MASTER IN ENVIRONMENT AND ENERGY TRANSITION
COMILLAS ICAI

Master Thesis

Biomethane Integration into Spain´s Residential Heating Sector

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Abstract: This report focuses on the future of biomethane integration into natural gas networks and especially in the energy transition of Spain´s residential heating sector. The production, uses, and advantages of biomethane will first be discussed. Later, an analysis of renovating residential natural gas boilers in Spain will be included to examine the potential energy and carbon emission savings that can be achieved. This study aims to determine whether outdated boilers should be upgraded to electric heat pumps or to more efficient natural gas boilers given their potential to utilize biomethane.

Keywords: biogas; biomethane; boilers; heat pumps; climate change; renewable fuel; energy; carbon emissions; decarbonization.

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1. Introduction

Two of the greatest problems the world faces today is climate change and geopolitical instability. Since the start of the industrial revolution, carbon dioxide and other greenhouse gases (GHGs) such as methane, nitrous oxide, ozone, etc. have expanded their presence in the planet´s atmosphere. This has been mainly due to the widespread use of fossil fuels to keep up with the increasing consumption of goods and services. These emitted gases have done more than just cause an increase of the temperature in our atmosphere; they are harmful to human health and have detrimental impacts on our biosphere. In 2009, Rockström et al published an article titled "Planetary Boundaries: Exploring the Safe Operating Space for Humanity" in which 9 planetary boundaries are outlined that have potential for "major human-induced environmental change on a global scale" [1]. These boundaries are ocean acidification, stratospheric ozone, biochemical nitrogen and phosphorus cycles, global freshwater use, land system change, biosphere integrity, chemical pollution, aerosol loading, and of course, climate change. Anthropogenic interferences causing the thresholds of these boundaries to be approached, or exceeded, is evidence that the Earth is becoming less stable and less habitable. In other words, the planet is currently experiencing its sixth mass extinction event, the "Holocene extinction". However, what makes this extinction event different from any other in the history of our planet is that it is a direct result of human activity. Although this sounds grave, it does not mean there is nothing to be done to prevent and/or reduce a global disaster. There is hope in the various projects and research occurring around the world to improve this planetary boundary's mitigation and adaptation. Since the 1970s, huge international campaigns have taken place to tackle climate change and global warming. One of the main focuses of climate activists and scientists is decarbonization, the reduction of CO_2 emissions.

The second problem, geopolitical instability, refers to international relationships between countries being affected by geographical factors. This is commonly observed in the balance of power between countries engaging in trade. Powerful countries that have more goods can take advantage of weaker countries that they know will depend on them for those specific products/services. In extreme cases, wars can break out over land and energy sources which affect markets in other countries which rely on that same land and energy for their own economic growth. Climate change only furthers these potential catastrophes. For example, countries that are main exporters of certain crops can suffer greatly if climate change and pollution prevent their farms from growing at expected capacity and quality. This in turn can affect the economy of all countries who have a stake in the matter. One way in which countries can reduce their dependence on others and avoid the consequences of geopolitical disasters is to become auto-sufficient in the production of energy needed to sustain their citizens.

An area in which both decarbonization and energy independence can be achieved is through biological natural gas. Currently, all fossil fuels such as coal, oil, and natural gas contribute greatly to our planet´s excess greenhouse gas problem. In 2019, coal, peat, and oil shale were responsible for emitting nearly 16,000 Mt of CO_2 equivalent gases. Oil and natural gas were responsible for 12,800 and 8,370 Mt CO_2 equivalent gases, respectively [2]. Typically, of these fossil fuels, natural gas tends to be the "cleanest" with an emission factor of 0.182 kg $CO_{2,eq}$/kWh. Whereas for coal it is

3.04 kg $CO_{2,eq}$/kg and for oil it is an average of 2.89 kg $CO_{2,eq}$/l [3]. Luckily, many countries have begun to reduce their dependence on coal as they become more environmentally conscious. In Spain, for example, coal made up 3% of the country´s whole energy supply in 2020. That is nearly a 20% decrease from 1990. Spain´s usage of natural gas, however, reached 26% that same year [4].

Although it is still a fossil fuel, the continued use of natural gas may be necessary until more carbon neutral options become accessible. One such alternative is biological natural gas, also known as biomethane. Derived from biogas, biomethane has the same chemical makeup as conventional natural gas (CH_4) but is produced from human, animal and plant waste instead of by fracking. To be clear, a renewable resource is one that will not run out over time. In other words, it has an “endless” supply through natural regeneration. Biogas/biomethane are renewable sources since humans, animals and plants will always produce waste.

When talking about decarbonization, a carbon neutral source is one that has net zero greenhouse gas emissions. Sometimes, carbon is even utilized as a feedstock in the production of these sources. One other decarbonization option that has been advocated quite strongly is electrification. This is to switch energy generation and usage from fossil fuels to “renewable” electricity that is produced via solar, wind, geothermal, hydro etc. energies. However, currently, electricity does not come from 100% renewable sources so its own emission factor will vary greatly until that is achieved. In addition, a lot of investments will need to be made in order to develop the proper infrastructure to support electricity powered lifestyles around the world. This includes, vehicle charging stations, large scale batteries, and new electrically compatible equipment. Although electricity has a lot of potential when derived from renewable sources, it may take too long to achieve this and may not have the capacity to replace every other non-renewable energy source. After the Paris Agreement in 2015, the European Union (EU) set a goal of reducing carbon emissions by 80-95% by the year 2050. Later in 2018, a decarbonization pathway study was done by Eurelectric that states that to achieve this, direct electricity consumption should make up 60% of the energy demand. It also includes that carbon-neutral fuels will need to make up another 30% of this demand. An image of said projection is shown below. Carbon neutral fuels include solar thermal energy, geothermal energy, and especially renewable fuel sources like biogas [5].

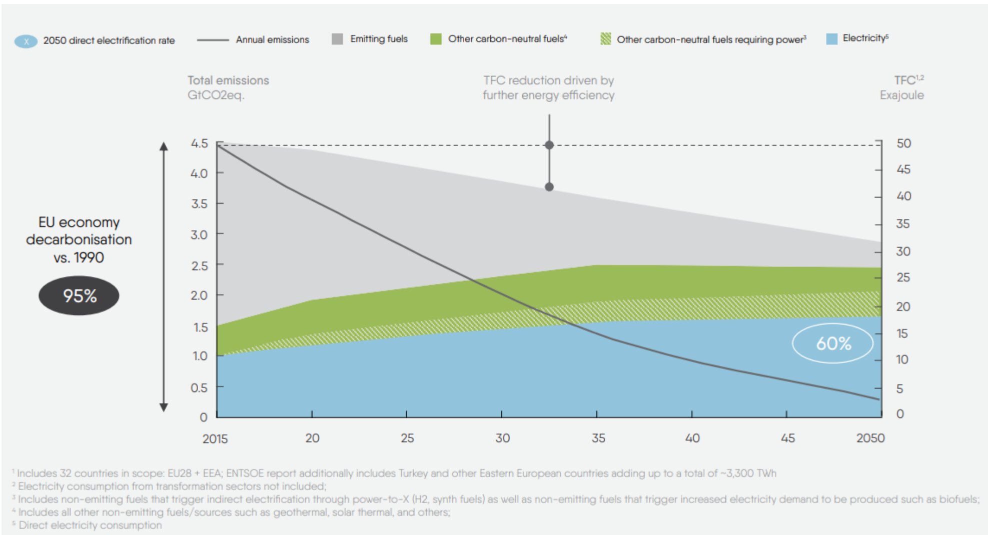


Figure 1. Impact of Electrification on Total Energy Consumption (TFC) and EU Economy Emissions [5].

