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Acetylene & MagneGas-2 Sustainability Assessment

A comparative environmental impact analysis of several acetylene production processes and the Taronis MagneGas-2 production process.

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1 Executive Summary

This report includes 3 major assessments on the main processes involved in producing acetylene as well as the process to produce MagneGas-2. The conclusions of each assessment are calculated values for the feedstock/consumables, waste, water, physical, electricity, and carbon footprints for acetylene production. The feedstock/consumables, waste, and electricity footprints are calculated in terms of their contribution toward the carbon footprint. The carbon footprint is the sum of these values. Table 1-1 summarizes the results for all processes.

Table 1-1. Feedstock consumption per unit of production [1,2]

		Feedstock $\frac{kg.CO2}{cu.ft.C_2H_2}$	**Waste** $\frac{kg.CO2}{cu.ft.C_2H_2}$	**Water** $\frac{gal.H_2O}{cu.ft.C_2H_2}$	**Physical** $\frac{sq.ft.yr}{cu.ft.C_2H_2}$	**Electricity** $\frac{kg.CO_2}{cu.ft.C_2H_2}$	**Carbon** $\frac{kg.CO_2}{cu.ft.C_2H_2}$
Thermal Cracking	POX	0.170	0.007	-	-	0.040	0.217
	Hüls	0.065	0.055	-	-	0.129	0.249
	Plasma Arc (Naphtha)	0.067	0.026	-	-	0.135	0.228
	Plasma Arc (Crude)	0.053	0.029	-	-	0.135	0.217
	Calcium Carbide	0.521	-	0.170	0.008	0.110	0.529
	MagneGas-2	0.011	0.014	-	0.004	0.055	0.08

2 Thermal Cracking Acetylene Sustainability Assessment

2.1 System Overview

Thermal cracking is performed by raising the temperature of hydrocarbons to the point that their atomic bonds break and can be reformed into more desirable products. For producing acetylene, various thermal cracking methods exist, and different fuels can be utilized. The form with the smallest yields by far is using petroleum fuels, in which acetylene is a small percentage of the products made from the process. The reaction using oils is shown below. As shown, there are numerous compounds made and thus, the process carbon footprint on an acetylene yield basis would be misrepresentative. However, there are still some commercial processes that use oil that will be analyzed further.

$$C_xH_y + H_2O + O_2 \longrightarrow C_2H_4 + C_2H_6 + C_2H_2 + H_2 + CO + CO_2 + CH_4 + C_3H_6 + C_3H_8 + C_4H_{10} + C_4H_8 + C_6H_6 + C + Heavy\ oils$$

Most of the acetylene produced by the thermal cracking process uses natural gas or methane rather than oils. The reaction is far more efficient in producing acetylene and there are various technologies with higher levels of yield than with oil. Among thermal cracking processes, there are only 2 commercially viable types: arc processes and partial oxidation of natural gas [1]. Figure 2-1 shows a simplified schematic of a BASF partial oxidation (POX) process.

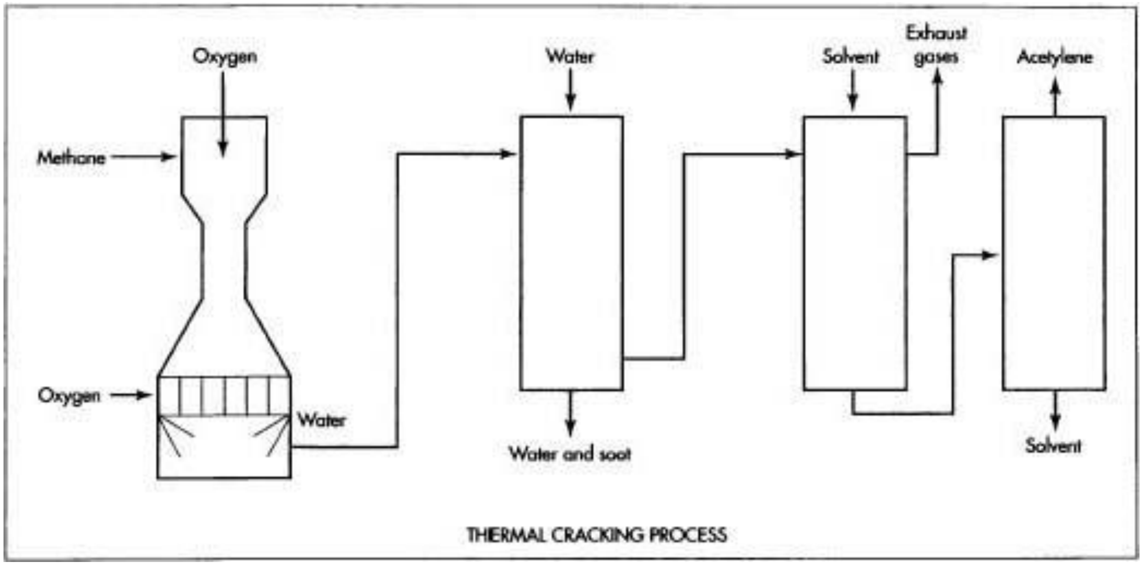

Figure 2-1. Schematic of Methane Thermal Cracking Process[1]

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[1] http://www.madehow.com/Volume-4/Acetylene.html

Methane pyrolysis can be performed with or without oxygen. Performed in the absence of oxygen, acetylene yield can be greater than 80%, while systems that use BASF POX method can only achieve approximately 33% yield with current technology [2]. The BASF facilities are the most common in the United States today for converting natural gas into acetylene.

The Hüls arc process produces acetylene and various other byproducts in an arc furnace using gaseous hydrocarbons as a feed. This process accepts both liquified natural gas as well as crude oil. A typical composition of the feed and cracked gas is shown in Table 2-1.

Table 2-1. Typical analysis of feed and cracked gas for Hüls Process [1]

	Feed gas, vol%	**Cracked gas, vol %**
C_2H_2	0.4	15.5
C_3H_4	1.4	0.4
C_4H_2	1.2	0.3
C_4H_4	1.7	0.4
C_2H_4	0.8	6.9
C_3H_6	3.6	1.0
Allene	0.4	0.2
C_4H_8	1.0	0.2
C_4H_6	0.9	0.2
C_5H_6	0.6	0.2
C_6H_6	0.5	0.5
CH_4	64.6	13.8
C_2H_6	7.5	0.4
C_3H_8	3.6	0.3
C_4H_{10}	4.6	1.0
C_5H_{12}	0.5	0.1
H_2	4.5	57.6
CO	0.5	0.6
O_2	0.1	0.0
N_2	1.6	0.4

The typical feed's specific energy consumption (SER) is 10.0 $\frac{kWh}{kg\ C_2H_2}$ (carbon number ≈ 1.5) [1]. For this report, the product, byproduct, and waste yields used will be from data using the feedstock in Table 2-1.

The plasma arc process utilizes liquid hydrocarbons rather than gaseous/gasified ones. In most cases it will use crude oil as its only feedstock along with electricity to drive the process. This design has not done as well in terms of economically producing acetylene and ethylene [1]. The two plasma arc processes that are analyzed in this report only differ in feedstock. One uses naphtha and the other crude oil. The fuels are injected into a hydrogen plasma arc within a reactor.

2.1 Feedstock & Consumables

The feedstock requirements for the four processes (BASF POX, Hüls, plasma arc using naphtha, and plasma arc using crude oil) are listed in Table 2-2.

