Evaluation of the potential for the use of Green Hydrogen and its derivatives in the industrial sector in Uruguay

Executive summary

In association with:

Study within the framework of the Development Facility in Transition Initiative with the support of the cooperation of the European Union

Iniciativa Facilidad de Desarrollo en Transición

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1 Executive Summary, Key Findings and Conclusions

This consultancy is part of the Transition Development Facility Initiative of the AUCI (Uruguayan Agency for International Cooperation)-EU (European Union) Bilateral Fund. It is developed with the contribution and support of European Union cooperation to the Green Hydrogen and Derivatives Roadmap, promoted by the national government of Uruguay.

The general objective of the study is to evaluate the feasibility of using Green Hydrogen and its derivatives as non-energy inputs in Uruguay's industrial sector. This will contribute to identify alternatives for decarbonizing the local economy and the potential for developing new sectors that might be driven by the Green Hydrogen and derivatives industry.

The scope of the study excludes uses already examined in the Green Hydrogen Roadmap in Uruguay, which includes utilization as a reducing agent in the iron industry and the production of ammonia for fertilizers.

1.1 Non-Energy Applications of Hydrogen and Its Derivatives

- **Green Hydrogen and Energy Transition:** Green hydrogen is gaining global recognition as an alternative to reduce emissions, especially in sectors where this is particularly challenging.
- **Main Uses Globally:** As a raw material for industry: in petroleum refining (hydrodesulfurization, hydrocracking) and in ammonia synthesis (primarily for use as fertilizer). Hydrogen is also used in combination with other gases as raw material in methanol synthesis, steel production, and as an energy source for industrial processes. Altogether, these uses represent about 90% of the current hydrogen consumption.
- An expansion in the use of hydrogen and its derivatives is anticipated as **fuel** for heavy transport, aviation, and maritime applications.
- **Hydrogen Roadmap in Uruguay:** Several of these applications are already outlined in the green hydrogen roadmap in Uruguay[1], for both domestic use and export, with different time horizons.
- **Other Applications:** Beyond these uses, there are other direct applications of hydrogen and its intermediate products (ammonia, methanol) as non-energy resources, which are the focus of this study.

[1] https://www.gub.uy/ministerio-industria-energia-mineria/sites/ministerio-industria-energia-mineria/files/documentos/noticias/H2_final.pdf

1.1.1 Non-energy Hydrogen uses

These include the use of hydrogen in the **food industry**, in the **glass manufacturing industry**, in the **fine chemicals and pharmaceutical industries**, and in the **synthesis of various chemicals**; in addition to some applications of ammonia and methanol (for non-energy purposes and not as fertilizers).

- **Food Industry**: H_2 is used to produce saturated fats in the manufacturing of processed foods, such as margarine and vegetable shortening, to increase the melting point and enhance oxidation resistance.
- **Glass Industry:** Hydrogen is introduced into the furnace to create a reducing atmosphere that prevents oxidation and the formation of impurities in the molten glass, which cause imperfections. To avoid oxidation processes, a protective atmosphere typically consisting of 90% nitrogen and 10% hydrogen is used. Hydrogen can also be utilized as a means to control temperature during the manufacturing process.
- **Chemical Synthesis:** Although ammonia and methanol are highlighted as the primary chemical products derived from hydrogen, a diverse range of additional chemicals also require hydrogen in their synthesis process.
- **Fine or Specialty Chemicals:** Focuses on the production of high-purity, high-value-added chemical compounds with pharmaceutical, agrochemical, electronic, cosmetic, and other applications. Hydrogen is essential in fine chemicals due to its ability to participate in selective hydrogenation reactions, act as a reducing agent in catalytic processes, and in hydrolysis reactions.

1.1.2 Non-energy methanol uses

Approximately 70% of methanol is used as a raw material for the production of **other chemicals**, and the remaining 30% is used as **fuel**. The sectors that demand the use of methanol include construction, automotive, electronics, packaging, coatings, paints, pharmaceuticals, cosmetics, appliances, and solvents.