Therefore, although electrification may lead society’s fight in healing the planet, it is unreasonable to believe it can achieve it all on its own. In fact, it shouldn’t have to. Various energy production technologies such as nuclear energy, hydrogen, biogas, etc. have proven to be reliable in reducing carbon emissions and have niche sectors in which they are especially advantageous. This report will discuss the potential for biogas to replace natural gas and aid in the decarbonization process therefore alleviating some of the difficulties an energy transition to only electricity might face. Spain´s potential to reach energy dependence through biogas use will also be discoursed. Later, a case study on the renovation of residential natural gas boilers in Spain will be presented to analyze and compare whether the country should upgrade domestic heat generation to gas or electric systems.

2. Biomethane

2.1 Biogas

Due to the increasing demand for new types of renewable energy sources to accelerate decarbonization, various new renewable fuel types are being explored. One such renewable fuel is hydrogen. Green hydrogen (its most eco-friendly form) is created through renewable energy and can create two to three times more energy than most other combustibles. Despite it being the most abundant chemical in the universe, using Hydrogen as an energy vector is still extremely costly and lacks infrastructure, so its full integration is not yet viable [6] (pg. 62-64). Instead, this report will discuss and explore a different renewable fuel- biogas. Biogas can be produced naturally, through gasification, power to methane, and biodegradation. This report will focus specifically on its generation by anaerobic digestion of organic waste, or biodegradation.

Anaerobic digestion refers to a degrative biological process that occurs in the absence of oxygen which allows bacteria to break down organic waste. This process is more efficient than an aerobic digestion (with oxygen) as it uses 40% less energy and converts up to 90% of the available energy [7]. The waste used to produce biogas can be taken from agricultural activity, livestock farms, organic municipal waste, landfills, and wastewater treatment plants. The two subproducts created are a digestate and biogas. The biogas is a typically a mixture of 25-45% carbon dioxide, 50-75% methane, 2-7% water vapor along with small concentrations of hydrogen sulfide, nitrogen, and ammonia. The digestate left behind is metabolized organic matter rich in inorganic nutrients which can be transported back to farms to be used as a fertilizer [6] (pg. 12).

The overall emission factor of biogas is 0,001 $CO_{2,eq}$/kWh when coming from biogenic origins. For carbon dioxide emissions specifically, it is actually considered to be 0, or carbon neutral. In terms of methane and nitrous oxide it has emission factors of 0,0025 and 0,003 g/kWh respectively [3]. In other words, its combustion accounts for very minimal greenhouse gas emissions.

As previously mentioned, besides carbon dioxide and methane, biogas is also comprised of hydrogen sulfide, water, siloxanes, and organic volatile compounds which are removed before further uses. The pretreatment will vary depending on the gas´s final use which can be electricity, heat and vapor, or biological natural gas. Pretreated biogas can produce electricity by means of gas turbines or internal combustion motors. Implementation of biogas in boilers produces thermal energy which can convert water to higher temperatures or to a vapor. Biomethane has a high heating value and can be substituted for natural gas in all its corresponding applications [6] (pg. 13).

2.2 Upgrading to Biomethane

Once the biogas is obtained, it can then be converted to biological natural gas through a process called upgrading. The point of upgrading is to filter out carbon dioxide molecules, and increase the proportion of methane (CH_4), usually up to 95-99,9%. This new gas achieved is also called biomethane. Upgrading can occur through various processes such as membranes, pressurized water scrubbing (PWS), chemical absorption, pressure swing adsorption (PSA), cryogenic separation, and biologic separation.

Biomethane is desirable as it is a carbon neutral fuel source. Although biomethane still emits carbon dioxide during its combustion, this is considered to be biogenic carbon dioxide because it would have been emitted anyways during the natural decomposition of the organic waste that undergoes anaerobic digestion. Furthermore, these organic materials naturally remove carbon dioxide from the atmosphere during their growth. Luckily, the extra carbon dioxide captured and filtered out during the upgrading progress can be mixed with green hydrogen (that is, hydrogen produced through renewable resources) to create even more biomethane. This process is called power-to-methane which can be used in the food and chemical industries for refrigeration, or in greenhouses [6] (pg. 104). All in all, if produced and managed correctly, biomethane has the potential to close the carbon cycle and prevent more carbon from being emitted into the atmosphere than is naturally expected.

Not only does biomethane have lower emissions than fossil fuels, but it also reduces emissions in the agricultural sector that occur from urine, slurry, and manures by including them in the anaerobic digestion process. The digestate created during this same process is high in nitrogen, potassium, and phosphorous. These nutrients come from the waste digested and are given a second “useful life” when the digestate is reused as a fertilizer. This in turn reduces the use of mineral fertilizers which are known for being large emitters of GHGs [6] (pg. 107).

The reason why biomethane is unique in the world of sustainability is because it has the same chemical makeup of natural gas. This means they are fully interchangeable so eventually, biomethane can replace natural gas completely and offer a carbon neutral alternative to industries such as electricity, heating, and transport. Moreover, in a world that is constantly consuming more and in turn, also wasting more, being able to convert any amount of waste into energy is beneficial. Turning organic waste into biogas can decrease landfill areas, reduce greenhouse gas emissions, and help to create a circular economy.

2.3 Ease of Transition

A great advantage of replacing biomethane with natural gas is that it will be an easy transition. Since biomethane and natural gas are made up of the same chemicals, they have the same properties. Therefore, this new green gas can be injected directly into already existing natural gas networks. Specifically in the case of individual heating and domestic hot water for homes, biomethane gas can be implemented into the supply without affecting the performance of the machines. Nedgia, the natural gas distributor of Naturgy, who is the largest natural gas distributor in Spain, has already begun to work with and support biomethane production plants. Even though there is not enough biomethane currently produced to replace natural gas completely, it can be injected into the grid and mixed with natural gas. The gas pipelines belonging to Nedgia reach 68% of the available market in the country, covering 10 out of the 17 autonomous communities [8]. The same applies to equipment. Natural gas boilers are currently designed to convert the incoming gas into steam, heat or hot water for residential purposes. If electrification is the future in this sector, clients will need to purchase new machines that are electricity driven, such as heat pumps. However, if biomethane is instead utilized, clients can maintain their current machines as the two gases are interchangeable. In the end, a biomethane infrastructure already exists so if this fuel source is augmented, homeowners can be happy knowing they won´t have to worry about extra costs associated with supporting new electricity gridwork and new heat generation units.

