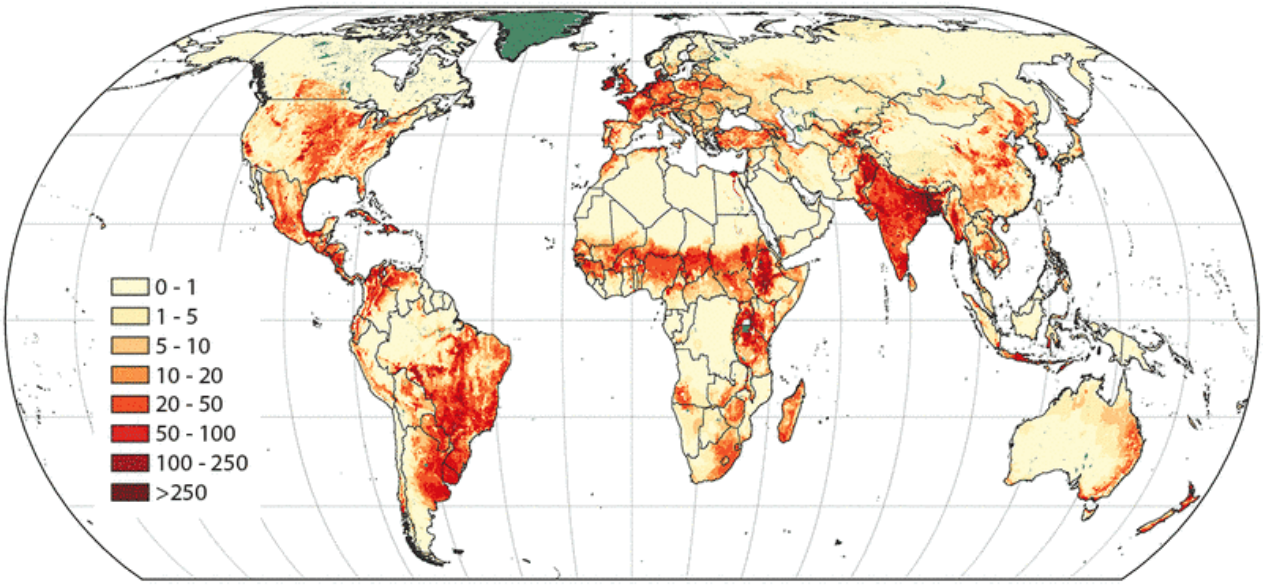


Fig 6. FAO. (2020). Gridded Livestock Density (Global – 2020 – 10 km) – GLW4. Food and Agriculture Organization of the United Nations.

Now we can compare this with the Climate Watch map in Figure 7, which shows the amount of methane emissions derived from agriculture by country.[34]

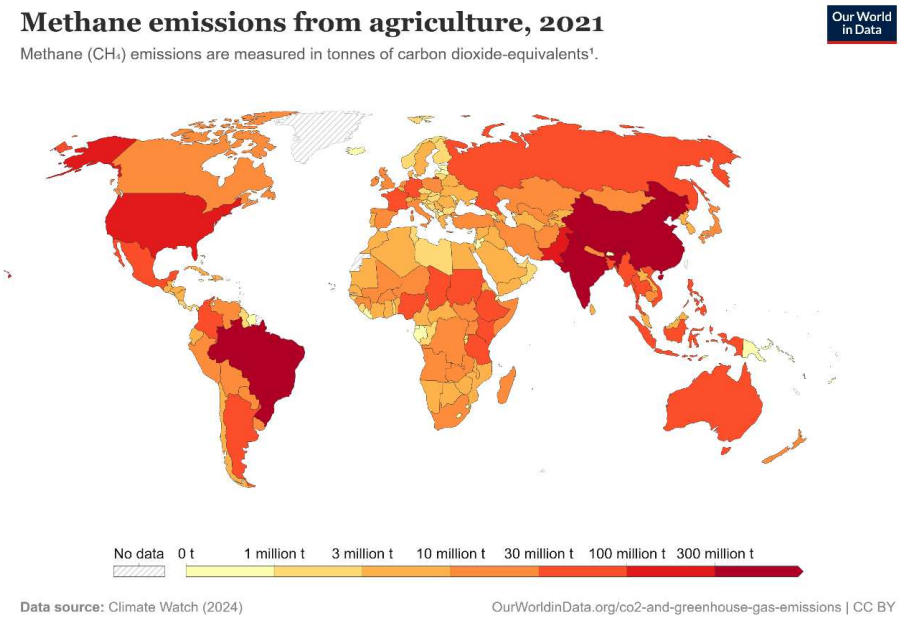


Fig 7. Map of emissions all over the world. Source: Climate Watch (2024), adapted from Our World in Data. Disponible in: https://ourworldindata.org/co2-and-greenhouse-gas-emissions. License: CC BY.

As anticipated, a correlation exists between countries with higher livestock density and those generating more methane emissions from agricultural activities. According to The Royal Society[28], regions of particular interest for methane emission reduction efforts include Latin American countries such as Mexico, Brazil, and Colombia. Other equally important regions identified are China, India, the U.S., the EU, Russia, and Australia.

Methodology

4. The Project

Reviewing a bit of what we know up to this point, hydrogen is a fundamental energy vector for a carbon-free economy, but its production currently depends almost entirely on natural gas, because the main production method is SMR. We also know that carbon capture systems can be implemented in SMR, but currently, these types of systems only sequester a small part of the carbon, and it's unrealistic to think they'll be more efficient in the immediate future. We also know that natural gas is so harmful because it's composed almost entirely of methane, and methane is a greenhouse gas with a warming potential several times greater than that of CO2. We can likewise recognize that reducing methane emissions, a potent short-lived greenhouse gas, is one of the most efficient measures to mitigate global warming in the short and medium term. Similarly, we reviewed that agriculture is the main industry responsible for methane emissions, with animal waste management, particularly from ruminants, being one of the activities that generates the most. Lastly, we saw that a country like Mexico coincides in several aspects with other regions of the world, in that it has a high potential for renewable resources (in this case, high solar irradiance), so it could benefit from hydrogen to store said renewable energy and then have distributed generation models, in addition to generating too many methane emissions as a consequence of one of its main industries being agriculture.

This is where our project takes shape. Our prototype consists of integrating a biodigester, which, through anaerobic digestion, utilizes agricultural waste as sediment, whether it be animal waste like excrement, plant waste like plants, leaves, and stems, and production waste like decomposing fruits and vegetables. This biodigester generates biogas; after being treated within the same biodigester, the biogas is subsequently subjected to a carbon capture process to sequester the CO2 and obtain practically pure Biomethane. To generate hydrogen, we never needed natural gas; in fact, in processes like SMR, natural gas is purified until it contains only methane. Therefore, the biomethane we produce can be processed to separate hydrogen from carbon. Our prototype guarantees the production of ultra-clean hydrogen, and that it is also in-situ so that it can truly be implemented on any farm, ranch, or agricultural sector in the world. Therefore, we use a method known as methane pyrolysis, in which methane is heated without combustion, with the aim of breaking its bonds and being able to separate hydrogen from carbon. The result is completely emission-free hydrogen, and carbon, part of which will be recycled within the same pyrolysis process and another part can be processed for use in industrial processes. Finally, the hydrogen is compressed and stored to be later utilized as a clean energy source. It is worth mentioning that the bio digestion process is completely mechanical, while the pyrolysis reactor and hydrogen storage parts require electrical energy, which can perfectly be obtained from renewable sources.

In summary, with this prototype, we reduce methane emissions from agriculture, generate clean hydrogen; indirectly reducing emissions from the oil and gas industry. By generating hydrogen, we contribute to the decarbonization of various economic sectors, and in turn contribute to a carbon-free future. We have a project that implements carbon sequestration, we use waste as raw material, the only external energy needed comes from renewable sources, and furthermore, we manage to implement a distributed generation model, democratizing the energy transition

Our proposal centers on implementing this prototype across different regions of Mexico to create a comprehensive solution. This approach would establish a local circular economy with the capacity to sustainably manage agricultural waste and mitigate methane emissions. The expected impact is threefold: to generate electricity for communities without access, to reduce the pressure on the national grid, and to foster energy self-sufficiency.