Table 2-2. Feedstock consumption per unit of production [1,2]

	Feedstock consumption per unit production			
Feedstock	**BASF POX**	**Hüls Arc**	**Plasma Arc (Naphtha)**	**Plasma Arc (Crude)**
Natural Gas ($\frac{kg\ CH_4}{cu.ft.C_2H_2}$)	0.132	-	-	-
Hydrocarbon Mix ($\frac{kg\ C_xH_y}{cu.ft.C_2H_2}$)	-	0.083	-	-
Naphtha ($\frac{kg\ Naptha}{cu.ft.C_2H_2}$)	-	-	0.083	-
Crude Oil ($\frac{kg\ Crude\ Oil}{cu.ft.C_2H_2}$)	-	-	0.021	0.116
Oxygen ($\frac{kg\ O_2}{cu.ft.C_2H_2}$)	0.161	-	-	-
Sulfuric Acid ($\frac{kg\ H_2SO_4}{cu.ft.C_2H_2}$)	0.005	-	-	-
Sodium Hydroxide ($\frac{kg\ NaOH}{cu.ft.C_2H_2}$)	0.0002	-	-	-
N-methylpyrrolidone (NMP)($\frac{kg\ NMP}{cu.ft.C_2H_2}$)	0.0002	-	-	-

2.1.1 Natural Gas/Methane (BASF POX only)

There is an abundance of literature surrounding the environmental impact of natural gas, regarding both obtaining it as well as burning it. Typical natural gas compositions in the United States contain approximately 95% methane and 2.5-4.2% ethane [4-6]. The methane and ethane content vary by region. Different countries will also have varying compositions. However, it is preferable to have a large methane content in natural gas for making acetylene. As feedstock, we are only concerned with the cradle-to-gate footprint, which includes the extraction, refining, and any other processes the gas undergoes by the time it reaches the acetylene plant. Data collected on 34 Chinese domestic conventional gas fields found an average cradle-to-gate greenhouse gas (GHG) intensity of $15.5\ \frac{g\ CO_2}{MJ}$ [7]. Compressed natural gas (CNG) has an energy density of approximately $53.6\frac{MJ}{kg}$ which will be used to calculate the carbon footprint contributions of the feedstock for the BASF POX process. Before this, we consider the natural gas leakage that is not considered in the above-mentioned values. It is estimated that 1.5% of all extracted natural gas is lost to the atmosphere [8]. The Environmental Protection Agency (EPA) considers methane to have a global warming potential of $25\frac{kg\ CO_2eq}{kg\ CH_4}$ [9]. This can be applied to the values given in Table 2-2. For example, the carbon footprint of the natural gas demand for the POX process is calculated as:

$$CF_{LNG-POX} = 0.0155\frac{kg\ CO_2eq}{MJ\ CH_4} \times 53.6\frac{MJ}{kg\ CH_4} \times 0.132\frac{kg\ CH_4}{cu.ft.C_2H_2} + 0.015 \times 0.132\frac{kg\ CH_4}{cu.ft.C_2H_2} \times 25\frac{kg\ CO_2eq}{kg\ CH_4} = \ 0.159\frac{kg\ CO_2}{cu.ft.C_2H_2}$$

2.1.1 Naphtha (Plasma arc only)

Naphtha, like LPG, is a refined fuel and can stem from both natural gas and crude oil. The atmospheric distillation process required to obtain crude naphtha is energy intensive. Crude naphtha has a much lower carbon intensity than natural gas derived naphtha. Crude naphtha has an upstream carbon intensity of approximately $14.2\frac{g\ CO_2}{MJ}$ with an energy density of $48.1\frac{MJ}{kg}$ [10]. The plasma arc process carbon footprint contribution due to its naphtha feedstock can be calculated:

$$CF_{Naphtha-plasma(naphtha)} =$$

$$0.083\,\frac{kg\ Naptha}{cu.ft.C_2H_2}\times 0.0142\,\frac{kg\ CO_2}{MJ}\times 48.1\,\frac{MJ}{kg\ Naptha}=0.057\ \frac{kg\ CO_2}{cu.ft.C_2H_2}$$

2.1.1 Crude Oil

The carbon intensity for crude oil is well documented. The intensity is estimated to be $10.3\,\frac{gCO_2eq}{MJ}$ for crude oil just before it enters a refinery [11]. Crude oil has an energy density of approximately $44\,\frac{MJ}{kg}$, leading to a carbon footprint per unit of weight of $0.453\,\frac{kg\ CO_2}{kg\ Oil}$. The carbon footprint of crude oil for the both plasma arc processes can be calculated. First for the Naphtha-derived plasma arc process:

$$CF_{crude-\mathrm{plasma(naphtha)}}=0.453\,\frac{kg\ CO_2}{kg\ Oil}\times 0.021\,\frac{kg\ Oil}{cu.ft.C_2H_2}=0.010\ \frac{kg\ CO_2}{cu.ft.C_2H_2}$$

The same is done for the crude oil derived plasma arc process:

$$CF_{crude-\mathrm{plasma(crude)}}=0.453\,\frac{kg\ CO_2}{kg\ Oil}\times 0.116\,\frac{kg\ Oil}{cu.ft.C_2H_2}=0.053\ \frac{kg\ CO_2}{cu.ft.C_2H_2}$$

2.1.1 Hydrocarbon Mix (Hüls Only)

An estimate for the mixture composition is made based on the feedstock percentages in Table 2-1. Many of these fuels have similar well-to-gate carbon footprints, so the margin for error on the estimate should not be significant. From Table 2-1, most of the fuel is methane and ethane (~80%, approximated as natural gas), while a large percentage of the rest is made of butane and propane. We will assume LPG is representative for calculations of propane and butane and it makes up the additional 20% of the fuel. Petroleum-derived LPG is measured to contribute $13.3\,\frac{gCO_2}{MJ}$ and have an energy density of $46.6\,\frac{MJ}{kg\ LPG}$ [12]. Thus, the weight basis carbon intensity is $0.620\,\frac{kgCO_2}{kg\ LPG}$. Previously, the contribution of CNG was calculated as $0.831\,\frac{kg\ CO_2}{kg\ CNG}$. The estimated intensity of the hydrocarbon mix is:

$$0.8\,\frac{kg\ CNG}{kg\ Mix}\times 0.831\,\frac{kg\ CO_2}{kg\ CNG}+0.2\,\frac{kg\ LPG}{kg\ Mix}\times 0.620\,\frac{kg\ CO_2}{kg\ LPG}=0.789\,\frac{kg\ CO_2}{kg\ Mix}$$

The carbon footprint due to the fuel feedstock for the Hüls arc process can be calculated as:

$$CF_{Mix-\mathrm{Hüls}}=0.789\,\frac{kg\ CO_2}{kg\ C_xH_y}\times 0.083\,\frac{kg\ C_xH_y}{cu.ft.C_2H_2}=0.065\ \frac{kg\ CO_2}{cu.ft.C_2H_2}$$

2.1.2 Oxygen (BASF POX only)

Pure oxygen is needed for the POX process. Oxygen separation from air is done in several ways but primarily using either cryogenics or pressure swing adsorption. Both methods have an expected energy consumption of 150 $\frac{kWh}{ton\ O_2}$ [13]. Using the electricity carbon footprint from section 2.4 and the value from Table 2-2, the contribution to the feedstock carbon footprint for the POX process is:

$$150\frac{kWh}{ton\ O_2} \times \frac{1\ ton\ O_2}{1000\ kg\ O_2} \times 0.39\frac{kgCO_2}{kWh} \times 0.161\frac{kg\ O_2}{cu.ft.C_2H_2} = 0.009\ \frac{kg\ CO_2}{cu.ft.C_2H_2}.$$

2.1.1 Sulphuric Acid (BASF POX only)

The production of sulphuric acid generates air pollutants such as sulphur oxides (SO_x) as well as CO_2. These are emitted from the exit stacks of the manufacturing plants and can have a large impact on the environment. A publication by the Environmental Protection Agency (EPA) lists the sulphur dioxide emissions based on the conversion efficiency of sulphur dioxide to sulphur trioxide [14].