2.4 Vehicular bio-Natural Gas

Utilizing natural gas as a fuel is already the cleanest vehicular combustion option on the market. This option can become further decarbonized with biomethane substitution. It also has potential to reduce NO_2 emissions by 85% and particulate matter emissions by 96% (from European regulation limitations) [6] (pg. 91). Like natural gas, when compressed, biomethane becomes a bio liquid natural gas (bioLNG) or bio compressed natural gas (bioCNG) which can serve as transport fuel. Liquefied natural gas can be easily stored and transported globally. At its stations it can be converted back into CNG for smaller vehicles with dedicated motors, CNG-electric hybrids, or those of bi-fuel and dual-fuel compatibility. It can also be kept in its liquid state for heavy transport and large distance vehicles. Circularity can even be achieved if this fuel type is supplied to the same waste vehicles that transport the digestible waste to biogas/biomethane plants. Overall, this fuel alternative is ideal for heavy transport vehicles that do not have the capability to be equipped with batteries for electrification and require longer distances of travel.

In Madrid, for example, the EMT (Municipal Transport Company) expects to have over 500 city buses running on compressed natural gas by 2023. Increases in production of nearby biomethane production plants, such as Valdemingómez, will allow for enough biomethane to be injected into natural gas networks that can supply these buses entirely. These measures will help comply with and achieve the National Integrated Energy and Climate Plan´s (PNIEC) goal of reaching a 42% share of renewable energy in final energy by 2030 [9]. Obviously, the use of biomethane or natural gas is advantageous in city buses as it prevents the greenhouse gas emissions and particulate matter that diesel fueled buses would produce.

In terms of refueling stations, as of June 3rd, 2022, Gasnam reported that Spain contains 123 open compressed natural gas (CNG) refueling stations with 32 currently in production. As well as 86 liquefied natural gas (LNG) stations with an additional 19 in production. Below are maps showing their locations throughout the country [10]. The yellow pins show already functioning CNG stations and the blue ones show already functioning LNG ones. On both maps, the gray pins represent stations in construction. As shown, there are already a large number of existing stations which make the refueling of these vehicles easy and accessible to everyone. As previously stated, the importance of natural gas vehicles is that their stations have the potential to include biomethane gases into their networks which is more environmentally friendly than natural gas. Since transportation currently makes up the sector with the greatest share of carbon emissions (27%) in Spain, implementing biomethane as vehicular natural gas is a great way to decarbonize it [11].

Figure 2. CNG (left) and LNG (right) stations in Spain [10].

2.5 Storage Capacity

Another advantage that biomethane offers is storage capability. A frequent problem with many renewable resources such as wind and solar energy for example, is storage. Obviously, the wind is not always blowing and the sun is not always shining. However, there are still energy demands during these periods. Even though there are cases when the production of these renewable sources is higher than the demand, it has proven difficult to save that excess production for future use. Currently, the main options for electricity reservation are large batteries and water reservoirs, but they are still under development with many improvements to be made. In the end, electricity cannot be stored without first being converted into some other form, so if the generation plant is not connected to batteries, reservoirs, etc, then the excess generation is lost. Consequently, the electricity needed at times where renewables cannot meet the demand is usually taken from non-renewable sources that tend to emit large quantities of greenhouse gases into the atmosphere. However, biomethane has the ability to change this. As it is a gas, it can be stored as such in holders or tanks. Alternatively, biogas/biomethane can be compressed or liquified into bioLNG or bioCNG for increased storage capacity and easier transport.

2.6 Economic Growth and Stability

The production of biomethane and the construction of its plants will also help create jobs and reduce depopulation. It is expected that at least 18 workers are needed to run each plant [12]. The figure below shows the European Biogas Association´s projection of how many jobs biogas and biomethane will provide in Europe by 2050. Within the 513,000 jobs estimated, about half will fall under plant operation, and a quarter each in plant construction and supply of the substrates [6] (pg. 120). Furthermore, most plants are expected to be constructed in rural areas because of these space´s capacity for agricultural growth. Unfortunately, rural areas in Spain have suffered a 28% decrease in population over the last 50 years [13]. The introduction of biomethane and biogas production into these areas have the potential to employ local inhabitants, curb depopulation, redevelop the area´s economy, and increase the quality of life.

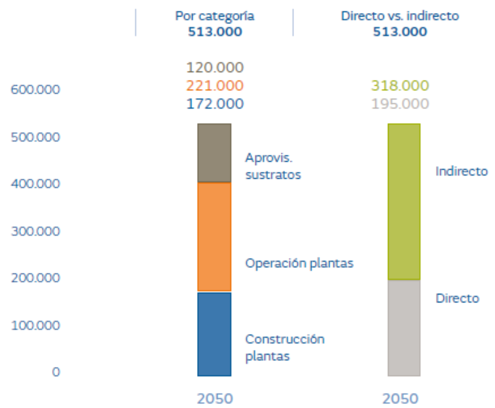


Figure 3. Job Estimation in the Biogas and Biomethane Sector for 2050 [6].

In addition, the internal production of biogas offers energy security for Spain. As seen with Russia´s war on Ukraine, dependence on other countries for fuel resources can be extremely unstable. Prices and supply can vary day to day if political tensions are high. They can also vary due to climate events which can affect the availability of the product. Although Spain only imported 8% of its natural gas from Russia in 2021, its main importer, Algeria, has already threatened to terminate its contract due to disputes involving Algeria´s neighboring country of Morocco. Algeria supplies nearly 43% of Spain´s natural gas so a contract termination would be detrimental. The war in Russia has opened the possibility of increasing Europe´s natural gas import from the United States. Spain already receives 14% of its supply from them [14]. This gas would have to be received in the form of LNG in order to be shipped across the ocean. The problem with this option is that it can be extremely costly and the high global demand would make it difficult to increase its supply across the world [12].

By producing biogas and biomethane within Spain´s borders, the dependence on other countries and the uncertainties that come with that will decrease. Consumers can feel comfort in knowing that their energy supply and energy bills will be steady. Additionally, if Spain has enough production, they can later decide to be an exporter of this gas. This offers the opportunity to strengthen the country´s economy on a European and possibly global level. Overall, biomethane is an extremely promising energy source with much to gain. In comparison to carbon dioxide, methane can trap 25x more heat in the atmosphere. Although it is not as present as the former, it is still a harmful greenhouse gas. Therefore, finding ways to capture and use it for energy is just another way the world can work towards reducing society´s overall carbon footprint.