In figure 8 we present a diagram of our proposed prototype:

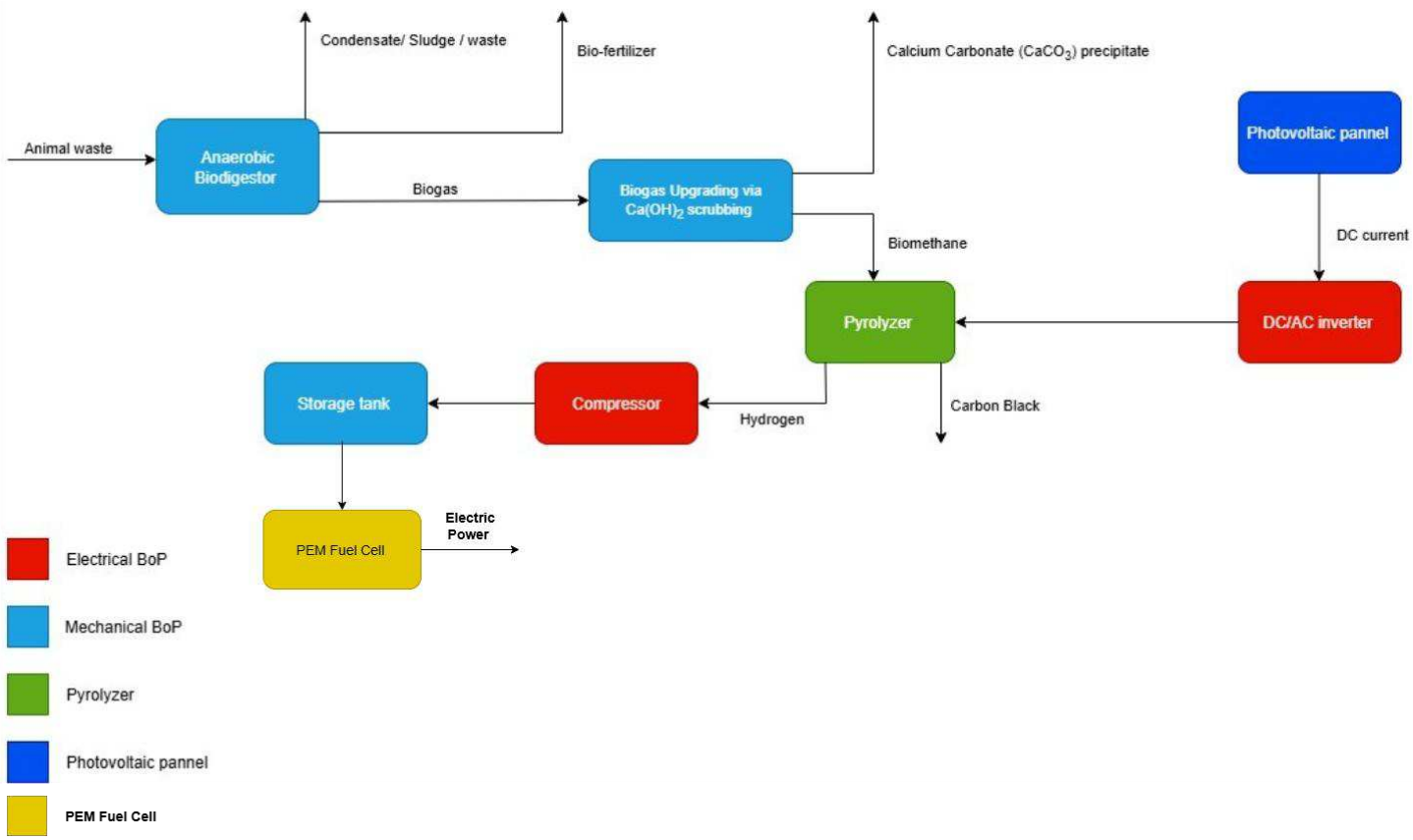


Fig 8. Our Proposed prototype diagram.

4.1) Methane from animal waste

Biogas is the product of a complex biochemical decomposition of organic materials. It consists primarily of methane (CH_4), at 60%-70%, and carbon dioxide (CO_2), at 30%-40%, as well as other gases in smaller amounts, such as ammonia (NH_3), hydrogen (H_2), and nitrogen (N_2). Biogas is obtained through anaerobic digestion by means of a consortium of bacteria and archaea in oxygen-free environments. Biogas is considered the most efficient method for producing CH4 from biomass.

The biogas process consists of 4 stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. We will examine these in more detail later.[35]

4.2) Anaerobic Digestion

Anaerobic digestion is a well-documented process to produce renewable energy from organic waste.[36] Biogas completely replaces natural gas and opens new channels and opportunities for the development of advanced techniques.[37]

Anaerobic digestion begins with the breakdown of complex carbohydrates, such as cellulose and hemicellulose, into simple sugars through hydrolysis. These monosaccharides are then fermented to produce volatile fatty acids (VFAs) and alcohols, which are subsequently oxidized to acetate, carbon dioxide (CO_2), and molecular hydrogen. In the final stages, different metabolic pathways transform these compounds into methane (CH_4), depending on the type of methanogenic archaea: acetoclastic archaea utilize acetate, methylotrophic archaea use compounds with a single methyl group, and hydrogenotrophic archaea reduce CO_2 with hydrogen or formate.[38]

Methanogenesis is the most sensitive step in anaerobic digestion, as its proper functioning is essential to maintain system stability. Methanogenic archaea are less diverse and more specialized than other microbial communities. Key groups include Methanobacteriales, Methanomicrobiales, and Methanosarcinales. The first two use hydrogen as an electron donor, and some species can also employ formate, ethanol, or isopropanol, although they generally cannot utilize acetate, except for the genus *Methanosphaera*. In contrast, Methanosarcinales exhibit greater metabolic versatility and can also use methanol, methylamines, and other methylated compounds. Within the latter group, the family Methanotrichaceae encompasses acetolactic methanogenic archaea.[38]

All methanogenesis pathways, regardless of the initial substrate, culminate in the reduction of methyl-coenzyme M to form methane. In the case of the acetoclastic pathway, the methyl group from acetyl-CoA is transferred to this coenzyme via intermediate coenzymes, and the carbonyl group provides the electron pair necessary to complete the reaction.[39]

The hydrolysis of carbohydrates is a slow process that depends on a highly diverse bacterial community. In biodigesters that process bovine manure, the predominant bacterial genera that ferment the hydrolyzed monomers are *Clostridium*, *Eubacterium*, and *Bacteroides*. Biochemical reactions in anaerobic digestion operate near thermodynamic equilibrium, which is why syntropy, the cooperation between microorganisms, is essential to keep intermediate product concentrations low and allow reactions to remain viable. An imbalance in this cooperation can cause VFA accumulation and acidification of the medium, which inhibits fermentation. Furthermore, for the oxidation of long-chain fatty acids to acetate to be viable, it is necessary to maintain very low hydrogen concentrations, which requires active methanogenesis. Likewise, low hydrogen concentrations, pH below 7, and elevated temperatures favor homoacetogenic bacteria in dissociating acetate into CO_2 and hydrogen, instead of carrying out the reverse process known as reductive acetogenesis.[38,39]

So, the first part of our project involves a biodigester that will use animal waste as its primary raw material to produce biogas through anaerobic digestion. However, it can really be fed with almost any organic waste from agriculture, like crop residues (leaves, stalks, straw, husks, etc.) or agricultural processing waste (fruit and vegetable scraps). In Figure 9, you can see our biodigester prototype.

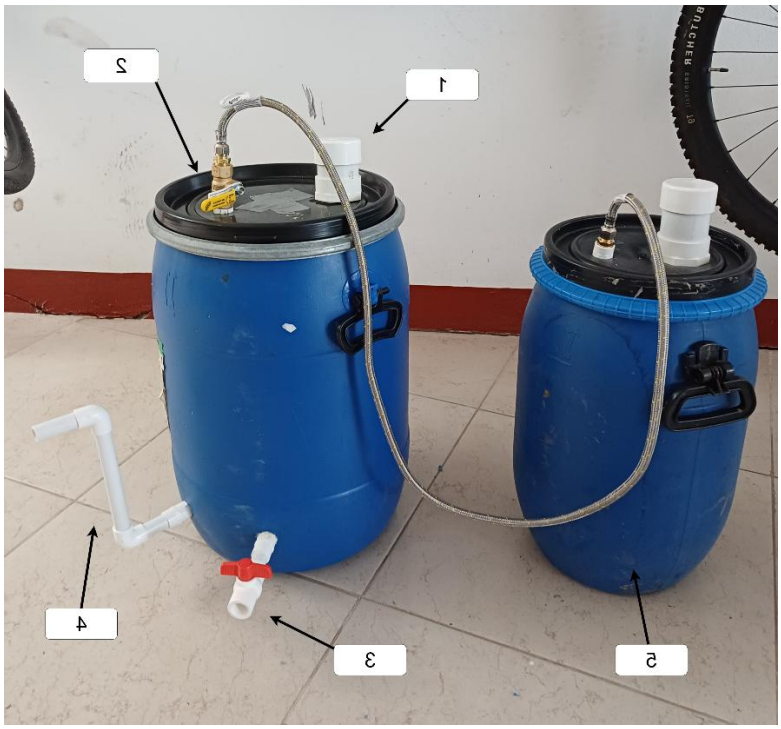


Fig 9. Biodigester made by the team

Here are the components of our prototype:

1. **Waste Inlet:** This is where we'll feed all the organic waste.
2. **Gas Valve:** This valve controls the flow of biogas into the second chamber.
3. **Solid Waste Outlet Valve:** We use this valve to remove the unusable solid residue.
4. **Bio-fertilizer Outlet:** Nutrient-rich liquid bio-fertilizer will exit through this pipe.
5. **Biogas Upgrading Chamber:** Biogas enters this chamber to be "cleaned" by removing CO2.

4.3) Biogas Upgrading

Biogas obtained from anaerobic digestion will be composed of CH_4, CO_2 and different halogens.[35]

The viability of using biogas for fuel, heat, or electricity production depends crucially on its chemical composition. Given that CO_2 constitutes between 30% and 50% of biogas content, its removal becomes the primary objective for recovering and purifying this resource. Furthermore, it is essential to remove other components like H_2S and H_2O to prevent corrosion; fortunately, as they are found in low concentrations, these compounds can be eliminated more easily.[35]

To reduce H_2S directly within the biodigester, we can apply a micro-aeration process. This involves injecting a small, controlled amount of air (or oxygen) into the biodigester or the space where biogas accumulates. The bacteria present oxidize the H_2S to elemental sulfur, which helps clean the biogas of this corrosive and toxic contaminant, and this sulfur remains in the bio-fertilizer. This is a simple and low-cost method for pretreatment.[40]

Next, the biogas (now with reduced H_2S) moves into a second chamber specifically designed for carbon dioxide (CO_2) removal. In this chamber, a calcium hydroxide solution ($Ca(OH)_2$), commonly known as slaked lime, is used. The CO_2 reacts with the calcium hydroxide to form calcium carbonate ($CaCO_3$), an insoluble solid that precipitates and can be separated.[41, 46]

The result of this second step is biogas enriched in methane (known as biomethane), which is much purer and ready to be used as a clean energy source, with calcium carbonate as a solid byproduct.