Below are the main products synthesized from methanol:

- **Formaldehyde** is one of the most important chemicals worldwide, as it is a necessary raw material for many industries, including polymers, resins, paints, and adhesives. The most relevant products made from formaldehyde are **industrial resins** such as melamine-formaldehyde, urea-formaldehyde, and phenol-formaldehyde.
- **Acetic Acid** is a widely used chemical compound in various industrial processes. Acetic acid derivatives can be used in adhesives, latex emulsion resins for paints, textile finishing agents, paper coatings, plastic cellulose cigarette filter tows, and cellulose acetate fibers.
- **Methanol-to-Hydrocarbons** (MTH) process is a key technology in the chemical industry that encompasses methanol-to-gasoline (MTG), methanol-to-olefins (MTO), and methanol-to-aromatics (MTA) processes. This process allows the production of basic petrochemical products from methanol (of various origins).
- **Ultra-Pure Dimethyl Ether** (DME) is commonly used as an aerosol propellant. It is

also used in the cosmetics industry, in the production of dimethyl sulfate, in the production of acetic acid or acetic anhydride via methyl acetate, to produce R723 refrigerant, and for the production of polyurethane and polystyrene foams.

- **Methyl Methacrylate** (MMA) is the raw material for the production of polymethyl methacrylate (PMMA, Plexiglas), a highly transparent and glossy polymer. Additionally, MMA is used in the production of oil additives (e.g., Viscoflex), film coatings in pharmaceutical preparations (Eudragit), and dental products. MMA is also used as a humectant and thickener for emulsion paints.
- **Methylamines** are produced through the reaction of methanol and ammonia, with dimethylamine being the most important product as it is essential for the synthesis of N,N-dimethylformamide (DMF). Monomethylamine follows in importance, used in the manufacture of methyl urea, N-methyl-2-pyrrolidone (NMP), and methyl taurine, the latter being employed in CO_2 capture and as an ingredient in washing agents. Trimethylamine is used in the synthesis of choline chloride. All three methylamines are vital intermediates in the production of solvents, insecticides, herbicides, pharmaceuticals, and detergents.

1.1.3 Non-energy ammonia uses

About 85% of global NH_3 is used in the production of **nitrogen fertilizers** (urea, UAN, nitrate, sulfate, and ammonium phosphates). The remaining 15% is explained by a variety of other NH_3 applications as follows:

- **Amines** are organic compounds derived from ammonia. They have a wide range of applications in industry, medicine, and the synthesis of organic compounds. Applications include the manufacture of agricultural chemicals, solvents, polymers, feed and food additives, cleaning products, pharmaceuticals, water and gas treatment, personal care products, cement, paints and coatings, textiles, etc.
- **Melamine** ($C_3H_6N_6$) is an organic compound widely used in the industry to manufacture melamine-formaldehyde resins. Melamine is obtained from urea and ammonia.
- **Nitric Acid** (HNO_3) is a strong acid, liquid under atmospheric conditions. It is corrosive and reacts with almost all metals except noble metals and some alloys. It reacts violently with many organic compounds and is miscible with water. Currently, nitric acid is one of the 15 most important commodities globally. About 80% of the nitric acid produced is used in the production of nitrogen fertilizers, while the remaining 20% is used in the production of various chemical compounds, such as explosives or intermediates for polymer production.
- Polymers can also be produced from ammonia, including acrylonitrile, polyamides, and polyurethanes.
- **Hydrogen Cyanide** (HCN) is an essential chemical for the production of adiponitrile (for nylon production), methacrylic esters (for methyl methacrylate production), sodium/potassium cyanides (used in mining), and some technically important amino acids.