2.7 Spain´s Biogas Potential

Currently, Spain is struggling to catch up to other European countries´ biogas production. The "European Biomethane Map 2020" published by the European Biogas Association (EBA) and Gas Infrastructure Europe (GIE) declares that Germany has 232 biomethane plants, the highest in Europe. It is followed by France with 131 plants and the United Kingdom with 80 [15]. Spain sadly only accounted for 2 biomethane plants. In terms of biogas plants, Spain has roughly 200 whereas Germany exceeds 10,000 [16]. Despite these low shares, Spain actually has a huge potential for biogas/biomethane production. In fact, in the European Union, Spain is projected to have the 3rd highest yearly production by the year 2050 at over 120 TWh/year. France comes in first with over 180 TWh/year and Germany in second with over 130 TWh/year [17].

However, the picture changes greatly when rotation crops are considered. These are crops that are taken from the same piece of land. Depending on which season it is will determine what crop is best fit to be grown. This increases the field´s yield and thus the biogas production. The digestate created during anaerobic digestion can be integrated into the farming process as a fertilizer to keep the soil rich in nutrients. If managed correctly, this agricultural process can help Spain reach 300 TWh by 2050 [12].

The image below is taken from Gasactual Issue N°163 and displays the biogas production from rotation crops in each Autonomous Community of Spain. Castilla y León has the highest potential at 95.32 TWh per year. Castilla La Mancha and Aragón follow with respective potentials of 48.28

and 42.88 TWh. Andalucía and Extremadura also both have notable production potentials around 30 TWh.

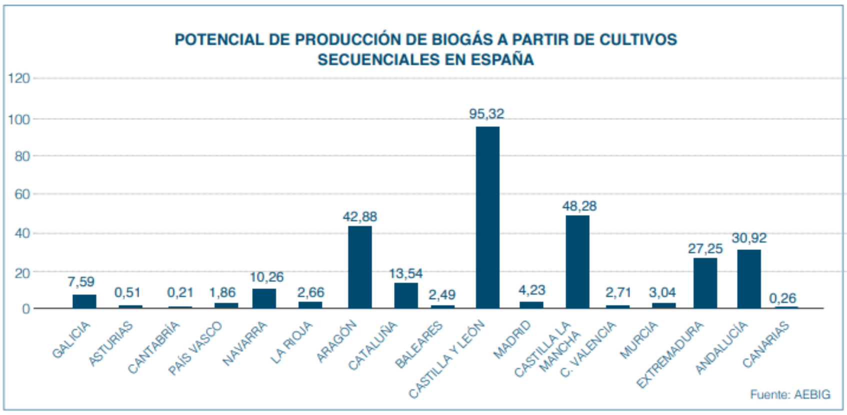


Figure 4. Potential Biogas Production from Rotation Crops in Spain [12].

Considering the gas demand in Spain reached 378 TWh in 2021, production of biogas/biomethane with a conservative projection of 120 TWh would cover 31.7% of the country´s needs. Data from Sedigas has a prediction of Spain´s production at 137 TWh which would increase that coverage to 36% [12]. If every kWh of natural gas produces 0.182 kg CO2, then by investing in this waste-to-energy source, Spain could reduce the emissions of 25 million tons of CO2 every year. Alternatively, the use of cultivation crops to reach a potential of 300 TWh by 2050 would cover 79% of the demand and prevent twice as many CO2 emissions. In addition, Nediga´s natural gas clients using residential heating boilers consume a total of approximately 52 TWh/year. With the help from Nedgia´s gas lines, this entire demand can be covered with the biomethane projections.

The current largest biogas plants in Spain are Valdemingómez and Butarque. The Valdemingómez plant is near Madrid and is actually the largest waste plant in Europe. It consists of 3 smaller plants: Las Lomas, where biogas pretreatment takes place, then La Paloma and Las Dehesas where biomethanization occurs. Recent reform to this plant has allowed its capacity to increase from 100 GWh/year to now 180 GWh/year. This biomethane is injected into the natural gas grid as thermal energy [9]. The other plant, Butarque, is also located in Madrid. It is firstly a wastewater treatment plant and has the capacity to inject 5 GWh of biomethane into Nedgia´s gas network per year [18].

The main reason this country has not been at the forefront of this energy source, despite their clear capability, is due to a lack of concrete measures which can support and legitimize the development and use of this renewable energy source. One such specifically is the Guarantees of Origin (GoO). This is typically an electronic certification that is used as a way to guarantee that the energy a final user is utilizing has come from a validated renewable source. It will be used to differentiate biogases from fossil fuels. This type of certification system already exists for renewable electricity generation. Luckily enough, on May 18, 2022, the Spanish government published Royal Decree 376/2022 which states the approval of a GoO system for biogas, biomethane, and even hydrogen. It will be similar to that of electricity in that every MWh of renewable gas will be issued a GoO that states when, where, and how the gas was produced. The decree also creates a census of gas production facilities along with a committee of producers which allows producers and buyers to exchange GoOs. This publication will incentivize those who produce industrial organic waste to become involved in this industry so that they can turn their waste into profits while helping the environment [19].

It is also worth noting that the "Hoja de Ruta del Biogas" published by the Spanish government in 2022 states that it only has the goal of producing 10.41 TWh of biogas and biomethane in 2030 [20]. This is over 12 times smaller than the country´s conservative potential. Hopefully the long-awaited introduction of Guarantees of Origin will push the country to exceed these expectations.

4. Boiler Renovation Case Study

4.1 Background of Study

In 2020, MITECO reported that 9.2% of Spain´s greenhouse gas emissions came from the Residential, Commercial, Institutional sector [11]. Although this may seem like a small percentage, it is still worthy of decarbonizing because any way in which carbon dioxide emissions can be reduced is crucial for the future of the planet.

This study will focus specifically on residential heating. In Spain, residential heating and domestic hot water is typically produced by two different types of equipment- boilers or heat pumps. At least 65% of the boiler fleet in Spain is of outdated technology which is causing excess energy consumption and carbon emissions. They need an efficient replacement option. A comparison will be made whether it is more "sustainable" to rehabilitate these old units with newer boiler models or to switch them out for electric powered heat pumps.

For the purposes of this report, boilers will be broken up into two categories- standard or condensation. Standard refers to atmospheric or low temperature while condensation boilers will be divided into analogical and digital types, in other words, with or without modulation capacity. Atmospheric boilers are ones in which the air needed for combustion is taken directly from the room in which the boiler is located. This can be problematic for two reasons. If the room is not ventilated, then the machine will have trouble drawing in air and consequently not function well. Also, since the combustion chamber is also located inside the unit, it can leak toxic fumes into the room which is only further exacerbated if ventilation is not well implemented. Because of this, in 2010, Spain made their installation prohibited. Low Temperature boilers are those capable of functioning with inlet water temperatures from 35-40°C whereas atmospheric boilers typically need that value to be at least 60°C. The air entering the unit will come from the outside so there is less risk for fume leakage inside the house [21].

Condensation boilers are generally more efficient than standard conventional types. Where conventional boilers tend to exhaust excess heat through stacks, condensation boilers can take advantage of said heat to pre-heat the entering water that is on its way to the primary heat exchanger. This allows for the units to use less energy to reach the same desired temperature. This technology is named condensation because of the how the excess heat vapor condenses into liquid droplets at the secondary heat exchanger. In fact, all gas boilers will experience condensation due to the combustion of methane and oxygen. But if the machine does not have the proper materials, the condensate can be very corrosive. This is why condensation boilers are usually made from stainless steel.