Table 2-3. SO_2 emissions based on SO_3 conversion efficiency

SO_2 To SO_3 Conversion Efficiency (%)	SO_2 Emissions ($kg.SO_2/Mg.H_2SO_4$)
93	48.0
94	41.0
95	35.0
96	27.5
97	20.0
98	13.0
99	3.5
99.5	2.0
99.7	2.0
100	0.0

CO_2 emissions are reported from the same source to be $4.05\ \frac{kg.CO_2}{Mg.H_2SO_4}$. The BASF POX process carbon footprint contribution due to sulphuric acid can be calculated as:

$$CF_{H_2SO_4} = 0.005\ \frac{kg\ H_2SO_4}{cu.ft.C_2H_2} \times 4.05\ \frac{kg.CO_2}{Mg.H_2SO_4} \approx 0$$

The carbon intensity from the use of sulphuric acid is negligible.

2.1.1 Sodium Hydroxide (BASF POX only)

Sodium hydroxide is a chemical used in small amounts in the BASF POX process. The GHG emissions have been estimated as $0.625 \frac{kg\ CO_2}{kg\ NaOH}$ [15]. The carbon footprint contribution due to sodium hydroxide can be calculated as:

$$CF_{NaOH} = 0.0002\ \frac{kg\ NaOH}{cu.ft.C_2H_2} \times 0.625 \frac{kg\ CO_2}{kg\ NaOH} = 0.0001 \frac{kg\ CO_2}{cu.ft.C_2H_2}$$

The contribution to the carbon footprint, like sulphuric acid, is quite negligible.

2.1.2 N-methylpyrrolidone (BASF POX only)

NMP is made primarily in the United States and it is a solvent used to produce acetylene. There are alternative solvents that can perform the same task, however, NMP is very common. For the arc processes, a different separation method may be used due to the higher concentration of acetylene in the products. There is very little literature surrounding NMP's impact, however, a report by the EPA states that for every 1,000 pounds of NMP, approximately $46.38\ MMBtu$ is consumed for raw materials, process energy, and transportation [16]. This leads to a calculated $29.9 \frac{kWh}{kg\ NMP}$. In a later section (section 2.4) it is found that the electricity carbon footprint is $0.39\ \frac{kg.CO_2}{kWh}$. Conservatively estimating the carbon footprint of NMP with the electricity carbon footprint, the consumption of NMP leads to $11.66 \frac{kg\ CO_2}{kg\ NMP}$ (transportation energy is lumped in due to being a small percentage of the energy). The consumption rate of NMP is used only in the BASF POX process at a rate of $0.0002 \frac{kg\ NMP}{cu.ft.C_2H_2}$, leading to a carbon footprint contribution of:

$$CF_{NMP} = 0.0002 \frac{kg\ NMP}{cu.ft.C_2H_2} \times 11.66 \frac{kg\ CO_2}{kg\ NMP} = 0.002\ \frac{kg\ CO_2}{cu.ft.C_2H_2}$$

2.1.1 Feedstock Carbon Footprints

The individual contributions from different feedstock are summed to calculate the total contribution to the carbon footprint from feedstocks. An example calculation using the feedstocks of the BASF POX process is:

$$CF_{feedstock-BASF} = CF_{LNG} + CF_{Oxygen} + CF_{H_2SO_4} + CF_{NaOH} + CF_{NMP}$$

$$CF_{feedstock-BASF} =$$

$$0.159\frac{kg\ CO_2}{cu.ft.C_2H_2} + 0.009\ \frac{kg\ CO_2}{cu.ft.C_2H_2} + 0 + 0 + 0.002\ \frac{kg\ CO_2}{cu.ft.C_2H_2} = \ 0.170\frac{kg\ CO_2}{cu.ft.C_2H_2}$$

Table 2-4 shows the results for all processes.

Table 2-4. Feedstock Carbon Footprints

	Feedstock Carbon Footprints			
	BASF POX	**Hüls Arc**	**Plasma Arc (Naphtha)**	**Plasma Arc (Crude)**
Carbon Footprint $\frac{kg\ CO_2}{cu.ft.C_2H_2}$	0.170	0.065	0.067	0.053

2.2 Byproducts/Waste

2.2.1 Byproducts

Byproducts of thermal cracking processes are more prevalent with feedstocks of higher hydrocarbons. Byproducts, in this report, do not contribute to the carbon footprint on a cradle-to-grave basis as waste streams do. Rather, only the cradle-to-gate contribution is considered. These are already taken into consideration when calculating the footprints for acetylene production as there are not any significant additional processes that handle these byproducts in a separate manner. Table 2-5 is a list of the byproducts produced by all four processes. All the values were taken or calculated from values in [1] and [2].

Table 2-5. Byproducts per unit of production [1][2]

	Byproduct production per unit acetylene production			
Byproducts	**BASF POX**	**Hüls Arc**	**Plasma Arc (Naphtha)**	**Plasma Arc (Crude)**
Crude Synthesis Gas $\frac{kg\ Synth.Gas}{cu.ft.C_2H_2}$	0.132	-	-	-
Ethylene $\frac{kg\ C_2H_4}{cu.ft.C_2H_2}$	-	0.083	-	-
Hydrogen $\frac{kg\ H_2}{cu.ft.C_2H_2}$	-	0.110	0.083	0.083
Aromatics $\frac{kg\ Aromatics}{cu.ft.C_2H_2}$	-	0.08	0.021	0.116
Fuel gas $\frac{kg\ Fuel\ gas}{cu.ft.C_2H_2}$	0.161	-	-	-

2.2.2 Carbon Dioxide

Carbon dioxide in the BASF POX process is shifted into the crude synthesis gas and becomes part of the byproduct. This is common in all processes where some of the off gases will be used as a fuel within the plant or sold as a part of a synthesis gas. It will vary by operation, however, there is no significant carbon dioxide released.

2.2.3 Carbon Soot

Carbon soot and carbon black are waste products of all the thermal cracking processes, some producing more than others. Both are assumed to be burned and convert into CO_2. Table 2-6 shows the soot and carbon black produced from each process.

Table 2-6. Soot waste produced [1][2]

	Soot production per unit acetylene production			
	BASF POX	**Hüls Arc**	**Plasma Arc (Naphtha)**	**Plasma Arc (Crude)**
Carbon Black/Soot $\frac{kg\ C}{cu.ft.C_2H_2}$	0.002	0.015	0.007	0.008

The balanced combustion equation for carbon with oxygen is:

$$C(s) + O_2(g) \longrightarrow CO_2(g)$$

For every mole of carbon, one mole of CO_2 is produced. The molar mass of carbon is $12.01\frac{g}{mol}$. The amount of CO_2 produced on a weight basis can be calculated:

$$\frac{1\ mol\ CO_2 \times 44.01\frac{g}{mol\ CO_2}}{1\ mol\ C \times 12.01\frac{g}{mol\ C}} = 3.66\frac{kg\ CO_2}{kg\ C}$$

Using this as well as the amount of waste produced and gas production, the expected waste footprint can be calculated. An example calculation is performed for the BASF POX process:

$$CF_{waste\_C} = 3.66\frac{kg\ CO_2}{kg\ C} \times 0.002\frac{kg\ C}{cu.ft.C_2H_2} = 0.007\frac{kg\ CO_2}{cu.ft.MG}$$

The waste carbon is the only waste that is contributing toward the carbon footprint. Table 2-7 shows the results of the carbon footprints from waste for all processes.