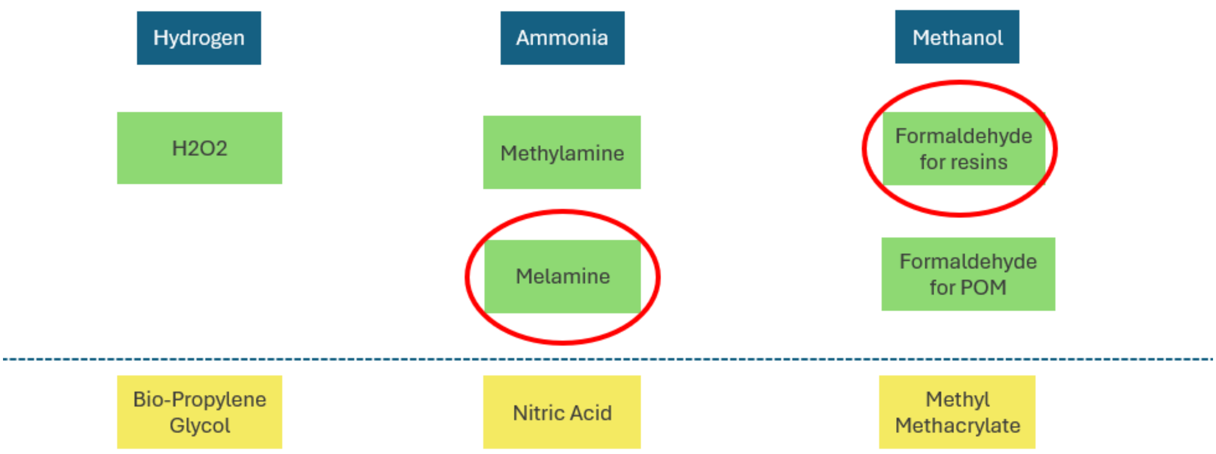
1.2 Most Promising Uses for Uruguay

From the entire set of identified precursors, a set of criteria was developed to select a subset of candidates with the highest development potential. These criteria were:

- Necessary Raw Materials for Production, considering their availability in Uruguay.
- Requirements for Fossil Inputs.
- Whether the Final Product is a Commodity or a Higher Value-Added Product.
- Level of Maturity of Production Technology.
- Restrictions Due to Toxicity or Hazardous Nature of the Final Product.
- Global and Domestic Demand, Market Routes.
- Final Uses and Applications.

Based on the aforementioned criteria, five cases were selected as the most promising for development in Uruguay (Figure 1).

Figure 1 Most promising uses in Uruguay, study cases



Source: Own elaboration

1.3 Description of Candidate Cases

1.3.1 Hydrogen Peroxide

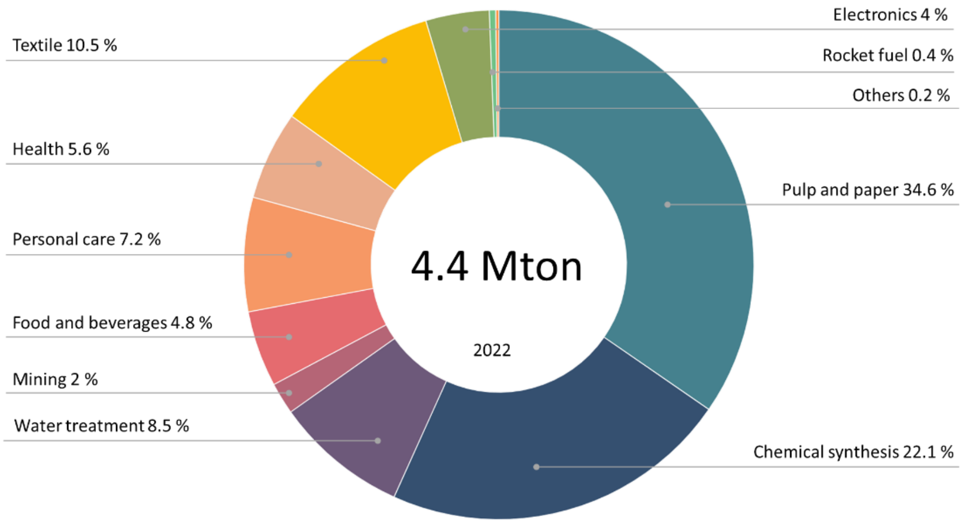
1.3.1.1 Current Production and Global Projection

In 2022, global production capacity reached 4.4 million tons. Annual production is estimated to be around 7 million tons by 2030. H_2O_2 is commonly marketed in aqueous solution across a wide range of concentrations (3-35% wt) for its various applications.

1.3.1.2 Uses

H_2O_2 is a powerful oxidant with a diverse range of uses, including as an oxidizing agent, bleaching agent (for textiles, cotton, wood, paper pulp, and the food industry [bleaching cheeses, chickens, meats, etc.]), rocket fuel component, in the production of organic chemicals such as propylene oxide, as an antiseptic and antibacterial agent, in the electronics industry (semiconductors and components), and in wastewater treatment. Figure 2 shows the main uses of H_2O_2 worldwide and its consumption percentage by sector.