Heat pumps (HP) are the other way in which heat can be created and supplied to a home. The heat pumps referred to in this study are electricity powered units that use refrigerants to convert cold outdoor air into heat that can be distributed inside. These units have been receiving a lot of support lately since they tend to have much higher efficiencies than boilers. The case study below will determine just how much energy and carbon emissions these boilers can save and if it is financially achievable.

4.2 Methodology

This study focuses on the comparison of upgrading the existing boilers in Spain to either digital condensation boilers (boilers with modulation) or electric heat pumps. First, the hypothetical renovation of atmospheric, low temperature and analogic condensation boilers to digital condensation boilers will be analyzed.

An approximation of the total amount of boilers per autonomous community was found by multiplying the total appliance stock of natural gas and biogas boilers, by the percentage of natural gas share each climatic zone in Spain uses. ERESEE published that in 2020, 7,159,436 gas boilers existed in Spain [22]. This is the number to be used in the calculations. In terms of climatic zones, in Spain there are three- Atlantic, Continental, and Mediterranean. The gas shares and corresponding percentages can be found in table 1 below. The data was obtained through Nedgia.

Climate Zone	Gas Share in 2020 (ktoe)	% Of Total Share
Atlantic Zone	292	0.128
Continental Zone	1415	0.620
Mediterranean Zone	574	0.252

Table 1. 2020 Spanish Natural Gas Share per Zone [23].

The resulting value found from this calculation is then multiplied by the percent of population that community accounts for per zone. These values can be found in table 2.

Atlantic Zone			Continental Zone			Mediterranean Zone		
Community	*Population*	*% per Zone*	*Community*	*Population*	*% per Zone*	*Community*	*Population*	*% per Zone*
Galicia	2696995	0,416	Comunidad de Madrid	6752763	0,464	Catalunya	7669999	0,293
Asturias	1013018	0,156	Castilla-La Mancha	2049455	0,141	Comunitat Valenciana	5045885	0,193
País Vasco	2185605	0,337	Castilla y León	2387370	0,164	Región de Murcia	1513161	0,058
Cantabria	583904	0,090	La Rioja	316197	0,022	Andalucía	8501450	0,325
			Navarra	657776	0,045	Islas Canarias	2244423	0,086
			Extremadura	1057999	0,073	Illes Balears	1219423	0,047
			Aragón	1331280	0,091			

Table 2. Autonomous Community Populations per Climate Zone in Spain.

The resulting boilers per autonomous community are as follows:

Autonomous Community	Total Boilers	Autonomous Community	Total Boilers
Andalucía	584724	Galicia	381482
Aragón	406286	Illes Balears	83871
Asturias	143288	La Rioja	96498
Islas Canarias	154370	Comunidad de Madrid	2060837
Cantabria	82591	Región de Murcia	104074
Castilla-La Mancha	625462	Navarra	200743
Castilla y León	728588	País Vasco	309147
Catalunya	527537	Comunitat Valenciana	347053
Extremadura	322884		

Table 3. Total Boilers per Autonomous Community

These boiler totals per autonomous community are then further multiplied to be broken up into each specific boiler type. 2021 data from Fegeca will be utilized. They published that last year in Spain, approximately 66% of installations in Spain were standard boilers while approximately 30% were condensation boilers [24]. Of standard type, 25% were calculated to be atmospheric and 75% of low temperature. For condensation type, 60% were calculated as analogic and 40% as digital. The graphics below show a breakdown of boilers in each autonomous community and the overall proportion of each boiler type in Spain.

Community	Standard Atmospheric Boilers	Low Temperature Standard Boilers	Analogic Condensation Boilers	Digital Condensation Boilers	Total Boilers
Andalucia	96231	288693	104829	69886	584724
Aragon	66864	200593	72839	48559	406286
Asturias	23582	70745	25689	17126	143288
Cantabria	13592	40777	14807	9871	82591
Castilla La Mancha	102935	308806	112133	74755	625462
Castilla Leon	119907	359722	130621	87081	728588
Catalunya	86819	260458	94577	63051	527537
Comunidad de Madrid	339162	1017487	369467	246311	2060837
Comunidad Valenciana	57116	171349	62220	41480	347053
Extremadura	53139	159416	57887	38591	322884
Galicia	62782	188347	68392	45595	381482
Islas Baleares	13803	41409	15036	10024	83871
Islas Canarias	25405	76216	27675	18450	154370
La Rioja	15881	47644	17300	11533	96498
Navarra	33037	99112	35989	23993	200743
Pais Vasco	50878	152634	55424	36949	309147
Region de Murcia	17128	51384	18658	12439	104074
Total	**1178264**	**3534792**	**1283543**	**855696**	**7159434**

Table 4. Boiler Types in Each Autonomous Community.

Figure 5. Boilers in Spain.

As seen in table 4, the communities with the most boilers in Spain are Madrid, Castilla La Mancha and Castilla y León. This is driven by the Continental zone having the highest share of natural gas usage. Overall, low temperature boilers take up the most space in this market accounting for over 50% of all boilers used in Spain.

The next step in this analysis is to calculate the energy consumption savings that can be achieved by upgrades in technology. The first piece of information needed to begin this process is the efficiency of each boiler. This information was extracted from the "Guía de la Edificación Sostenible" published by IDAE (Instituto para la Diversificación y Ahorro de la Energía), Ministerio de Fomento, and Institut Cerdá. The efficiencies are taken from "Calefacción. Sistemas individuales" which can be found in figure A1 of the appendix A. The performance value of 0.79 corresponds to atmospheric boiler types, 0.85 to low temperature boilers, and 0.93 to analogic condensation boilers [25]. It is assumed that digital condensation boilers have an efficiency of 1.0. Next, the energy consumption of each boiler type in each autonomous community ($E_{\text{boiler type}}$) can be calculated using the formula:

$$E_{boiler\ type} = \frac{Annual\ Consumption\ per\ Autonomous\ Community * Average\ Efficiency}{Efficiency\ of\ Boiler}$$

The annual energy consumption per Autonomous Community was provided by Nedgia, the gas distributor of Naturgy, and can be referenced table 5. Since Nedgia only supplies to 10 out of the 17 autonomous communities, the unserved communities were given values equal to those geographically next to them. The variable- Average efficiency is a sum of all the boiler efficiencies multiplied by how many of each type exists in Spain, then divided by the total amount of boilers. Its value is approximately 0.8375.

Autonomous Community	Annual Consumption (MWh/year)	Autonomous Community	Annual Consumption (MWh/year)
Andalucía	7.71	Galicia	6.89
Aragón	9.97	Illes Balears	7.48
Asturias	6.89	La Rioja	7.09
Islas Canarias	7.71	Comunidad de Madrid	6.64
Cantabria	6.89	Región de Murcia	7.29
Castilla-La Mancha	7.59	Navarra	7.46
Castilla y León	7.35	País Vasco	6.89
Catalunya	7.48	Comunitat Valenciana	7.29
Extremadura	7.59		

Table 5. Annual Energy Consumption per Autonomous Community in Spain [23].