In the next figure (10), we can see a simulation of how the biodigester works.

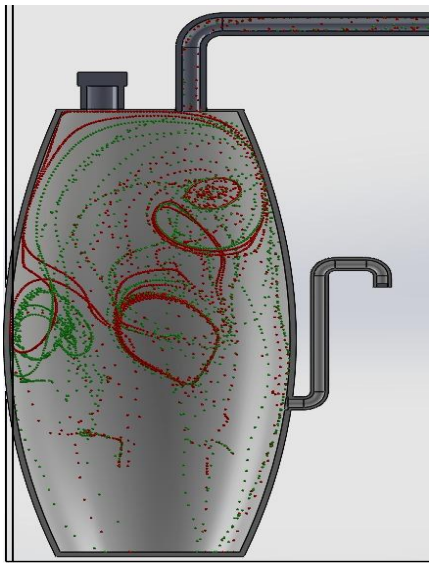


Fig 10. Biodigester simulation

The green dots specifically represent the methane (CH_4) molecules generated within our biodigester's anaerobic digestion process. These are the desired products of the initial decomposition. Meanwhile, the red dots signify the carbon dioxide (CO_2) molecules that are also produced as a natural byproduct of this same biochemical process. It's crucial to note that while hydrogen sulfide (H_2S) is initially present, it's addressed by the micro-aeration process within or near the biodigester itself. This means the H_2S is converted into elemental sulfur, which then remains integrated with the solid bio-fertilizer byproduct. Therefore, as the gas leaves the first chamber or initial step of our prototype, only methane and carbon dioxide proceed to the next stage for further purification.

Figure 11 depicts the input of methane and CO_2 molecules into the upgrading chamber. As the CO_2 is effectively separated in this stage, the chamber's output consists solely of purified methane (biomethane) molecules.

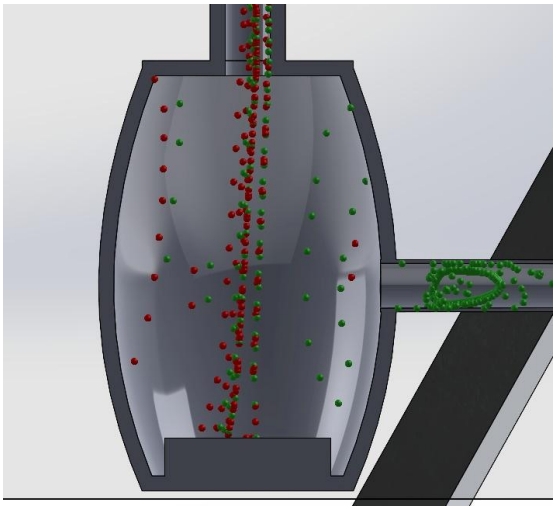


Fig 11. Molecules of CH_4 and CO_2 entering the upgrading biogas chamber, and Methane (CH_4) molecules leaving for the next stage

4.4) Methane Pyrolysis

Methane pyrolysis is the thermal decomposition of methane into carbon and hydrogen.[42]

According to standard reaction enthalpies, 37.5 kJ of energy are needed for one mole of hydrogen via methane pyrolysis.[43]This is considerably much less than the energy required for processes like SMR, which needs 63.4 kJ, or water electrolysis, which requires 285.8 kJ.[44]
Steinberg calculates the overall thermal efficiency of SMR + CCS (blue hydrogen) at 60% and methane pyrolysis at 58%.[45]

This demonstrates that methane pyrolysis, and subsequently the production of turquoise hydrogen, has energy requirements like SMR + CCS (i.e., blue hydrogen production) but with considerably lower emissions.[21]The thermochemical equation stands at:

$$CH4 \rightarrow C(s) + 2H2; \Delta H = 37.5 \text{ kJ mol}^{-1} H_2$$

Methane pyrolysis is an endothermic reaction, and it demands seriously high reaction temperatures, usually over 1,000°C, especially if you're not using a catalyst. This is necessary because of methane's stable, non-polar tetrahedral molecular geometry and the high energy of its C-H bonds. The conversion equilibrium for the pyrolysis process is influenced by both temperature and pressure. Based on Le Chatelier's principle, cranking up the temperature will lead to an increase in the conversion equilibrium. Similarly, since we're forming three moles of product (two H_2 and one C) for every mole of reactant (CH_4), an increase in pressure would lead to a decrease in conversion.[21,46]

Now, there are different paths you can take to perform pyrolysis, as well as different types depending on whether they use catalysts or not, and what kind of catalysts. All this eventually guides you to the type of reactor you'll use. At this point, we're not going to dive deep into all the catalyst types out there, because for our prototype, we're focusing on a method that doesn't use them. That means we must heat the methane to over a thousand degrees. While this is a challenge, our goal is for this prototype to eventually be usable in agricultural sectors worldwide, so we really want to prioritize simplicity in both design and operation.

4.5) Non-Catalytic reactors

The three primary reactor types investigated for methane pyrolysis are fixed-bed reactors, fluidized-bed reactors, and moving-bed reactors. While their application has largely focused on catalytic pyrolysis due to its lower temperature requirements, these same reactors are perfectly suitable for non-catalytic pyrolysis, which is our specific area of interest. In the latter case, inert materials like ceramics, glass beads, or carbon granules are used to enhance phase contact, optimize heat transfer, and ensure uniform flow. Despite this versatility, most of the reported literature primarily focuses on using these reactors for catalytic methane pyrolysis.[21.47]

For our prototype, the moving-bed reactor holds the most interest. We'll briefly review the other two reactor types before delving into greater detail about our chosen reactor.

For a quick overview, we'll briefly review the other reactor types before focusing on the one that interests us. Fluidized-bed reactors stand out for their superior effectiveness in improving mixing, as well as heat and mass transfers; in these systems, solid catalyst particles are kept in suspension by the upward flow of gases or liquids, a fluidization that significantly optimizes both mixing and contact between the catalyst and reactants, which in turn leads to improved heat and mass transfer. Conversely, fixed-bed reactors were fundamental in the early research on methane pyrolysis, primarily at a laboratory scale; although they presented challenges like the rapid deactivation of catalysts due to carbon deposition, they also demonstrated potential, achieving high methane conversions and significant hydrogen concentrations, with a notable aspect being that carbon black, a valuable byproduct of pyrolysis, could be used in these reactors, suggesting a path towards material self-sufficiency in the process.[48,49]

Moving-bed reactors are incredibly versatile for methane pyrolysis, suitable for both catalytic and non-catalytic processes. These systems can be designed for either co-current flow (where the feed gas and solid particles move in the same direction) or counter-current flow (where they move in opposite directions). Although

counter-current designs might face challenges with gas flow distortion due to solid entrainment, they are often preferred because they significantly enhance heat transfer.[21,43]

Furthermore, moving-bed reactors offer several significant operational advantages, including low pressure drops, reduced maintenance costs, and optimized gas-solid surface contact. A key feature is the use of carbonaceous materials, such as carbon black, as solid heat transfer media. Their composition is similar to the carbon produced during pyrolysis, making them highly compatible. This carbon stream can be directly heated by electricity, allowing the reactor to reach the high temperatures (up to 1400∘C) necessary for efficient methane conversion. Notably, companies like BASF have been actively developing this moving carbon bed reactor technology since 2013. It's also worth mentioning that moving-bed reactors can also be implemented with a catalyst if an additional regeneration reactor is incorporated.[21, 51]
This last point highlights a crucial area for future optimization: recovering waste heat. There is a significant opportunity to improve the efficiency of the pyrolysis process by developing designs that allow for the utilization of heat contained in the reactor's outlet gas. This would not only contribute to more efficient heat integration processes within the system (reducing overall energy consumption) but could also facilitate and optimize the subsequent purification of the produced hydrogen.[21,47]
Due to the advantages, we have decided to utilize this reactor model for our prototype.

4.6) *Moving bed reactor*

As previously mentioned, the operation of a moving-bed reactor for methane pyrolysis requires the reactor to be filled with carbon black – a valuable subproduct of the pyrolysis process itself. This carbon bed is then continuously heated to temperatures as high as 1,400∘C, often achieved through direct electrical heating. Upon entering, the methane decomposes into gaseous hydrogen and solid carbon, with the latter being efficiently deposited onto the surface of the existing carbon black granules. The hydrogen, now separated from the solid carbon, exits the reactor and proceeds to the subsequent stage of our system, where it is compressed and stored.[21,47,51]

As solid carbon is deposited onto the carbon black granules within the moving bed, these particles progressively increase in size. In the reaction zone, the carbon bed is directly heated by electrodes, and the pyrolysis process primarily takes place on the surface of these growing carbon granules. Digging deeper into the advantages of this method, we can emphasize that when the solid carbon particles are deposited onto the carbon granules (given their similar material composition), they do not require chemical or mechanical separation from a different medium. Furthermore, a significant advantage is the implementation cost, as there is no need for a specialized or excessively expensive medium. Fundamentally, the moving carbon bed pyrolysis process uniquely utilizes carbon as its main medium for transferring heat to the methane.[47]

In the following figure, we can observe a diagram illustrating the operation of a moving carbon bed reactor.