Table 2-7. Waste Carbon Footprints

	Waste Carbon Footprints			
	BASF POX	**Hüls Arc**	**Plasma Arc (Naphtha)**	**Plasma Arc (Crude)**
Carbon Footprint $\frac{kg\ C}{cu.ft.C_2H_2}$	0.007	0.055	0.026	0.029

2.3 Water Consumption

Water is utilized in all these processes for quenching the gas after the reactor. The water will also collect the soot at this stage and carry it away from the rest of the process. This quenching water can be almost completely recycled in each process as it is only used for cooling. There is steam involved in the process as well, which will have water lost to the atmosphere. There is very little literature on water consumption of cracking plants. One report stated the difference of water consumption between a refinery with and without a cracking plant, being $24 \frac{gal\ H_2O}{barrel\ of\ crude}$ [20]. A barrel of crude oil is about $140\ kg$ of crude oil. The plants discussed in the report were all likely BASF POX plants, however, not using natural gas. With only the data available in literature, it is not feasible to assess the water consumption of these processes on an acetylene yield basis.

2.4 Electrical Consumption

The U.S. Energy Information Administration stated in a 2020 report that the average mix of electricity is currently at 38% natural gas, 23% coal, 20% nuclear, 17% renewable, and 1% petroleum [21]. This mix of electricity generation will be assumed for calculating the carbon footprint associated with the electricity consumption of an acetylene plant. Coal produces approximately 1 metric ton of CO_2 per MWh, while natural gas produces 0.42 metric tons of CO_2 per MWh [22]. Everything else is assumed to produce zero carbon footprint and petroleum is neglected. A weighted average is used to estimate the amount of CO_2 per kWh. This will be called the electricity carbon footprint, *ECF*, and is defined as:

$$ECF = 0.23 \times 1 \frac{kg.CO_2}{kWh} + 0.38 \times 0.42 \frac{kg.CO_2}{kWh} = 0.39 \frac{kg.CO_2}{kWh}$$

Data is available on the electricity consumption per ton of acetylene produced. This is listed in Table 2-8 in the form that will be used for further calculations.

Table 2-8. Electricity Consumption [1][2]

	Consumption per unit acetylene production			
	BASF POX	**Hüls Arc**	**Plasma Arc (Naphtha)**	**Plasma Arc (Crude)**
Electricity Consumption $\frac{kWh}{kg\ C_2H_2}$	3.1	10.0	10.5	10.5

The POX process uses minimal electricity in its process. However, both the Hüls and DuPont processes use a large amount of electricity. The specific energy requirements were stated previously. An example of solving the electricity carbon footprint for the Hüls process is:

$$CF_{electricity-\text{Hüls}} = 0.39\ \frac{kg.CO_2}{kWh} \times 10.0\frac{kWh}{kg\ C_2H_2} \times 0.033\frac{kg\ C_2H_2}{cu.ft.C_2H_2} = 0.129\ \frac{kg.CO_2}{cu.ft.C_2H_2}$$

The results for all processes are listed in Table 2-9.

Table 2-9. Electricity Carbon Footprint

	Electricity Carbon Footprint			
	BASF POX	**Hüls Arc**	**Plasma Arc (Naphtha)**	**Plasma Arc (Crude)**
Electric Carbon Footprint $\frac{kg.CO_2}{cu.ft.C_2H_2}$	0.040	0.129	0.135	0.135

2.5 Physical Footprint

There is insufficient data on the facility requirements for these processes. Thermal cracking plants are, in most cases, very large in comparison to their acetylene output, when comparing to other methods. This is due to the many other processes going on to produce the many other products at these types of plants. It is not a fair comparison to compare the plants physical footprint for producing acetylene to other methods.

2.6 Carbon Footprint

The carbon footprint, *CF*, is a globally used metric for the environmental impact of products, processes, etc. To compare the impact of the fuels in this report the carbon footprint will be used in a standardized form across the report. The assessment of this chemical process of producing acetylene has generated a total carbon footprint of:

$$CF_{Total} = CF_{feedstock} + CF_{waste} + CF_{electricity}$$

Plugging in the values found in the previous sections, an example calculation is shown for the BASF POX process:

$$CF_{Total-BASF} = (0.170 + 0.007 + 0.040)\frac{kg\ CO_2}{cu.ft.C_2H_2} = 0.217$$

This is not including certain elements of the production that could also contribute, but are not quantifiable due to lack of data, including sulphuric acid, solid media, and all chemical waste streams.

2.7 Summary

The footprints of each section have been summarized into Table 2-10. This table will be used to compare values with the other types of facilities in this report.

Table 2-10. Summary of Thermal Cracking Acetylene Plant Footprints

	Feedstock $\frac{kg.CO2}{cu.ft.C_2H_2}$	**Waste** $\frac{kg.CO2}{cu.ft.C_2H_2}$	**Water** $\frac{gal.H_2O}{cu.ft.C_2H_2}$	**Physical** $\frac{gal.H_2O}{cu.ft.C_2H_2}$	**Electricity** $\frac{kg.CO_2}{cu.ft.C_2H_2}$	**Carbon** $\frac{kg.CO_2}{cu.ft.C_2H_2}$
POX	0.170	0.007	-	-	0.040	0.217
Hüls	0.065	0.055	-	-	0.129	0.249
Plasma Arc (Naphtha)	0.067	0.026	-	-	0.135	0.228
Plasma Arc (Crude)	0.053	0.029	-	-	0.135	0.217

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3 Calcium Carbide Acetylene Sustainability Assessment

3.1 Feedstock & Consumables

The process feedstock is defined as the raw material that is used to manufacture another product. When analyzing the environmental impact of the feedstock, the impact of the material prior to being used in the current process should be considered. Acetylene forms in the generator from the chemical reaction between water and calcium carbide. Calcium carbide is fed into the generator typically via a screw conveyor where it meets the water. The process is an exothermic reaction described by:

$$CaC_2(s) + 2H_2O(l) \rightarrow C_2H_2(g) + Ca(OH)_2(aq) + 27000\ cal.$$

The products of the chemical reaction are the intended acetylene, hydrated lime, and heat. Recirculated water is used to remove the heat and prevent dangerous conditions. Excess water can be separated from the hydrated lime and be reused in the process. To operate a production facility of this manner, there are additional feedstocks/inputs required including acetone and electricity. Based on an existing plant, the following values were calculated as the necessary feedstock for producing acetylene using calcium carbide and water. The primary feedstock materials are compiled in Table 3-1 [1]. The values are given in both pounds and kilograms which will be used for later calculations.

Table 3-1. Feedstock consumption per unit of production

Feedstock	**Consumption per unit of production**
Calcium Carbide	$0.21\ \frac{kg}{cu.ft.C_2H_2}$
Acetone	$0.0025\ \frac{kg}{cu.ft.C_2H_2}$
Water	$0.17\ \frac{gal}{cu.ft.C_2H_2}$

Other chemicals are used or produced throughout the components of a plant. Sulphuric acid, sodium hydroxide and sodium carbonate are used as purification agents that the acetylene gas passes through. These, along with other chemicals and reagents, are ancillary to the feedstock of the process and are covered in the waste section of the analysis. Although water is also a feedstock in this process, this will be covered in section 1.4.