With this information, the consumptions for each boiler upgrade (from atmospheric, low temperature, or analogic) to digital condensation types can be calculated. The formula for Consumption Reduction (CR) is as follows:

$$\boldsymbol{CR = (Consumption\ of\ old\ boiler - Consumption\ of\ digital\ condensation\ boiler) * Amount\ of\ old\ boilers}$$

The next calculation of interest is the emission savings through upgrade to digital condensation boilers. An important multiplier to take into consideration is the emission factor. This is the amount of CO_2 emitted for every kWh of energy used. This value varies depending on the type of energy source used. For natural gas, this value is 0.182 kg $CO_{2,eq}$/kWh [3]. The consumption savings previously calculated above for each boiler type can be multiplied by this emission factor to achieve what the projected emission savings are. As the energy consumption reduction will be calculated in MWh, by dividing the value by 1000 one can easily convert it from kg into tons.

The second portion of this study will focus on the upgrade of standard boilers (atmospheric and low temperature) to heat pumps, instead of digital condensation boilers. Analogical condensation boilers have been left out as they have similar efficiencies to digital condensation ones. The calculations in this process are similar to that of the boiler-to-boiler upgrade. However, in this case, the efficiency of heat pumps will vary for each autonomous community. The values seen below are estimations provided by Nedgia.

Autonomous Community	Annual Consumption (MWh/year)	Autonomous Community	Annual Consumption (MWh/year)
Andalucía	3.5	Galicia	3
Aragón	3	Illes Balears	3
Asturias	3	La Rioja	2.5
Islas Canarias	3.5	Comunidad de Madrid	3
Cantabria	3	Región de Murcia	3.5
Castilla-La Mancha	2.5	Navarra	2.5
Castilla y León	2.5	País Vasco	3
Catalunya	3	Comunitat Valenciana	3.5
Extremadura	3		

Table 6. Heat Pump Efficiency per Autonomous Community [23].

These are the values that will be substituted for "Efficiency of Boiler" in the $E_{boiler\ type}$ type equation to find the approximate energy consumption of a single heat pump per year, in each autonomous community. Then, to find the Consumption Reduction, the "consumption of digital condensation boilers" will be replaced with the yearly consumption of a heat pump unit in each autonomous community.

To extract the carbon dioxide emission savings, it will first be necessary to find how much CO_2 each heat pump unit typically emits per year. Since the heat pumps considered in this study would be powered directly by electricity, the emission factor for electricity is needed. Published by the Comisión Nacional de los Mercados y la Competencia (CNMC), in 2021, Spain´s electricity generation mix still relied fairly heavily on natural gas and other fossil fuel/non-renewable sources so it´s emission factor was actually greater than that of natural gas. The value from said report which will be used in this study is 0.259 kg $CO_{2,\ eq}$/kWh [26]. The source of this value can be seen in figure B1 of appendix B. Since boilers and heat pumps have different emission factors, the formula for emission reduction in this case is as follows:

$$\boldsymbol{CO_2\ savings\ for\ HP} = (\boldsymbol{CO_2\ emissions\ per\ boiler} - \boldsymbol{CO_2\ emissions\ per\ heat\ pump}) * \boldsymbol{Amount\ of\ boilers}$$

4.3 Results

This portion displays all the graphical results from the above calculations. Figure 6 below shows the potential energy reduction, in TWh, that can be achieved by switching all older boiler models to that of a digital condensation type boiler.

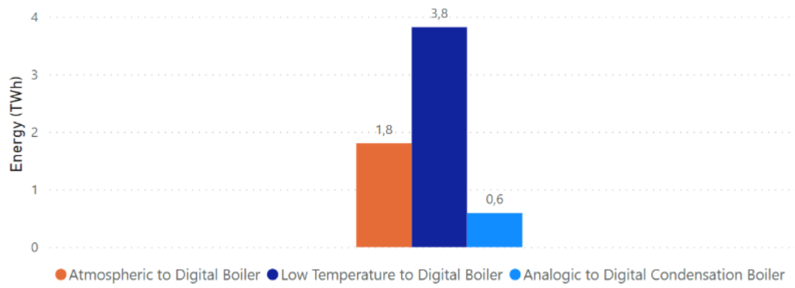


Figure 6. Energy Reduction by Upgrade to a Digital Condensation Boiler.

As shown above, the way to achieve the largest reduction in energy consumption is through upgrading low temperature boilers to those of digital condensation. Although atmospheric boilers have the lowest efficiency in the market, there are not many of them left in usage. In addition, since analogic and digital condensation boilers have similar efficiencies, the energy reduction is not as drastic. The overall boiler energy use in Spain has the potential to be reduced by 6.2 trillion watt-hours per year.

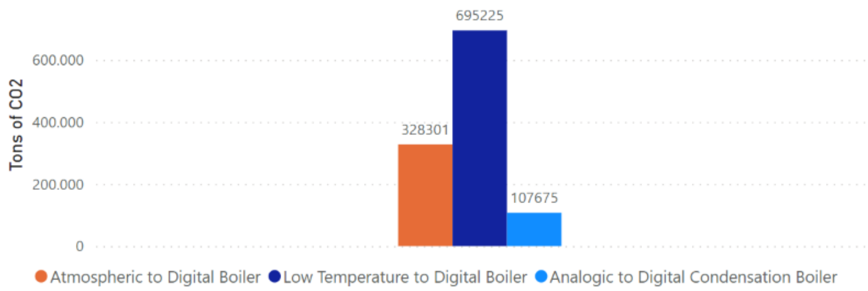


Figure 7. Emission Reduction by Upgrade to a Digital Condensation Boiler.

Figure 7 above portrays the carbon dioxide emission savings due to each boilers upgrade to the digital condensation type. Similar trends are seen as in figure 6. There is an expected total of 1.25 million tons of CO2 emissions that can be prevented per year with this boiler renovation.

Figure 8 below displays a comparison of the total energy reduction achieved by upgrading atmospheric and low temperature boilers to digital condensation boilers versus upgrading them to heat pumps. It shows that heat pumps can offer an additional 19.1 TWh reduction in energy consumption because of their high efficiencies.

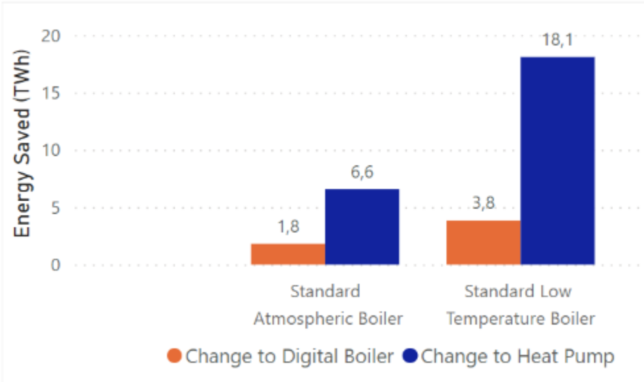


Figure 8. Energy Reduction by Upgrade to Boilers vs. Heat Pumps.