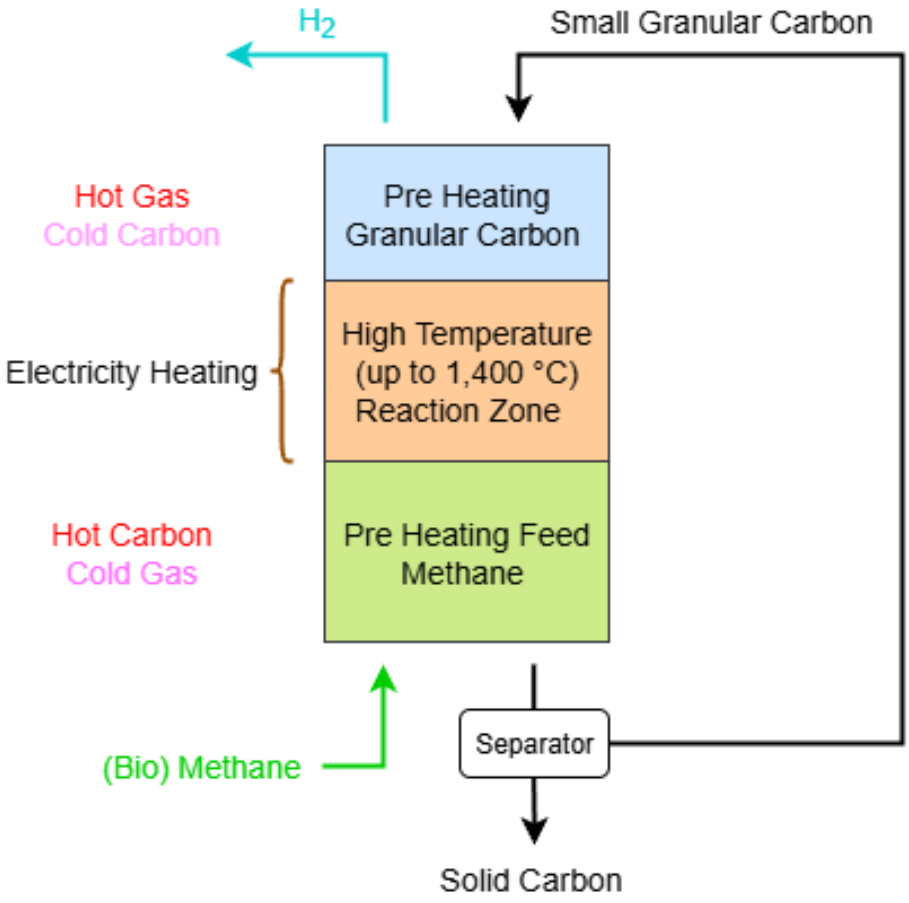
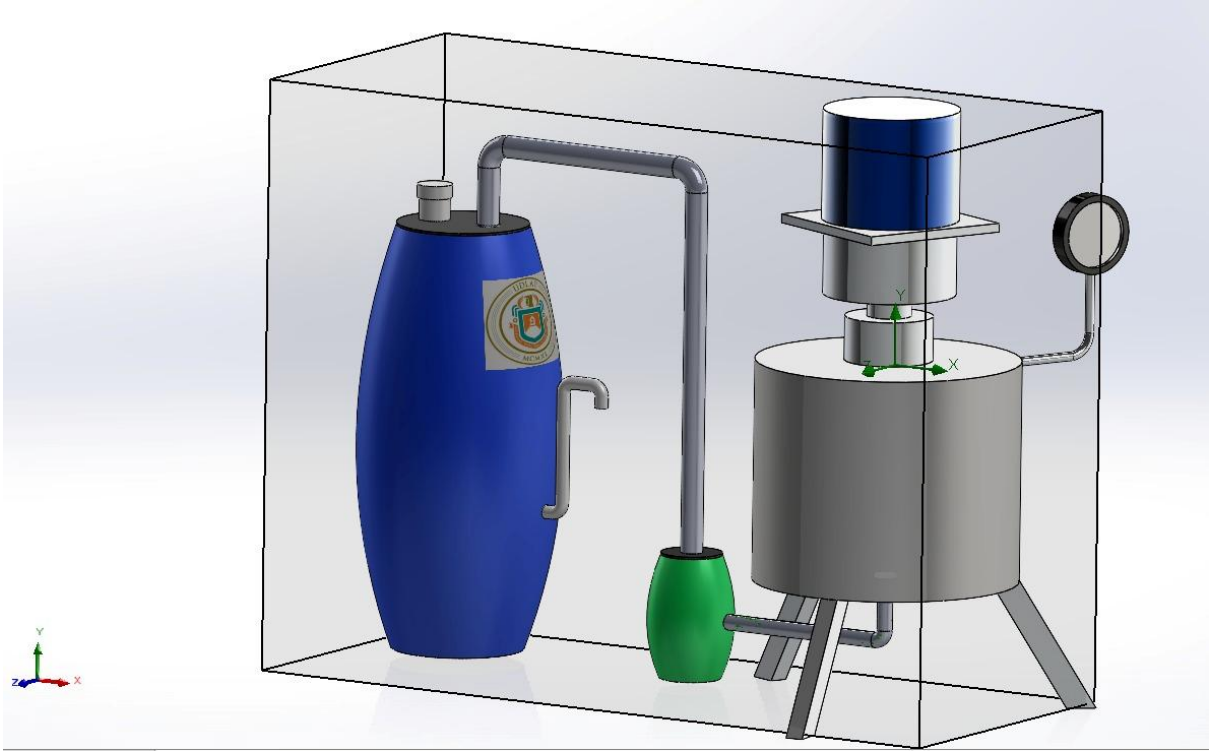


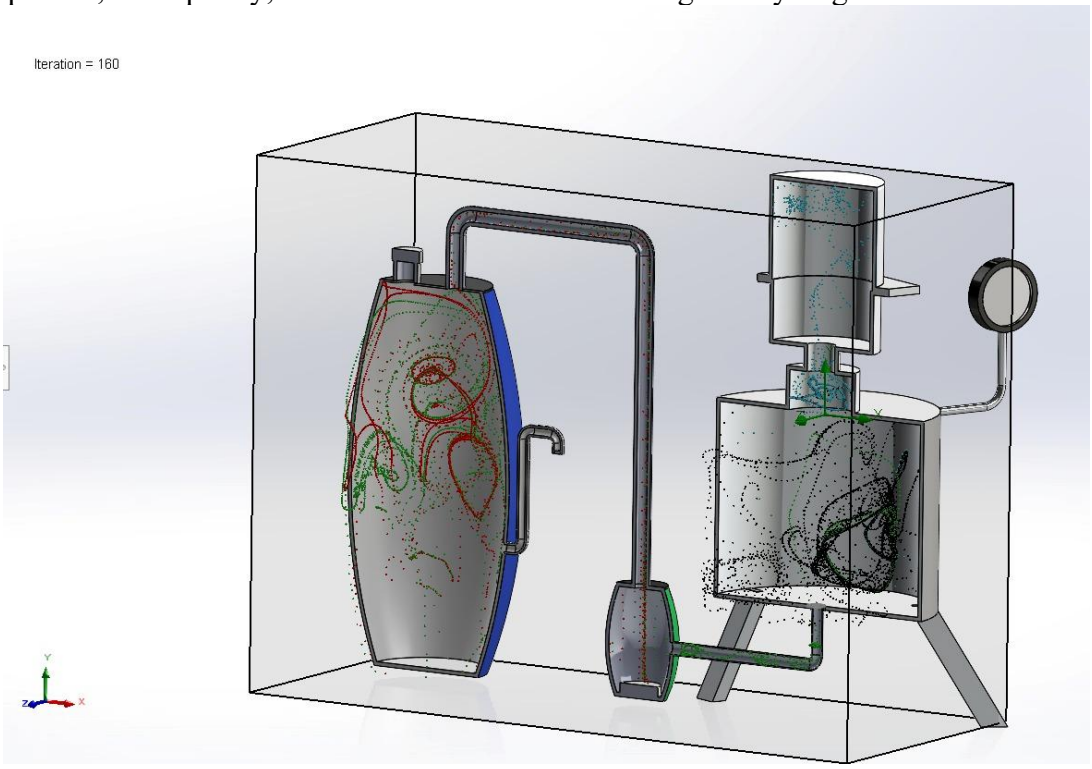
Fig 12. Moving bed reactor schematics and flow, adapted from source: Moghaddam, A. L., Hejazi, S., Fattahi, M., Kibria, M. G., Thomson, M. J., AlEisad, R., & Khan, M. A. (2025). Methane pyrolysis for hydrogen production: navigating the path to a net zero future. *Energy & Environmental Science*, *18*(X), 2747–2790. https://doi.org/10.1039/D4EE01602A

Furthermore, we simulated both the pyrolizer itself, but also, how the molecules inside act and how the hydrogen would be produced.