3.1.1 Calcium Carbide

A demand for calcium carbide creates the need for manufacturing it. The manufacturing of commercial calcium carbide produces significant emissions. An article in the *International Journal of Greenhouse Gas Control* states that the production of calcium carbide creates $5.2\ \frac{kg\ CO2}{kg\ Carbide}$ [2]. As this material has the highest consumption of calcium carbide in these facilities, it will be a large contributor to the overall carbon footprint of the process. Using the calcium carbide consumption value from Table 3-1, the carbon footprint contribution is $0.52\ \frac{kg\ CO2}{cu.ft.C_2H_2}$.

3.1.2 Acetone

Acetone is used during the cylinder filling and is dissolved under pressure. Acetylene cylinders are unique as acetylene is not stored as a compressed or liquefied product but is dissolved in acetone. The acetone is adsorbed onto a porous mass that inhibits the decomposition reaction. Acetone is primarily emitted to the air when it evaporates with use. It will degrade in air and most other environments quickly and does not bioaccumulate in animals, soil, plants, or humans [3]. A study on the carbon footprints of recycled solvents found that the carbon footprint of acetone for recycled and virgin acetone is $421\ \frac{kg\ CO_2eq}{tonne}$ and $2{,}040\ \frac{kg\ CO_2eq}{tonne}$, respectively [4]. For this analysis it is assumed that a 1:1 ratio of recycled and virgin acetone is used with a carbon footprint equal to the average of the mix ($1.23\ \frac{kg\ CO_2}{kg\ Acetone}$). This results in a contribution to this process' carbon footprint of $0.0014\ \frac{kg\ CO2}{cu.ft.C_2H_2}$.

3.1.3 Sulphuric Acid

The production of sulphuric acid generates air pollutants such as sulphur oxides (SO_x) as well as CO_2. These are emitted from the exit stacks of the manufacturing plants and can have a large impact on the environment. A publication by the Environmental Protection Agency (EPA) lists the sulphur dioxide emissions based on the conversion efficiency of sulphur dioxide to sulphur trioxide [5].

Table 3-2. SO_2 emissions based on SO_3 conversion efficiency

SO_2 To SO_3 Conversion Efficiency (%)	**SO_2 Emissions ($kg.SO_2/Mg.H_2SO_4$)**
93	48.0
94	41.0
95	35.0
96	27.5
97	20.0
98	13.0
99	3.5
99.5	2.0
99.7	2.0
100	0.0

CO_2 emissions are reported from the same source to be $4.05\ \frac{kg.CO_2}{Mg.H_2SO_4}$. The quantity of sulphuric acid used in producing acetylene using calcium carbide and water is not generally reported and thus, difficult to quantify. Based off the consumption of sulphuric acid in the other processes, it is expected to be a negligible contribution to the carbon footprint.

3.1.4 Solid Media

Adsorbents and other solid purification media are typically used in this process as well as periodic feedstock. Many of these use ferric chloride and ferric oxide as active agents. These also contain mercuric chloride or cupric chloride catalysts in most cases. The production of these materials also have carbon footprints associated with them. However, they are smaller than most other components. Some of the carbon footprints for these materials are available through literature. Ferric chloride (42% *wt./wt.*) is reported to have a CO_2-eq between 214 and 629 kg [6].

The quantity of ferric chloride used in the process is unknown and it should be noted that this makes the final carbon footprint an underestimation.

3.2 Waste

Waste products are generated in the process like lime and batches of chemicals for the purpose of scrubbing and purification. In many cases in this industry, the lime can be considered a by-product as it is often sold to other industries. Below is a list of the potential waste streams in the process.

- Lime
- Sulphuric Acid
- Chromic Acid
- Sodium hydroxide (NaOH)
- Sodium carbonate (Na_2CO_3)
- Ferric chloride ($FeCl_3$)
- Ferric oxide (Fe_2O_3)
- Mercuric chloride ($HgCl_2$)
- Cupric chloride ($CuCl_2$)
- Calcium carbide dust
- Calcium Chloride ($CaCl_2$)
- Generator water
- Oil

Some of these chemicals are placed in the lime pits after use. Sulphuric acid is neutralized there but cannot exceed certain limits. Lime exceeding 2% in SO_4 is not used by the wastewater treatment and construction industry and the lime would no longer be labelled as a by-product [7]. Sodium hydroxide, sodium carbonate, and calcium chloride are diluted in the lime pits. As these waste streams are a part of the lime by-product, it is not considered to contribute to the carbon footprint of the acetylene. Other spent chemicals that are disposed of via special treatment may be considered to contribute to the footprint. Data on the quantities for these waste streams are unavailable and it should be noted that the final carbon footprint for this process is expected to be an underestimation.

3.3 Water Consumption

Water is in persistent use in this process. According to the previously mentioned example plant, $0.17 \frac{gal\ H_2O}{cu.ft.C_2H_2}$ consumed for producing acetylene. Some water is recycled back to the generators after being removed from the hydrated lime. The hydrated lime sits in lime pits and some excess water evaporates.

3.4 Electrical Consumption

The U.S. Energy Information Administration stated in a 2020 report that the average mix of electricity is currently at 38% natural gas, 23% coal, 20% nuclear, 17% renewable, and 1% petroleum [11]. This mix of electricity generation will be assumed for calculating the carbon footprint associated with the electricity consumption of an acetylene plant. Coal produces approximately 1 metric ton of CO_2 per MWh, while natural gas produces 0.42 metric tons of CO_2 per MWh [12]. Everything else is assumed to produce zero carbon footprint and petroleum is neglected. A weighted average is used to estimate the amount of CO_2 per kWh. This will be called the electricity carbon footprint, *ECF*, and is defined as:

$$ECF \ = 0.23 \times 1 \frac{kg.CO_2}{kWh} + 0.38 \times 0.42 \frac{kg.CO_2}{kWh} = 0.39 \ \frac{kg.CO_2}{kWh}$$

From the example plant used previously, the required electricity was approximately $0.02 \frac{kWh}{cu.ft.C_2H_2}$. This would lead to the electrical consumption contributing:

$$CF_{electricity} = 0.39 \ \frac{kg.CO_2}{kWh} \times 0.02 \frac{kWh}{cu.ft.C_2H_2} = 0.0078 \ \frac{kg.CO_2}{cu.ft.C_2H_2}$$

3.5 Physical Footprint

Using the same facility description used for calculating the other values, a lot size of 23,739 ft^2 was needed for a plant that can produce $2.12 \ \frac{\text{million } cu.ft.}{yr}$ of acetylene. This equates to $0.011 \ \frac{sq.ft.}{cu.ft.C_2H_2}$ required. This number will be used to compare to the other facilities.

3.6 Carbon Footprint

The carbon footprint, *CF*, is a globally used metric for the environmental impact of products, processes, etc. To compare the impact of the fuels in this report the carbon footprint will be used in a standardized form across the report. The assessment of this chemical process of producing acetylene has generated a total carbon footprint of:

$$CF_{Total} = CF_{feedstock} + CF_{waste} + CF_{electricity} + CF_{end-use}$$

Plugging in the values found in the previous section:

$$CF_{Total} = \left(0.52 \frac{kg.CO2}{cu.ft.C_2H_2} + 0.0014 \frac{kg.CO2}{cu.ft.C_2H_2}\right) + 0 + 0.0078 \frac{kg.CO2}{cu.ft.C_2H_2} + 0.112 \frac{kg.CO2}{cu.ft.C_2H_2} = 0.6412 \frac{kg.CO2}{cu.ft.C_2H_2}$$

This is not including certain elements of the production that could also contribute, but are not quantifiable due to lack of data, including sulphuric acid, solid media, and all chemical waste streams.