The graphic below represents the carbon dioxide emission reduction that can be achieved through the renovation to either digital condensation boiler or to heat pumps. Similar to the case of energy reduction, heat pumps offer a much larger potential for emission reduction. An additional 3.28-million-ton reduction of carbon dioxide can be met.

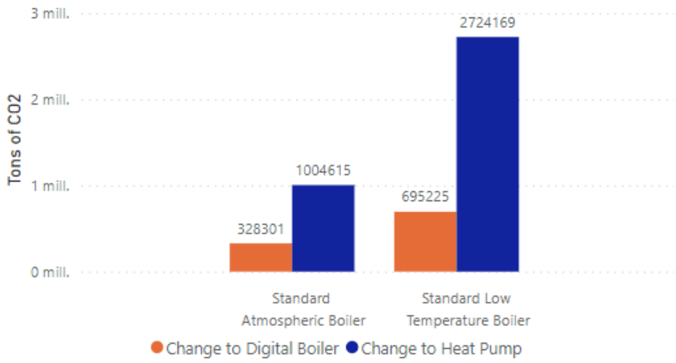
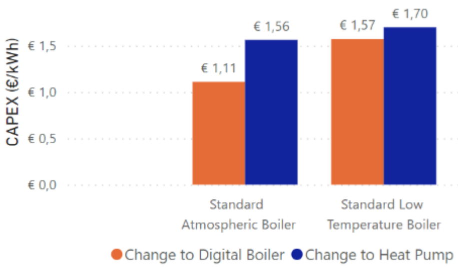


Figure 9. Emission Reduction by Upgrade to Boilers vs. Heat Pumps

This last section of the renovation analysis will provide an economic viewpoint. The first piece of data that will assist in calculating inversion costs for both upgrade options is the approximate cost per machine today. The average cost of a digital condensation boiler is €1,700, and the average cost of a heat pump is €8,700 [27][28]. The overall inversion to update all 4.71 million standard boilers (atmospheric and low temperature) to the digital condensation type will cost €8 million. To instead convert them to heat pumps, it will cost €41 million, which is 5x more than the former.

With this information, the CAPEX for energy saved can be calculated by dividing the total inversion by the wattage saved. The same can be done for carbon emissions. Instead of dividing by wattage, the denominator becomes emissions saved. The two graphs below (figures 10 and 11) show how much one can expect to pay per kWh or ton of CO2 they will save in either upgrade type.



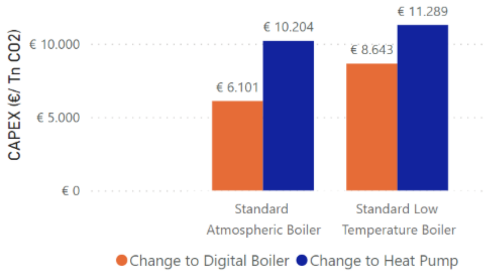


Figure 10. Unitary CAPEX for Energy Savings **Figure 11.** Unitary CAPEX for CO2 Emission Savings

Both graphs show that the consumer can invest less money to achieve the desired savings with digital condensation boilers. However, despite heat pumps costing 5x more, the increase in CAPEX is less than 60% more in each scenario. This is due to how much energy and emission reductions can be achieved with these high efficiency machines.

On the other hand, it is also helpful to see how much energy and emissions savings will be achieved per euro spent. Table 7 below displays the values saved (in kWh or grams of CO2) per euro invested in each technology type. The takeaway from this table is that the boiler-to-boiler upgrade will generally give the customer better savings for their investment.

Upgrade Option	**kWh saved per € spent**	**g CO_2 saved per € spent**
Boiler-to-Boiler	0.7	127.75
Boiler-to-Heat Pump	0.6	90.94

Table 7. Reductions in Energy Use and Carbon Emissions per Euro Invested.

In addition, it is important to point out that Royal Decree 691/2021 establishes various government subventions that are offered for improving energy efficiency in buildings. In table C1 of appendix C, a graphic taken from the decree is provided. It shows that a subsidiary of 40% of the customer´s cost will be provided for improvements based on thermal installations which is applicable to the heat pump upgrade [29]. This reduces the consumer price for a heat pump by €3,480. This same subvention could also pay for 2 digital condensation boilers.

4.4 Discussion

It is important to note that the boiler renovation study only accounts for emissions during the useful lifetime of the machines. The emissions that occur during the manufacturing and transport of the materials, as well as during their disposal, was not included. A life cycle analysis (LCA) would need to be reviewed before knowing the true total lifetime emissions each technology incurs. In addition, the presented energy consumed is only the final energy. Conversion factors for each energy source (natural gas and electricity) would be needed to calculate the additional primary energy each machine uses over their lifetime as well as those corresponding emissions. This can affect the true amount of energy and emission savings achievable for both renovation options.

Another way the emissions can vary greatly is due to the electricity generation mix. Electricity is obtained through different mediums of generation (renewable and non-renewable sources). Over time, as more renewable sources become viable, the electricity mix should move towards lower percentages in carbon equivalent emissions. However, it is hard to predict how long it will take to reach 100% generation by renewable sources. This also will affect the price of electricity which can determine whether or not users will be more willing to switch to electric appliances considering how costly their installation already is.

In addition, although the electrically powered heat pumps are much more efficient than natural gas-powered boilers right now, anywhere from 2.5-4 times more, this could change. As technology is always changing and improving, it is possible for these boilers to one day see efficiencies that are more competitive to that of electric heat pumps. Conversely, both boilers and heat pumps can expect to see reductions in their efficiencies throughout their useful lifetime due to natural degradation of the equipment.

In the end, the choice depends on the capabilities and the needs of the client. Their priority to reduce their carbon footprint or reduce their utility bill will be the main decision driver. For example, if their priority is to reduce the most amount of carbon emissions that they can, then electric heat pumps are currently the best choice. However, these units are much more expensive than boilers and it is unrealistic to expect everyone to be able to afford that type of upgrade. As seen in the economic analysis, a client will actually save more energy and carbon emissions per euro spent with a digital condensation boiler upgrade. In addition, electricity currently costs more than natural gas therefore, the operating costs for a heat pump will be larger than that for boilers. Even with a government subsidiary, it might take a while before the consumer begins to see a return on investment.

As seen above, neither natural gas nor electricity currently are 100% free of carbon emissions. Although, as increased investments in renewable electricity generation occur, the emission factor of electricity will decrease greatly, making it the more “sustainable” energy source in comparison to natural gas. However, if biomethane meets its projected production in the upcoming years, then it can become a legitimate, respected, alternative green energy source to electricity and especially to natural gas. As seen in the study above, it will have the ability to convert at least the residential heating industry into a carbon neutral one. By opting for the upgrade of residential boilers with newer models such as digital condensation boilers with the expectation that natural gas will be either mixed with biomethane at large proportions or replaced completely with this biogas, electricity generation can be reserved for other industries. This option will not only be cheaper but also more convenient as the grid connections and compatible equipment already exist.