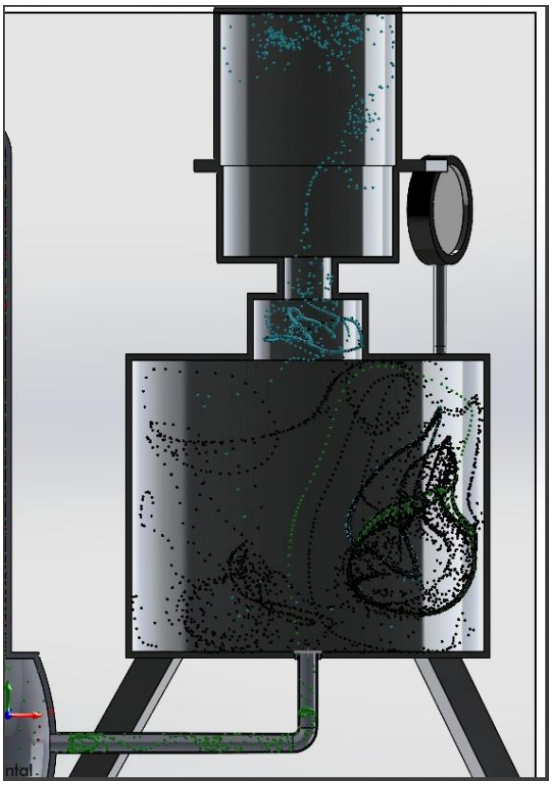
In figure 13 we can see the full integrated prototype up to this point, with the anaerobic generator, the upgrading biogas chamber, and finally the moving bed reactor.



In figure 14 we can see the prototype in section, and how the different molecules work from inside, we can notice that after the pure methane molecules left the upgrading chamber, they enter the pyrolizer, and then hydrogen is formed which would be exiting from the top of the pyrolizer. This type of hydrogen, produced by pyrolysis would be called “turquoise”, colloquially, because it is between blue and green hydrogen.



In figure 15 we can observe more clearly how methane molecules enter the pyrolizer and just hydrogen would come out at the top.



To close this section, we have a comparative table of the emissions generated by SMR, water electrolysis, and methane pyrolysis:

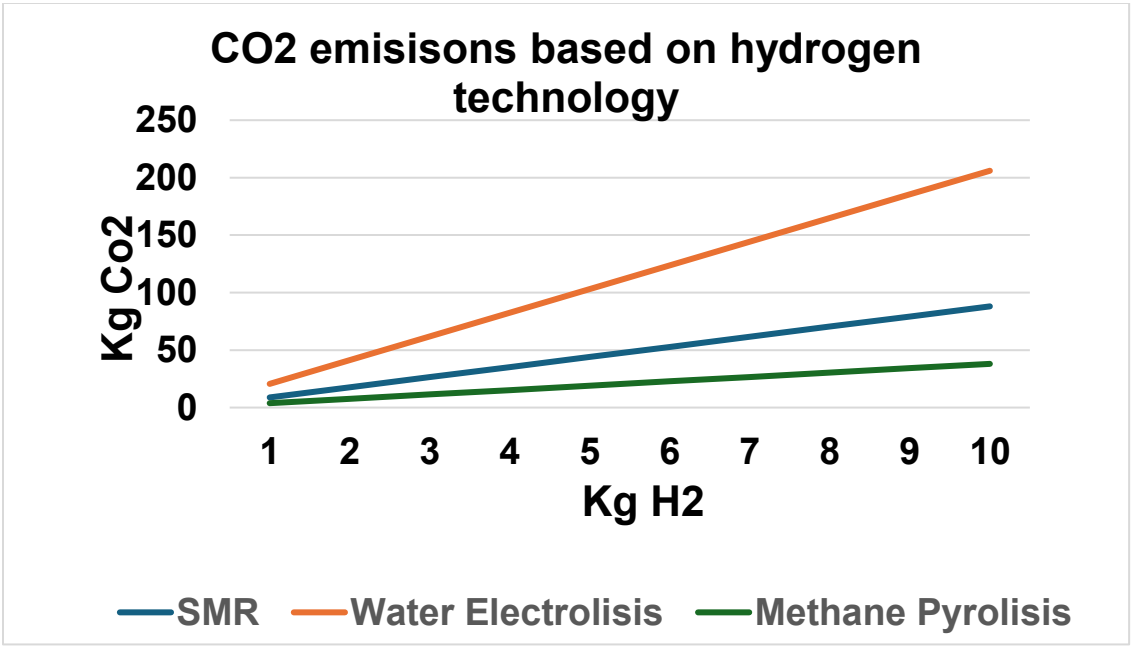


Fig 16. Different hydrogen technologies emissions, adapted from source: 51) Flick, D., Rieck, D., & Bode, J. (2022, May 18). Methane Pyrolysis – a new process for hydrogen production without CO2 emission [Conference presentation]. WIC Conference – Joinin

4.7) Hydrogen Storage

The balance equation of methane pyrolysis is the following:

$$CH_4 \rightarrow 2H_2 + C$$

Methane pyrolysis offers an efficient route for the production of hydrogen and carbon. Stoichiometrically, each mole of methane (CH4) decomposes to yield two moles of hydrogen (H2) and one mole of carbon (C).

Considering the molar masses, where methane weighs 16.05 g/mol, carbon 12.01 g/mol, and molecular hydrogen 2.02 g/mol.

By processing one kilogram of methane (approximately 1,500 liters in volume as a gas), which is equivalent to 62.305 moles, the reaction allows us to obtain approximately 252 grams of hydrogen and 748 grams of carbon. This means that, in theory, methane pyrolysis can recover almost a quarter of a kilogram of hydrogen for every kilogram of methane fed, offering a notable gravimetric efficiency.

Up to this point, we know how to produce biogas from animal waste, then purify it to get mostly methane. Furthermore, we've processed that biomethane to separate it into hydrogen and carbon. The next critical and fundamental step is to store hydrogen.

There are various storage methods that leverage both the intrinsic properties of different materials (such as metal hydrides or MOFs)[1,21] and the inherent physical characteristics of hydrogen itself. It's worth remembering that hydrogen, being a gas, is highly compressible and can undergo changes of state.[18,53]

In the following image, we can see the different types of hydrogen storage:

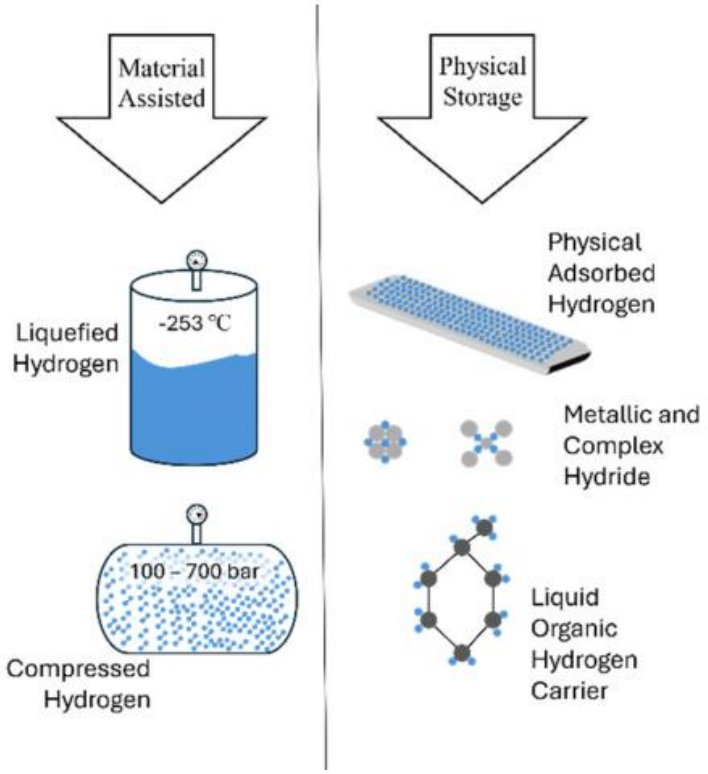


Fig 17. Different hydrogen storage methods. Note. Reproduced from Moghaddam, A. L., Hejazi, S., & Fattahi, M. (2025). Methane pyrolysis for hydrogen production: navigating the path to a net zero future. Energy & Environmental Science, p. 8. CC BY-NC 3

We should also remember that hydrogen has a high energy density. Those 250 grams would be equivalent to 30 MJ of energy, or 8.33 kWh, which is more than enough to supply the energy needs of any person in Mexico. [1, 54]

An average adult beef cow generates approximately 25 kg of manure per day, while a dairy cow generates an average of 35 kg per day. We will take 30 kg as a daily average. From this amount, the manure as a raw material generates 15-25 m³ of biogas per ton of mass (with 10% dry matter). Considering that biogas has a methane content of approximately 60%, this means a single cow can provide about 0.36 m³ of pure methane (CH4) per day, or 360 liters per day. This means that with 4 cows, we would already be producing 1,500 liters of pure methane per day, or one kilogram, from which we can extract 250 grams of hydrogen. The production of biogas will ultimately depend on the specific substrate used.[55]

Since hydrogen isn't an ideal gas, its behavior under compression is nonlinear. This means at low pressures, the gas is highly compressible, and density changes significantly with small pressure variations. However, as pressure increases and molecules cluster, the gas becomes less compressible. This requires much larger pressure changes to achieve comparable density variations. In industry, the standard for compressing and storing hydrogen is 35 MPa or 70 MPa. For efficiency and cost, it's more convenient to use a 35 MPa compressor because at lower pressures, gases are more compressible, and density changes more significantly. At higher pressures, molecules cluster more, the gas is less compressible, and density changes are smaller.

To calculate the density at 35 MPa and the resulting volume, the "Standardized Equation for Hydrogen Gas Densities in Fuel Consumption Applications," proposed by the National Institute of Standards and Technology (NIST)[58], is used. In the equation, **Z** is **1.222**, **MW = 2.01588 kg/kmol**, **R = 8.31477 kJ/kmol·K**, and the temperature is considered at two values: 273 K (0 °C) for standard conditions and 298 K (25 °C) as an approximation for real operating conditions.

$$\rho = \frac{MW\ x\ P}{ZRT(1{,}000)} = 25.44 \text{ g/L (1)}$$

$$\rho = \frac{MW\ x\ P}{ZRT(1{,}000)} = 23.3 \text{ g/L (2)}$$

To determine the resultant volume, one must divide the mass of hydrogen by its calculated density. For illustrative purposes, consider that 1 kilogram of methane is known to yield 252 grams of hydrogen. Under standard pressure and an ambient temperature of 25 °C, this quantity of hydrogen occupies approximately 3,100 liters.