3.7 Summary

The footprints of each section have been summarized into Table 3-3. This table will be used to compare values with the other types of facilities in this report.

Table 3-3. Summary of Calcium Carbide Acetylene Plant Footprints

Feedstock $\frac{kg.CO2}{cu.ft.C_2H_2}$	**Waste** $\frac{kg.CO2}{cu.ft.C_2H_2}$	**Water** $\frac{gal.H_2O}{cu.ft.C_2H_2}$	**Electricity** $\frac{kg.CO_2}{cu.ft.C_2H_2}$	**Physical** $\frac{sq.ft.}{cu.ft.C_2H_2}$	**Carbon** $\frac{kg.CO_2}{cu.ft.C_2H_2}$
0.521	-	0.17	0.008	0.11	0.529
98.5%			1.5%		100%

3.8 References

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4 Magnegas-2 Sustainability Assessment

4.1 System Overview

MagneGas-2 is a syngas made by Taronis Fuels using a patented plasma arc reactor. A diagram of the complete system is shown in Figure 4-1.

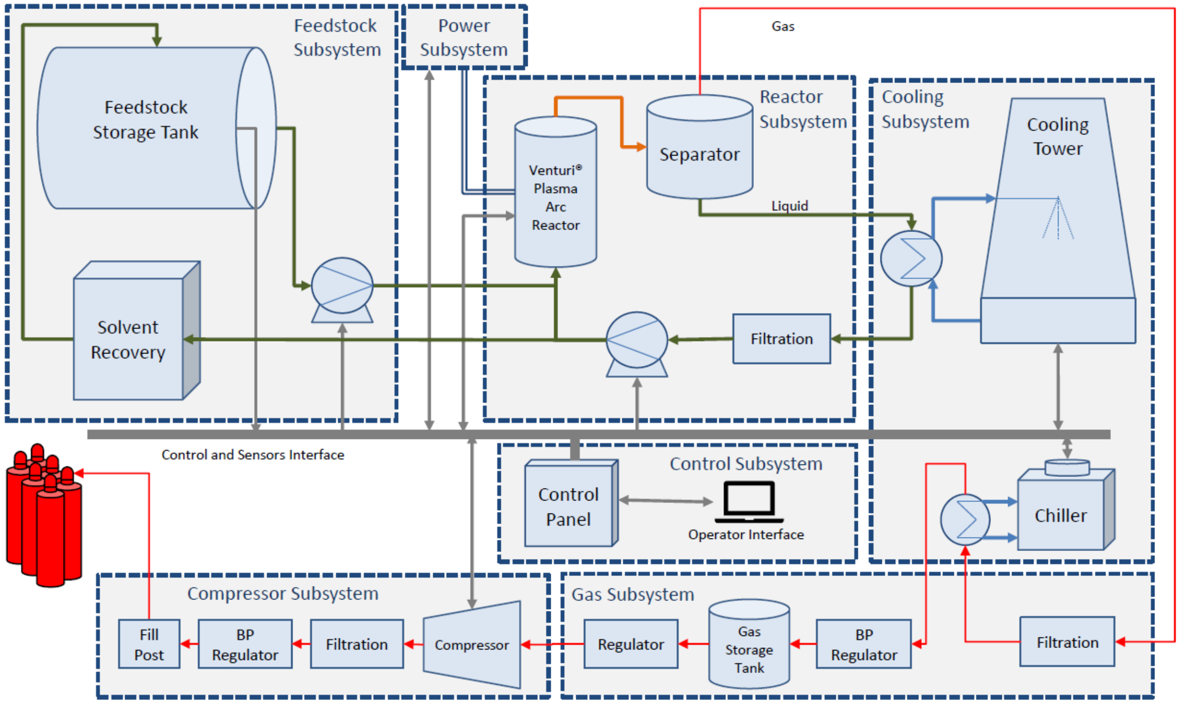

Figure 4-1. Diagram of Taronis Fuel's MagneGas-2 manufacturing process

The system is comprised of seven subsystems:

- Power
- Feedstock
- Reactor
- Cooling
- Control
- Gas
- Compressor

The arc reactor consists of two electrodes surrounded by granite. A plasma arc is generated between the electrodes creating a high temperature environment, radiation, and an electric field. The liquid feedstock passes through this plasma arc region and is broken down into primary elements, ions, and simple hydrocarbon chains. The resulting composition constituents MagneGas-2. The gas that is produced is separated from any liquid and filtered, cooled, and compressed. The liquids are also cooled and filtered but sent to the solvent recovery system to extract usable feedstock. In this report each component in the system was analyzed for its environmental footprint.

4.1 Feedstock & Consumables

The feedstock into the arc reactor is a high purity ethanol. Any ethanol that makes it past the reactor is cooled then sent to the solvent recovery system after carbon is filtered out of it. The feedstock typically consists of a 2:1 ratio of new ethanol to recycled ethanol coming from solvent recovery.

The gas generated in the reactor is also filtered then cooled by a chiller. Both the chiller as well as the heat exchanger for the recycled ethanol utilize a single cooling tower that is the only source of water consumption in this production system.

The incoming feedstocks and consumables for this system are listed in Table 4-1. The feedstock does not consider the recycled ethanol as it never leaves the system.

Table 4-1. Feedstock consumption per unit of production

Feedstock	Consumption per unit of production
Ethanol	$0.0086 \frac{gal. C_2H_5OH}{cu. ft. MG}$
Anodes/Cathodes (*graphite rod)*	$0.002 \frac{kg\ Graphite}{cu. ft. MG}$

The implications of ethanol as a feedstock is discussed in section 4.1.1.

4.1.1 Ethanol

It is important to note that even the new ethanol feedstock is a byproduct of another industry that requires 99.9% ethanol for its processes. One example of an industry that disposes of very pure ethanol is the pharmaceutical industry. Waste ethanol of the necessary purity has high availability. The reactor in this process can use slightly lower purities and thus does not contribute to increasing the demand for ethanol production. For this reason, the ethanol feedstock is not considered to pose any negative environmental impacts.

4.1.2 Graphite Rods

Graphite rods are used to produce the arc needed for the reaction. The global impact of making these rods is well studied mainly due to the analysis of lithium batteries. One article in the Materials Science Forum shows an equivalent emission of $5.316 \frac{kg\ CO_2 eq}{kg\ graphite}$ [1]. As stated in Table 4-1, the production of MagneGas-2 requires $0.002\ \frac{kg\ graphite}{cu.ft.MG}$. The feedstock carbon footprint contribution is strictly from the use of these rods. The feedstock carbon footprint can be calculated as:

$$CF_{feedstock} = 5.316 \frac{kg\ CO_2 eq}{kg\ graphite} \times 0.002\ \frac{kg\ graphite}{cu.ft.MG} = 0.011\ \frac{kg\ CO_2}{cu.ft.MG}.$$

4.2 Waste

Waste is generated primarily from the recovery process. The waste streams are comprised of two categories: spent solvent and carbon. Occasionally, recovered ethanol may be removed from the system as waste if it becomes too diluted with water or other contaminants. This is referred to as spent solvent. The carbon waste comes from the anode and cathodes used for the arc after they can no longer be used. The possibility of recycling the spent anodes and cathodes will be discussed in the recommendations section of the report. The amount of waste generated from a 200-kW system is accounted for in this analysis. Table 4-2 summarizes the waste streams based on available data.

Table 4-2. Summary of Waste Streams

Data Collection Dates	Gas Production (cu.ft.MG)	Waste (kg)
Jan 2020 – Aug 2020	209,399	$220\ gal\ (657\ kg)\ C_2H_5OH$
Sept 2019 – Aug 2020	296,228	$632\ kg\ C$

Both the solid and liquid waste streams are labelled as hazardous waste and are handled by combustion. The impact of these waste streams can be calculated based on their combustion emissions.