Figure 2 Global H_2O_2 consumption and applications

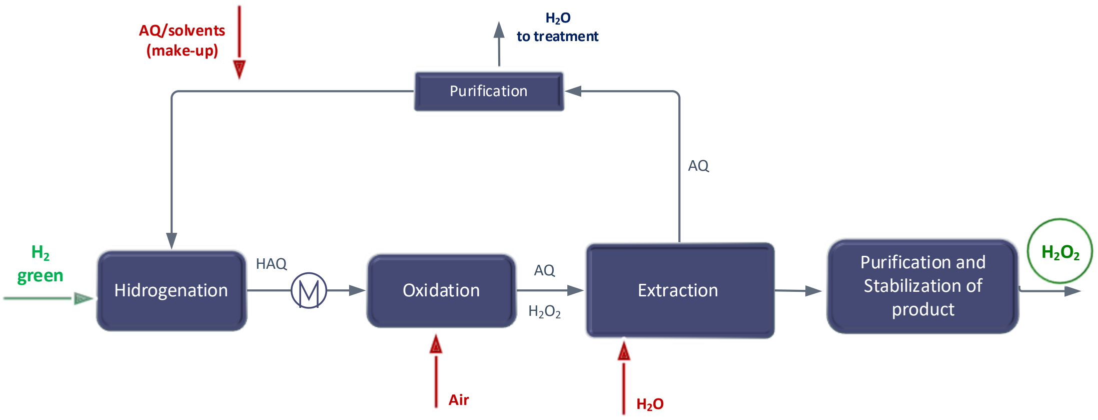


Source: Own elaboration

1.3.1.3 Production Process

Currently, H_2O_2 is almost exclusively produced by the "anthraquinone process." This is a cyclic process in which anthraquinone (AQ) is successively hydrogenated and oxidized, releasing H_2O_2 in each cycle. Figure 3 shows a simplified diagram of the process.

Figure 3 H_2O_2 synthesis process scheme



Source: Own elaboration

1.3.2 Formaldehyde / Urea-Formaldehyde Concentrate (UFC) / Urea-Formaldehyde Resins (R-UF)

1.3.2.1 Current Production and Global Projection

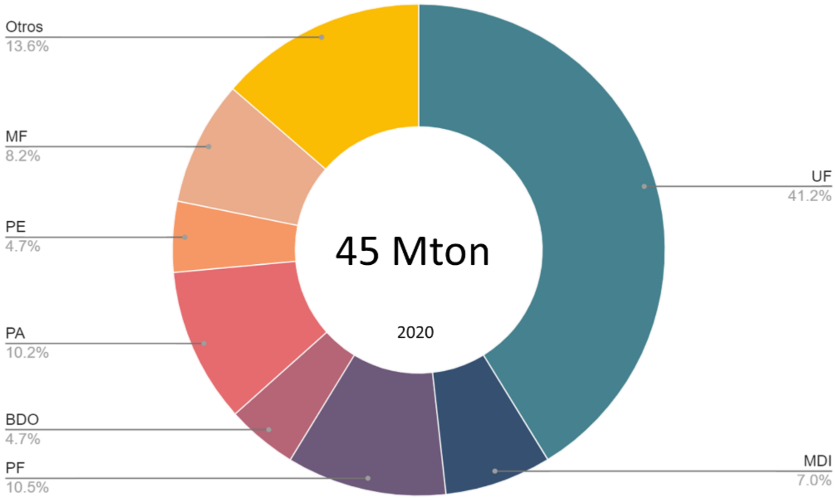
The global formaldehyde market, estimated at 45 million metric tons in 2020, is projected to reach 63 million tons by 2027, with a compound annual growth rate (CAGR) of 4.9%.

It is important to note that formaldehyde is a gas at room temperature, whereas formalin is an aqueous solution of 37-40% wt formaldehyde. Methanol (10-12% wt) is typically added to the solution as a polymerization inhibitor.

1.3.2.2 Uses of Formaldehyde

Figure 4 presents the percentages allocated to the main derivatives of formaldehyde. This diversity of products impacts a wide range of applications in the construction, automotive, aviation, pharmaceutical, and cosmetic industries.

Figure 4 Global consumption and uses of formaldehyde



References: Urea-Formaldehyde Resins (UF), Phenol-Formaldehyde Resins (PF), Polyacetals (PA), Melamine-Formaldehyde Resins (MF), Methylene Diphenyl Diisocyanate (MDI), Pentaerythritol (PE), and 1,4-Butanediol (BDO).