However, when this same mass of hydrogen is compressed to the specified pressure of 35 MPa, its volume is significantly reduced to 10.82 liters. Here relays the critical importance of hydrogen compression for practical and efficient storage applications.

Also, we must mention that, for this prototype, we consider a special type of storage container tank that can outstand those pressures.

4.8) Distributed generation and reconversion to electricity.

Distributed generation (DG), also known as decentralized energy, is a radical shift from the traditional power grid model. Instead of relying on a few massive, centralized power plants that send electricity over long-distance transmission lines, DG involves producing electricity from numerous small-scale power sources located close to where the energy is consumed. Think of it as moving from a single giant factory to thousands of smaller workshops scattered throughout a city. [73]

These sources can be as small as rooftop solar panels on a home or as large as a small wind farm or a combined heat and power plant serving a neighborhood. They are typically connected to a local distribution grid but are not part of the main, high-voltage transmission network. By bringing power generation closer to the end-user, DG can significantly improve grid resilience, reduce transmission losses, and lower energy costs. [71]

The main benefits of distributed generation are its ability to make the power grid more reliable and efficient, and to democratize the energy landscape itself. In this model, consumers are no longer just passive clients; they become active participants in the energy network they consume. By bringing power generation closer to the end-user, it significantly minimizes transmission losses, the energy that is typically lost over long distances from central power plants to consumers. From a sustainability perspective, DG is a key enabler for the energy transition, as it allows for the rapid integration of a greater number of renewable sources like solar and wind into the energy mix. [72]

A primary challenge with renewables like solar is their intermittency; their output fluctuates based on weather conditions and time of day. This creates a need for energy storage solutions, but traditional options like batteries are often expensive and not entirely green due to their reliance on finite resources like lithium. This is where hydrogen emerges as an ideal storage solution, providing a way to capture and store energy generated during peak production for use when the sun isn't shining. [70]

Our prototype directly addresses this challenge. By producing turquoise hydrogen in situ from agricultural waste and then upgrading it to methane for pyrolysis, we generate a significant amount of carbon-free hydrogen. This innovative process not only mitigates methane emissions but also provides a decentralized, on-site energy storage method that helps achieve true distributed generation, transforming waste into a reliable power source.

4.9) Hydrogen to electricity

To convert Hydrogen to electricity we must use a Fuel Cell. Fuel cells offer a highly efficient and clean method for generating electricity. Fuel cells efficiently convert the chemical energy of fuels such as clean hydrogen into electricity. When hydrogen is used as a fuel source, the conversion process is particularly clean, yielding only electricity, water, and heat.[1]

A fuel cell is a device that generates power and heat continuously, unlike a conventional battery. Its operation is based on the controlled flow of hydrogen and air across two electrodes, the anode and the cathode, which are separated by an electrolyte. At the anode, a catalyst initiates the process by separating hydrogen molecules into protons and electrons. The electrons are then diverted through an external wire, creating electricity, while the protons take a different route through the electrolyte. These particles ultimately meet at the cathode, where they combine oxygen from the air to produce water, completing the power generation cycle.[1]

Fuel cells offer significant advantages over other technologies in various power applications, largely because of their high efficiency in converting chemical energy directly into electricity. A key feature is that a fuel cell's power (determined by the size of the fuel cell stack) and its energy capacity (determined by the amount of hydrogen stored) are separate. This means you can increase the energy capacity without changing the physical size of the fuel cell itself. Furthermore, fuel cells are easily scalable; individual cells can be stacked to meet a wide range of power demands, which helps lower costs through economies of scale.[1,74]

Polymer electrolyte membrane (PEM) fuel cells are currently a key focus of research and development. These cells are composed of multiple layers, with the membrane electrode assembly (MEA) serving as the central component. The MEA itself includes the membrane, the catalyst layers, and the gas diffusion layers (GDLs). This

core assembly is then integrated with essential hardware, such as gaskets for sealing and bipolar plates for stacking individual cells and creating channels for the flow of fuel and air. [75]

Furthermore, the components and how they work are the following[75]:

- **Membrane Electrode Assembly:** The membrane electrode assembly (MEA) of a PEM fuel cell is a core unit composed of the membrane, catalyst layers (at the anode and cathode), and diffusion media.

- **Polymer Electrolyte Membrane:** The polymer electrolyte membrane (PEM) is a specially treated, thin material that acts as a selective filter. It allows only positively charged ions to pass through while blocking electrons, which is a critical function for the fuel cell to work.

- **Catalyst Layers:** A layer of platinum-based catalyst is applied to both sides of the membrane. On the anode side, this catalyst splits hydrogen molecules into protons and electrons. On the cathode side, it enables oxygen to react with these protons and electrons to produce water.

- **Gas Diffusion Layers:** The gas diffusion layers (GDLs) are situated on the outside of the catalyst layers. They are responsible for delivering the reaction gases to the catalyst and for removing the water that is produced, with a special coating to prevent water from blocking the flow of the gas.

- **Hardware:** While the MEA is the component that generates electrical power, it requires other hardware parts to function effectively within a complete fuel cell.

- **Bipolar plates:** Because each individual MEA produces less than 1-volt, multiple MEAs are connected in a series to achieve a higher, usable voltage. This is done by stacking them together with bipolar plates in between each cell.

- **Gaskets**: To ensure the entire fuel cell stack is gas-tight and to prevent leaks, gaskets, made of a rubbery polymer, are placed around the edges of the MEA, sandwiching it between the bipolar plates.

In figure 18 we can see a basic fuel cell works.

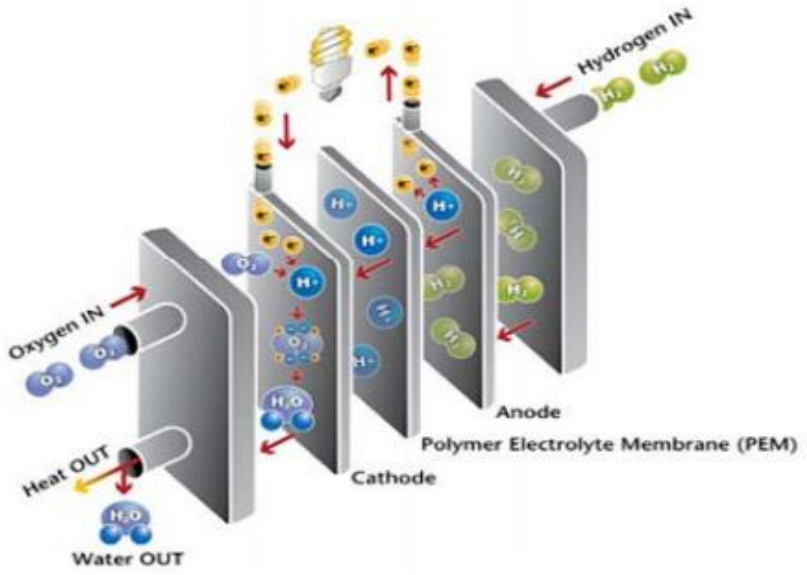


Fig 18. Basic operation of a PEM fuel cell, important to near-term high-impact end uses. Additional cells. Source: Adapted from reference 75 (DOE, public access)

5) Case Study: México

5.1) Potential for prototype implementation

Various institutions, agencies, and studies identify Latin America as a region of particular interest for the topics addressed in this research.

First, the International Energy Agency has pointed to the region as an area with high potential for implementing hydrogen in its economic activities. The International Energy Agency (IEA), recognize in their report *Global Hydrogen Review 2024.* Latin America is well-placed to produce low-emissions hydrogen and its derivatives, building on its abundant natural and renewable energy resources and largely decarbonized electricity mix. [59]

As one of Latin America's five largest economies, Mexico is a significant contributor to the region's hydrogen demand, which reached approximately 4 Mt in 2023.

Latin America possesses a wealth of renewable resources, including vast coastlines with strong wind energy, substantial geothermal potential, and extensive river systems for hydropower. However, the region particularly excels in solar irradiance, with many areas receiving some of the highest levels of solar radiation in the world. Mexico stands out as a country with an exceptionally high solar potential, positioning it as a prime candidate for producing green hydrogen at a competitive cost. This immense solar resource could be a key driver for the country's clean energy transition.[60]

Furthermore, specialized literature highlights the impact of Latin American countries, such as Brazil and Mexico, in the field of anaerobic digestion.