The balanced combustion equation for ethanol (spent solvent) is:

$$C_2H_5OH(l) + 3O_2(g) \longrightarrow 2CO_2(g) + 3H_2O(g)$$

Per mole of ethanol, two moles of CO_2 are produced. The molar masses of ethanol and CO_2 are $46.07\,\frac{g}{mol}$ and $44.01\,\frac{g}{mol}$, respectively. The amount of CO_2 produced on a weight basis can be calculated:

$$\frac{2\;mol\;CO_2 \times 44.01\,\frac{g}{mol\;CO_2}}{1\;mol\;C_2H_5OH \times 46.07\,\frac{g}{mol\;C_2H_5OH}} = 1.91\,\frac{kg\;CO_2}{kg\;C_2H_5OH}$$

Using this as well as the amount of waste produced and gas production, the expected waste footprint can be calculated:

$$CF_{waste\_eth} = \;1.91\,\frac{kg\;CO_2}{kg\;C_2H_5OH} \times \frac{657\;kg\;C_2H_5OH}{209{,}399\;cu.ft.MG} = 0.006\,\frac{kg\;CO_2}{cu.ft.MG}$$

Similarly, we can calculate the emissions from the waste carbon:

$$C(s) + O_2(g) \longrightarrow CO_2(g)$$

For every mole of carbon, one mole of CO_2 is produced. The molar mass of carbon is $12.01\,\frac{g}{mol}$. The amount of CO_2 produced on a weight basis can be calculated:

$$\frac{1\;mol\;CO_2 \times 44.01\,\frac{g}{mol\;CO_2}}{1\;mol\;C \times 12.01\,\frac{g}{mol\;C}} = 3.66\,\frac{kg\;CO_2}{kg\;C}$$

Using this as well as the amount of waste produced and gas production, the expected waste footprint can be calculated:

$$CF_{waste\_C} = \;3.66\,\frac{kg\;CO_2}{kg\;C} \times \frac{632\;kg\;C}{296{,}228\;cu.ft.MG} = 0.008\,\frac{kg\;CO_2}{cu.ft.MG}$$

The total contribution from waste streams is:

$$CF_{waste} = \;CF_{waste\_eth} + CF_{waste\_C} = 0.014\,\frac{kg\;CO_2}{cu.ft.MG}$$

4.3 Water Consumption

Water consumption at the facility was found to only be attributed to facility restrooms and other personnel use. Therefore, there is no water footprint for this process.

4.4 Electrical Consumption

Electricity will be consumed in all subsystems with the majority consumed in the reactor, chiller, and compressor subsystems. The U.S. Energy Information Administration stated in a 2020 report that the average mix of electricity is currently at 38% natural gas, 23% coal, 20% nuclear, 17% renewable, and 1% petroleum [2]. This mix of electricity generation will be assumed for calculating the carbon footprint associated with the electricity consumption of Taronis Fuels acetylene plant. Coal produces approximately 1 metric ton of CO_2 per MWh, while natural gas produces 0.42 metric tons of CO_2 per MWh [3]. Every other energy source is assumed to produce zero carbon footprint and petroleum is neglected. A weighted average is used to estimate the amount of CO_2 per kWh. This will be called the electricity carbon footprint, *ECF*, and is defined as:

$$ECF\ = 0.23 \times 1 \frac{kg\ CO_2}{kWh} + 0.38 \times 0.42 \frac{kg\ CO_2}{kWh} = 0.39\ \frac{kg\ CO_2}{kWh}$$

Data on the power consumption of a 200-kW production system is available at a resolution as high as 5-minute intervals. Figure 4-2 shows a single day of operation at 5-minute intervals.

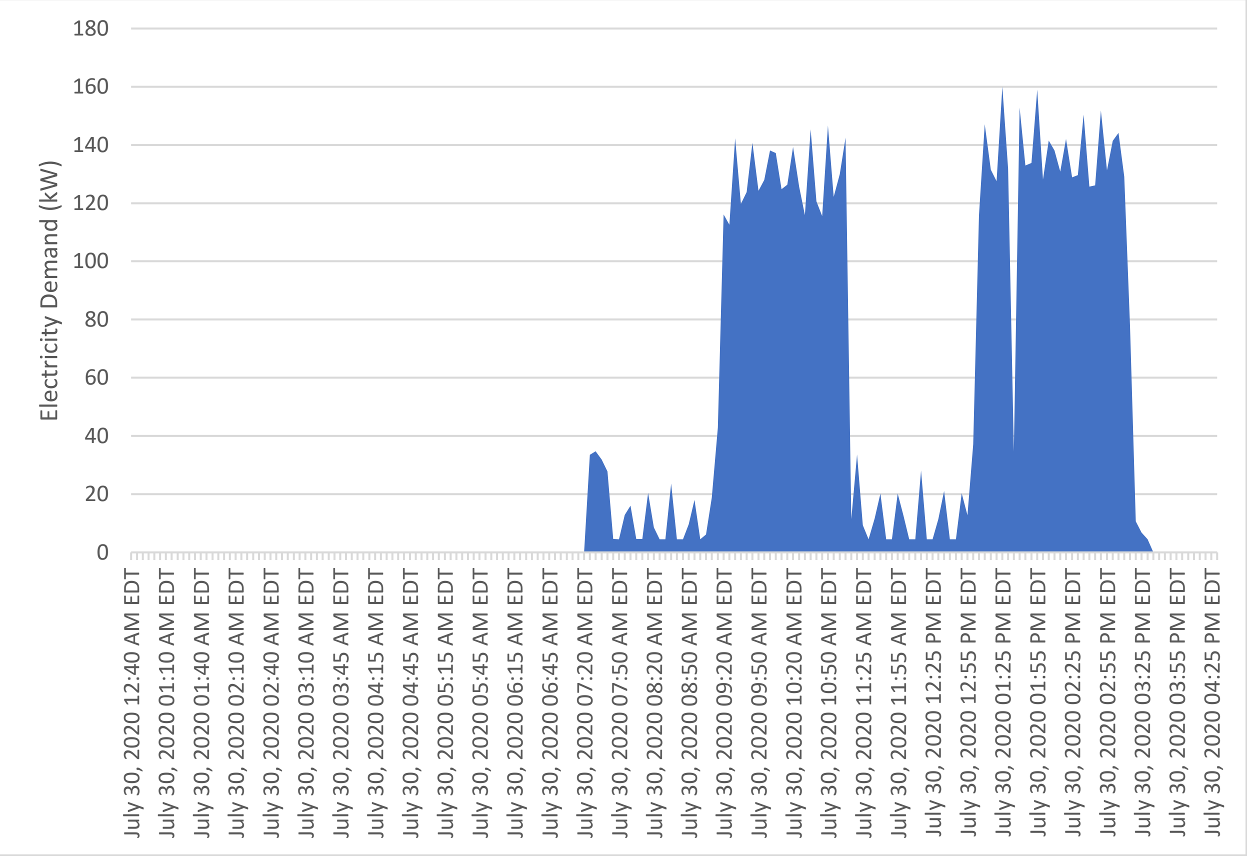

Figure 4-2. Plot of electrical demand data

The spiking demand for electricity is likely due to ancillary equipment that cycles frequently, like air compressors. Approximately 85% of the demand appears to correspond to the baseline demand during production. Table 4-3 shows captured electrical consumption data from the facility and its corresponding production of gas.