7. Conclusions

As mentioned in the introduction, climate change is but one of the problems our society is currently facing. In 2015, the United Nations published the 2030 Agenda for Sustainable Development that is the culmination of decades of research on building a sustainable future for the planet. In it, 17 Sustainable Development Goals (SDGs) are presented that serve as key areas that need to be improved to make the planet a happier and more habitable place. These SDGs cover all three pillars of sustainability- social, environment, and economics. They are as follows: 1. No Poverty, 2. Zero Hunger, 3. Good Health and Well-being, 4. Quality Education, 5. Gender Equality, 6. Clean Water and Sanitation, 7. Affordable and Clean Energy, 8. Decent Work and Economic Growth, 9. Industry, Innovation and Infrastructure, 10. Reduced Inequalities, 11. Sustainable Cities and Communities, 12. Responsible Consumption and Production, 13. Climate Action, 14. Life Below Water, 15. Life on Land, 16. Peace, Justice and Strong Institutions, and 17. Partnerships for the Goals. It is the responsibility of countries and industries to work towards improving themselves in each of these categories to create a better world. Biomethane integration can help achieve progress in many of these categories [30].

For example, biomethane is a carbon neutral fuel source that already has infrastructures in place to support its integration. This corresponds to SDG 7 (Affordable and Clean Energy) because it can heat homes and power cars while not adding any more non-biogenic carbon dioxide. Utilizing it in already existing natural gas networks reduces installation costs, which will support communities that do not have the means to invest in electrical grid systems, heat pumps, etc.

Its continued growth in research and production cover SDGs 8 and 9 (Decent Work and Economic Growth and Industry, Innovation and Infrastructure). Obviously, increasing the amount of biogas/biomethane production plants will create jobs. Workforce growth as well as the potential export of the gas will strengthen the economy. Additionally, this energy source is not perfect and still requires various improvements to its supply chain. One such problem is methane leakage. A study done by the Imperial College London, UK found that biogas and biomethane production leak “more than twice as much methane as previously thought”, typically in few locations throughout the supply chain. Oil and gas companies do not often experience the same issues since they have received larger investments which have allowed their systems to be more robustly designed. If biogas and biomethane were to be financed properly, innovation for leak solutions can be explored and the correct measures can be implemented to fix the issues [31].

Lastly, and maybe most obviously, it aligns with SDG 13 (Climate Change) as its decarbonization aspect will directly fight climate change and contribute towards the EU´s goal of a 95% reduction in carbon dioxide equivalent emissions by 2050. As previously mentioned, methane is 25x more effective in trapping heat in the atmosphere than carbon dioxide. Even though it only survives for approximately a decade, whereas carbon dioxide typically is present for over a century, nonetheless, its emissions should be taken seriously. Turning waste into energy will prevent tons of organic waste from sitting in landfills and emitting methane into the atmosphere.

In conclusion, although electrification is still a great way to push decarbonization and will most likely take the lead in renewable energy sources, biomethane should be another option as its use is reliable, convenient, and modular. In the end, it must not be forgotten that climate change is something that will affect every single person on this planet despite where they live, how much money they make, or how large their individual carbon footprint is. Therefore, options to choose a more sustainable lifestyle must be realistically achievable and subsequently affordable to everyone. Whether the future is biomethane, electricity, hydrogen, or some new technology yet to be invented, greed and capitalism will need to be put aside so that sustainable changes can be partaken by every member of society. It is the only way to pursue the United Nation´s vision of "peace and prosperity for the people and the planet, now and into the future" [30].

Funding: This research received no external funding.

Conflicts of Interest: During the time of this study, the author was employed as in intern at Nedgia (Naturgy).

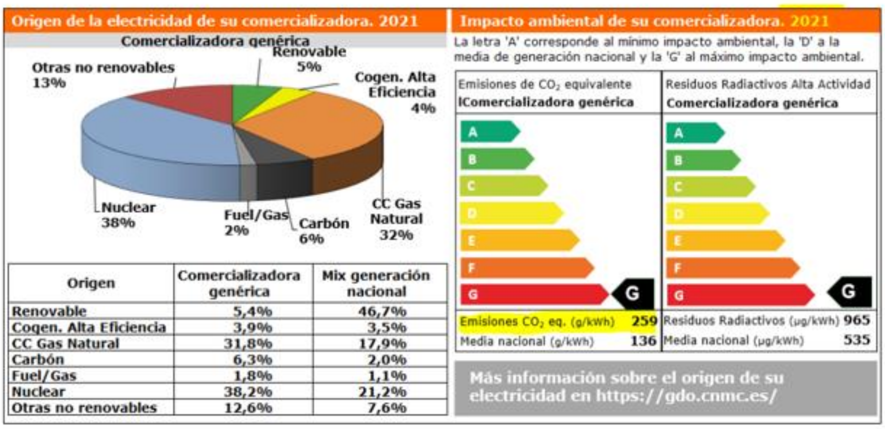
Appendix A: Boiler Efficiencies

Figure A1. Boiler Efficiencies in Spain [24].

INSTALACIONES INDIVIDUALES A GAS	$\eta = \eta_g \times \eta_d \times \eta_r$
Calefacción. Sistemas individuales	
– Caldera con quemador atmosférico	0,79
– Caldera de alta eficiencia	0,85
– Caldera de condensación	0,93
– Generadores de aire	0,71
Calefacción. Sistema unitario	
– Convectores murales	0,80
Agua caliente sanitaria	
– Calentador instantáneo	0,76
– Caldera con acumulador	0,68
– Caldera mixta	0,76

Appendix B : Electricity Mix in Spain

Figure B1. Electricity Mix Emission Factor in Spain in 2021 [25].



Origen	Comercializadora genérica	Mix generación nacional
Renovable	5,4%	46,7%
Cogen. Alta Eficiencia	3,9%	3,5%
CC Gas Natural	31,8%	17,9%
Carbón	6,3%	2,0%
Fuel/Gas	1,8%	1,1%
Nuclear	38,2%	21,2%
Otras no renovables	12,6%	7,6%

Appendix C: Subsidiaries

Table C1. Subsidiaries Provided by the Spanish Government for Energy Efficiency Improvements [26].

Base Aid Intensity Option A		
Types of Upgrades (% s/eligible cost)	**Base Aid**	**Additional help due to social criteria, energy efficiency or integrated upgrade**
Type 1. Improvement to energy efficiency of thermal envelope	50%	Depending on the use of the building and in accordance with Annex IV, for the type of operation. The sum base aid and the additional aid shall not, as the case may be, exceed the limit laid down in Regulation (EU) 651/2014.
Type 2. Improvement to energy efficiency of the thermal installations	40%	
Type 3. Improvements to energy efficiency of lighting installations	20%	

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