Specialized literature highlights Mexico's impact in the field of anaerobic digestion. According to an article from the Royal Society, Mexico is identified as a priority region for reducing methane emissions, particularly from manure management and food waste. This is a critical point given Mexico's high methane generation and its notable agricultural production, especially from the breeding of ruminants. This unique geographical and economic alignment underscores the country's potential to simultaneously address agricultural waste management and generate clean energy from these materials.[28,62]

The significant interest in Mexico as a key region for methane emission reduction is no coincidence. In figure 19 we can see how much emissions are generated in México by agriculture:

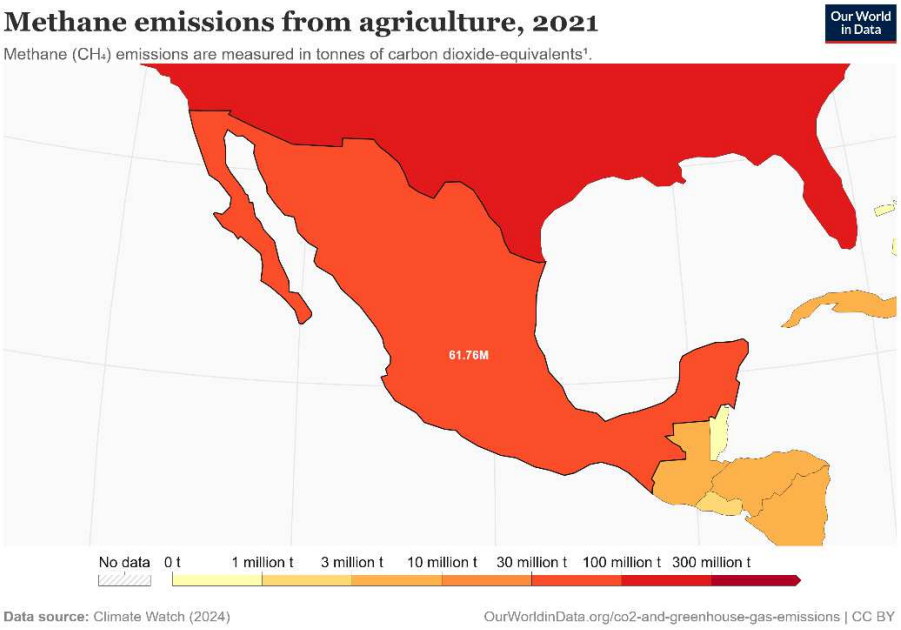


Fig 19. Methane Emissions from Agriculture. Note. Adapted from Methane Emissions from Agriculture, with data from Climate Watch (2024), by Our World in Data (2024). https://ourworldindata.org/...

In addition, in figure 20, we can see a map showing how many cattle there is in México. Making it no coincidence the high amount of methane emissions coming from agriculture.

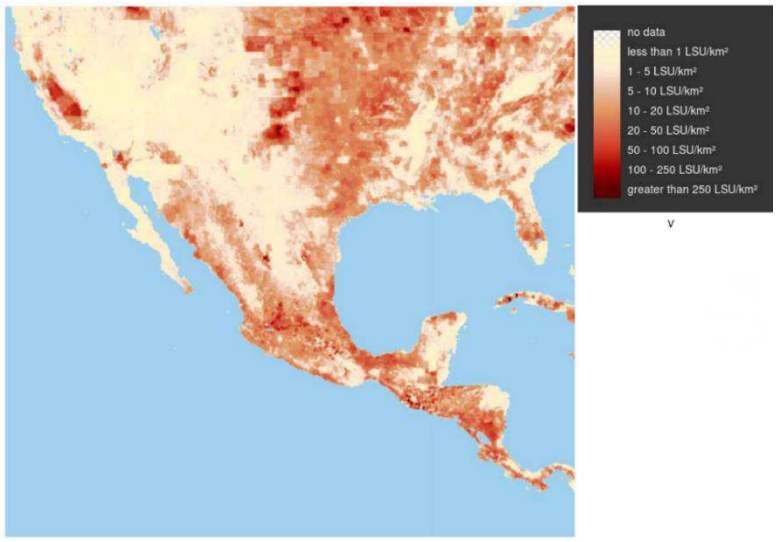


Fig 20. Cattle Distribution in Mexico. FAO, Note. Map created with data from Gridded Livestock of the World (GLW), by Food and Agriculture Organization of the United Nations (FAO), 2020 (https://www.fao.org/aquastat/en/water-resources/livestock-glw/).

As we know, Agriculture is the first cause of methane emissions, but Oil and Gas industry is the second, so, in figure 21 we can see a map of how much methane emissions are being generated in México by the exploitation of fossil fuels.

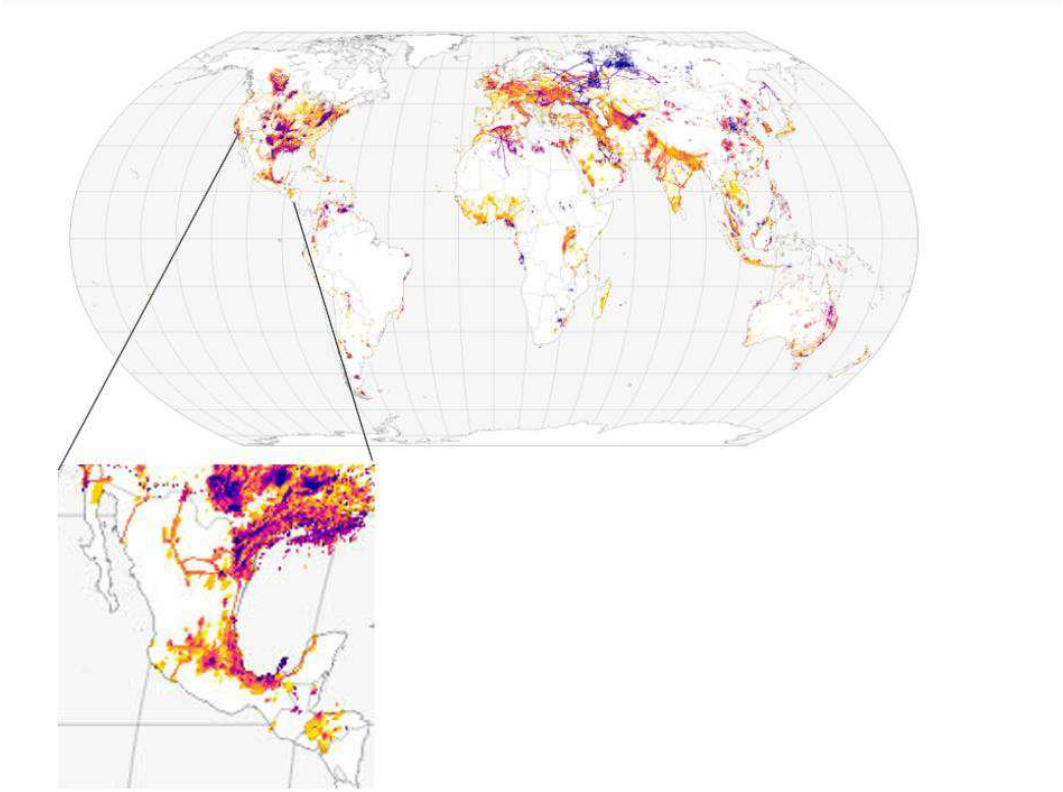


Fig 21. Mapping Methane Emissions from Fossil Fuel Exploitation. Note. Adapted from Image of the Day for January 25, 2022, by the National Aeronautics and Space Administration, 2022, URL: https://earthobservatory.nasa.gov/images/149374/mapping-methane-emissions-from-fossil-fuel-exploitation

This is easily explained, because, as we can see in figure 22, México deeply relies on natural gas for its electric production. In the figure, we can see how many plants that function with natural gas function in México and its capacity.

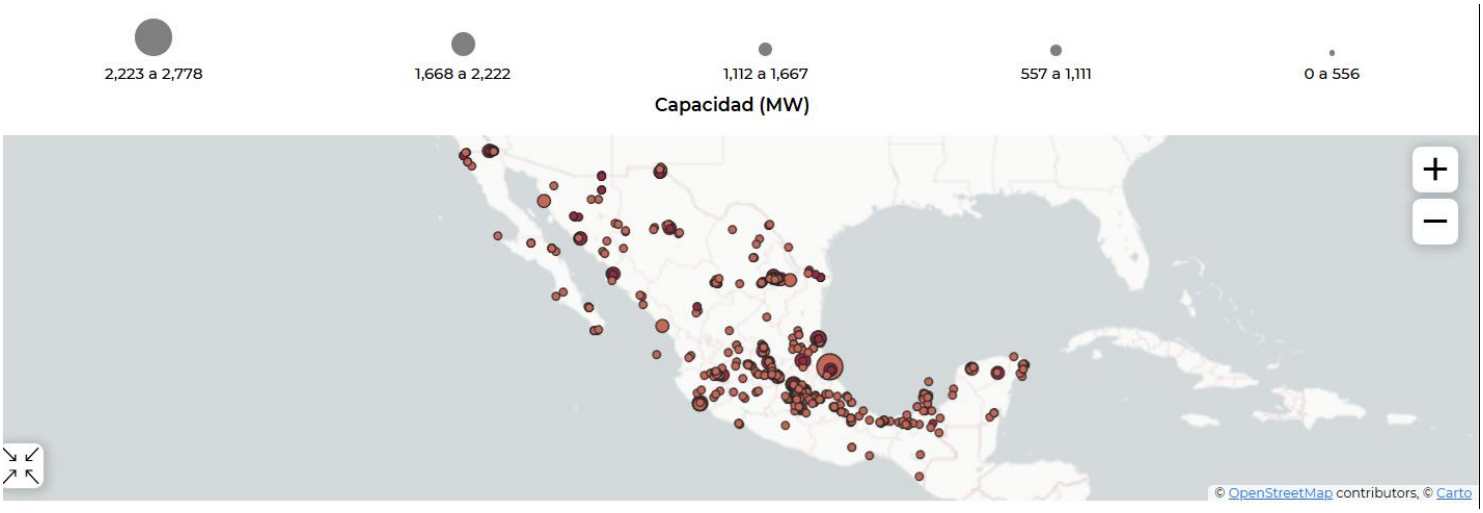


Fig 22. Map of Electricity Generation based on natural gas in México. Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT). (s.f.). Capacidad de Generación. Plataforma Nacional de Energía, Ambiente y Sociedad (PLANEAS). Retrieved from https://energia.conacyt.mx/planeas/electricidad/capacidad-generacion

For contrast, in figure 23 we can see how many plants (and its capacity) are in México that operate under renewable sources.