Table 4-3. Electricity consumption by MagneGas-2 production

Production (cu.ft.MG)	**Electricity (kWh)**
5,150	1,649
32,033	5,307
48,101	3,610
58,916	12,055
51,294	6,142
37,183	3,218

From the data, the required electricity was approximately $0.14\frac{kWh}{cu.ft.MG}$ on average This would lead to the electrical consumption contributing:

$$CF_{electrical} = 0.39\ \frac{kg\ CO_2}{kWh} \times 0.14\frac{kWh}{cu.ft.MG} = \ 0.055\frac{kg\ CO_2}{cu.ft.MG}$$

Turkey is specifically of interest for production. The Turkey mix of electricity contains 18.9% natural gas and 37.3% coal generation, with the rest clean-air sources [5]. This leads to an electrical carbon footprint for Turkey of:

$$CF_{electrical-Turkey} = (0.189 \times 0.42 + 0.373 \times 1.0)\frac{kg\ CO_2}{kWh} \times 0.14\frac{kWh}{cu.ft.MG}$$

$$= 0.063\ \frac{kg\ CO_2}{cu.ft.\ MG}$$

Turkey's electricity mix is still slightly more dependent on conventional thermal plants and has a higher carbon intensity.

4.5 Physical Footprint

The physical footprint, based on designs for a 300-kW system, is estimated to be 4,875 sq.ft. and can produce 11.8 million cu.ft. of gas per year. This leads to a normalized footprint of $0.0004\frac{sq.ft.yr}{cu.ft.MG}$.

4.6 Carbon Footprint

The carbon footprint is a globally used metric for the environmental impact of products, processes, etc. To compare the impact of the fuels in this report the carbon footprint will be used in the form of $\frac{kg\ CO2}{cu.ft.\ MG}$. The electrical carbon footprint from the U.S. perspective will be used in this calculation. Further analysis of the total carbon footprints with different levels of clean-air energy will be discussed in the planned carbon reductions section. The assessment of the MagneGas-2 process has generated a total carbon footprint of:

$$CF_{Total} = CF_{feedstock} + CF_{waste} + CF_{electricity}$$

Plugging in the values found in the previous section:

$$CF_{Total} = (0.011 + 0.014 + 0.055)\frac{kg.CO2}{cu.ft.MG} = \ 0.08\frac{kg.CO2}{cu.ft.MG}$$

4.7 Summary

The footprints of each section have been summarized into Table 4-4. This table will be used to compare values with the other types of facilities in this report.

Table 4-4. Summary of Taronis Fuels MagneGas-2 Plant Footprints

Feedstock $\frac{kg.CO2}{cu.ft.MG}$	**Waste** $\frac{kg.CO2}{cu.ft.MG}$	**Water** $\frac{gal.H_2O}{cu.ft.MG}$	**Physical** $\frac{sq.ft.}{cu.ft.MG}$	**Electricity** $\frac{kg.CO_2}{cu.ft.MG}$	**Carbon** $\frac{kg.CO_2}{cu.ft.MG}$
0.011	0.014	-	0.0004	0.055	0.08
13.75%	17.5%	-	-	68.75%	100%

4.8 References

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5 Recommendations

5.1 Produce in a Different Area

Production in the European Union (EU) would lead to a much smaller electrical carbon footprint. This is due to the average electricity mix having higher levels of renewable and other clean-air generation sources. Thermal power plants (coal and gas) only make up 42.8% of the electricity mix, with the rest being clean-air sources [4]. As it is not indicated, it is assumed most of the thermal power plants utilize natural gas. The electrical carbon footprint for the EU is calculated as:

$$CF_{electrical-EU} = 0.428 \times 0.42 \frac{kg\ CO_2}{kWh} \times 0.14 \frac{kWh}{cu.ft.MG} = 0.025 \frac{kg\ CO_2}{cu.ft.MG}$$

The total carbon footprint in the EU is estimated as:

$$F_{Total} = (0.011 + 0.014 + 0.025) \frac{kg.CO2}{cu.ft.MG} = 0.05 \frac{kg.CO2}{cu.ft.MG}$$

This is a 38% reduction in the carbon footprint for producing in an area with this mix of sources.

5.2 Increase Dependence on Clean Energy Sources

It is expected that worldwide electricity generation will continue to increase the amount of renewable generation supporting the grid. Coal-fired power plants, as they are considerably worse than natural-gas plants, have, for the most part, stopped being commissioned. Natural gas-fired plants are replacing them and is planned to be a supporting source to a more dominant renewable mix. MagneGas-2 production is heavily electricity dependent and thus, so is its carbon footprint. Using the U.S. mix of sources, electricity is responsible for 69% of its carbon footprint. Figure 4-3 shows the carbon footprint reduction as the percentage of clean sources increases.

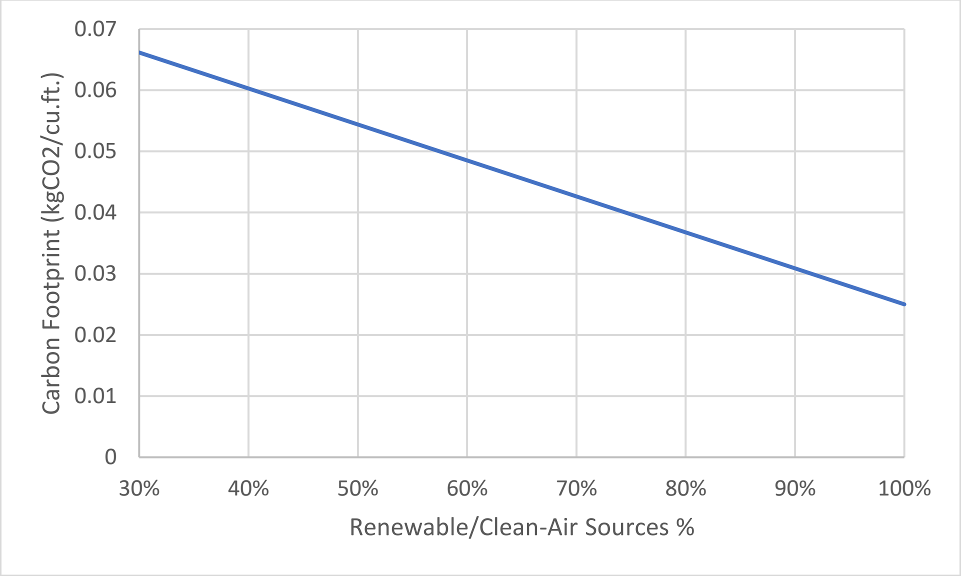

Figure 4-3. MagneGas-2 carbon footprint with increasing amounts of clean energy sources

The carbon footprint of MagneGas-2 could see considerably reduced with renewable penetration that will be achieved soon. Taronis may also take steps to reduce their dependence on carbon-intense sources by installing their own renewable generation. Solar photovoltaics and battery storage can very effectively reduce the MagneGas-2 carbon footprint.

5.3 Recycle Waste Streams

In addition to energy, it is planned that the spent carbon rods will be recycled using a third party. There are applications, such as being used as a carbon riser, that allow graphite rods to be recycled. Carbon risers are used to increase the carbon content of other materials. If the rods can be recycled, a carbon footprint reduction of $0.008 \frac{kg\ CO_2}{cu.ft.MG}$ is expected.

Although the spent ethanol, that is currently sent to be burned, has impurities, there is a possibility that it could be repurposed or cleaned. It is advised that this possibility be further explored as it would reduce the carbon footprint by $0.006 \frac{kg\ CO_2}{cu.ft.MG}$.