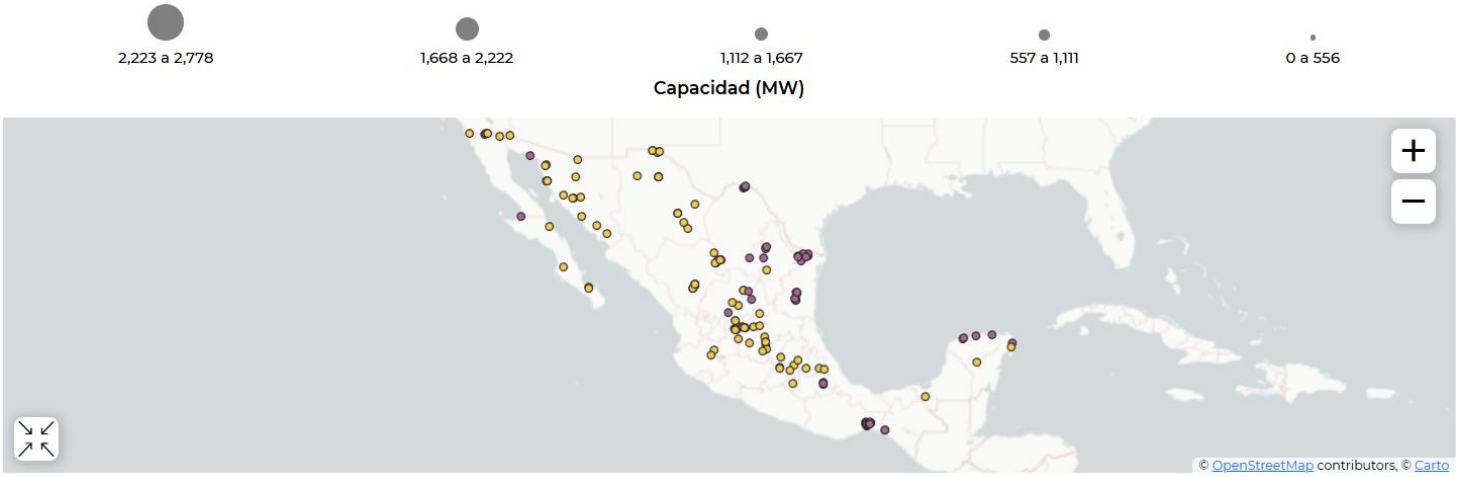


Fig 22. Map of electricity generation in México based on Renewable resources. Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT). (s.f.). Capacidad de Generación. Plataforma Nacional de Energía, Ambiente y Sociedad (PLANEAS). Retrieved from https://energia.conacyt.mx/planeas/electricidad/capacidad-generacion

As we mention, México has a privileged location, because it is very rich in irradiation, as we can see on figure 24.



Fig 24 . Photovoltaic power potential map of Mexico. Adapted from Global Solar Atlas 2.0 (World Bank Group, 2020). Retrieved from: https://globalsolaratlas.info/download/mexico

Mexico generates nearly 66.7% of its electricity from fossil fuels[64], which has driven up costs for consumers and solidified the power sector as responsible for 17% of national CO_2 emissions, with CFE as the main actor. This is compounded by structural failures: each year, around 12% of generated electricity is lost due to deficiencies in the distribution grid (SENER, 2023). These shortcomings directly impact on the population, especially in marginalized areas, where access to energy remains limited. According to INEGI (2023), more than 1.4 million people in Mexico lack electricity service.

Energy demand is growing at a rate of 3.5% annually, far exceeding population growth (1.1%). This indicates that the country is not only growing in population but also demanding more electricity per capita, whether due to industrial expansion, the increase in data centers, or chaotic urbanization without sustainable planning. This gap reveals a system in crisis: centralized, polluting, and unequal.

Furthermore, the electric system operates with a reduced safety margin. In 2023, installed capacity surpassed demand by a mere 6.4% leaving little room for contingencies.[61] Worse yet, while demand grows three times faster than the population, installed capacity only increases by 2.5% annually. If this trend continues, Mexico could face widespread blackouts in less than five years.

5.2) Distributed generation

In Mexico, only around **1.5%** of the total electricity generation is currently produced under a distributed generation model. This reflects the low level of adoption of this strategy nationwide, but also its enormous growth potential. Furthermore, within this segment, **92.3%** corresponds to solar photovoltaic systems.[63]

However, this solution still faces structural limitations, such as high intermittency. Although it offers advantages like low cost, long-term profitability, low emissions, and growing technological maturity, its operational viability remains a challenge. In the case of photovoltaic energy, for example, generation decreases considerably on cloudy days or at night, as it depends on environmental conditions.

5.3) Feasibility

Considering these challenges, we have the perfect scenario for our prototype. Mexico is a country that generates a significant amount of methane from agriculture, primarily due to manure management and crop waste. Furthermore, the country produces substantial methane emissions from the natural gas infrastructure used for electricity generation.

Despite this, the country is not meeting its energy demand, and millions of people lack access to electricity; a number that is only projected to rise in the coming years. Mexico also has vast potential for generating electricity from solar power, yet this resource remains largely untouched. But even if Mexico were to fully harness this potential, a critical challenge remains energy storage. The energy generated by intermittent sources like solar power that is not used instantly goes to waste, and Mexico lacks sufficient lithium reserves to build the batteries needed to store so much power.

This is where hydrogen enters the equation. It can store this surplus energy, and it also offers a significant economic advantage. Domestic ammonia production, a crucial component for fertilizers, completely shut down in 2019 due to the high cost of natural gas. By generating hydrogen locally, different regions could become more economically self-sufficient, revitalizing a key industry that was previously lost.

This leads us to our proposal: what if we were to implement this prototype in different regions of Mexico? This approach would establish a localized circular economy by efficiently managing agricultural waste, mitigating methane emissions, and generating electricity for those who do not have access to it, all while alleviating the strain on the main grid.

6) **Results:**

This section provides a quantitative analysis of the prototype's potential, focusing on the initial conversion of a single cow's manure into biogas and biomethane. The following calculations are based on standard industry and academic data for anaerobic digestion.

Manure-to-Biogas Conversion

A single mature dairy cow produces an average of approximately **35 kg (~77 lbs)** of fresh manure per day. This manure serves as the primary feedstock for the biodigester. Through the process of anaerobic digestion, this quantity of waste is converted into a significant volume of biogas.

- **Daily Manure Output per Cow:** 35 kg
- **Biogas Yield per kg of Manure:** 20 L
- **Total Biogas Produced per Day per Cow:** 35 kg×20 L/kg=700 L

This translates to a daily biogas production of approximately 0.7 m3 for a single cow. The composition of this raw biogas is a crucial factor, as it contains a high percentage of methane, the key component for the pyrolysis stage.

Biogas Composition and Biomethane Production

The biogas produced from cow manure typically has methane content ranging from 50% to 75%. For our analysis, we assume a conservative average of 60% methane content.

- **Daily Biogas Volume:** 0.7 m3
- **Assumed Methane Content:** 60%
- **Daily Biomethane Volume:** 0.7 m3×0.60=0.42 m3

The output of the biodigester, a purified stream of 0.42 m3 of biomethane per day, is the renewable feedstock that would be directed to the methane pyrolysis reactor.

The final stage of the process is methane pyrolysis, which separates the biomethane into ultra-clean hydrogen and solid carbon. Based on theoretical yields, the pyrolysis of methane produces approximately 250 grams of hydrogen for every kilogram of methane feedstock.

- **Daily Biomethane Volume (at STP):** 0.42 m^3
- **Molar Volume of Gas (at STP):** 0.0224 m3/mol**.**
- **Molar Mass of Methane (**CH_4**):** 16.04 g/mol**.**

- **Daily Biomethane Mass:** $\frac{0.42 \text{ m3 } CH4}{0.0244 \text{m3 } /mol}$ * 16.04g / mol = 300.75 gr = 0.301 kg.

Using the conversion rate of 250 grams of hydrogen per kilogram of methane, we can calculate the daily hydrogen yield per cow:

- **Daily Hydrogen Production:** 0.301 kg of CH_4 * $\frac{250\ g\ of\ CH4}{1\ kg\ of\ CH4}$ = 75,25 gr.

This means that a single cow's daily manure output, when processed through the entire system, has the potential to generate approximately 75 grams of pure hydrogen gas.

Finally, to calculate the total energy output of the hydrogen, we use its energy density of 120 MJ per kilogram. This means that a single cow's daily output produces an energy equivalent of 9 MJ. This is equal to an average continuous power of 104.5 Watts stored in the hydrogen's chemical energy. When this is converted into electricity by a fuel cell with a conversion efficiency of 60%, we can generate approximately 63 Watts of electrical power per cow. In Mexico, the average energy consumption of one person per month is around 7.2 kWh[61]. Based on this, a person could satisfy their energy needs with the output from just four cows. The system is scalable to match the number of cows an individual owns, and it is also worth noting that other substrates may offer a larger biogas production yield. Therefore, this prototype is well-suited to supply the energy needs of an individual, a family, or even a whole community. The surplus electricity generated could also be fed back into the grid, enabling distributed generation.

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