Source: Own elaboration

As observed, the predominant use of formaldehyde is as a raw material for the production of urea-formaldehyde (UF) resins, followed by the synthesis of phenol-formaldehyde (PF) resins, polyacetals (PA) or polyoxymethylene (POM), and melamine-formaldehyde (MF) resins. These compounds constitute 70% of the formaldehyde usage.

1.3.2.3 Production Processes for Formaldehyde / UFC

Virtually all global industrial production of formaldehyde is obtained by catalytic oxidation of methanol. Subproducts such as carbon monoxide and carbon dioxide, methyl formate, methane, and formic acid may also be formed. Industrial processes for formaldehyde production are classified based on whether they operate with air deficiency or excess.

Air Deficiency Processes (or Silver Catalyst Processes)

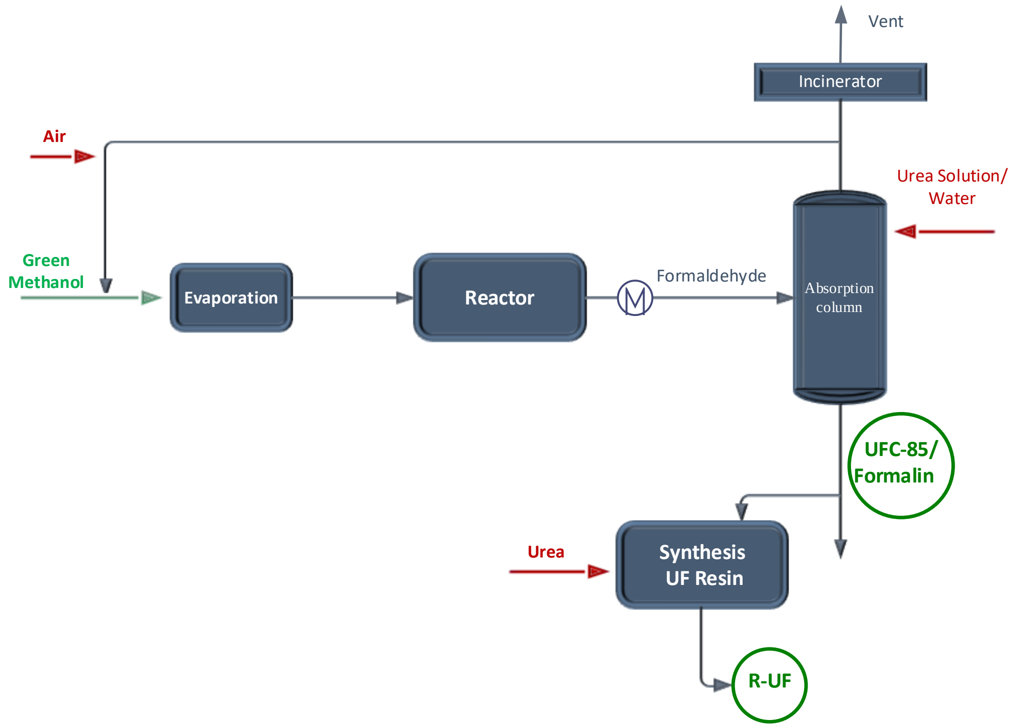
In the air-deficient process, methanol reacts through dehydrogenation and partial oxidation reactions to produce formaldehyde. Major technologists using this process include BASF, Borden, Bayer, Degussa, Imperial Chemical Industries (ICI), Celanese, DuPont, Mitsubishi, and Mitsui.

Air Excess Processes (or FORMOX Process)

The other process, known as the Formox process, employs excess air, and only partial oxidation of methanol occurs (used by Lummus, Montecatini and Hiag/Lurgi).

Figure 5 presents a schematic of the FORMOX process for producing formaldehyde / UFC solutions. The production of urea-formaldehyde resins (R-UF) is included according to the description provided in the following section.

Figure 5 FORMOX synthesis process scheme



Source: Own elaboration

1.3.2.4 Production Process for Urea-Formaldehyde Resins (R-UF)

The production of R-UF (like other amino resins) consists of two stages: hydroxymethylation (monomer formation) and condensation (polymerization). Depending on the reaction conditions, hydroxymethylation is accompanied to a greater or lesser extent by condensation.

Hydroxymethylation occurs in slightly alkaline or slightly acidic media, while condensation requires a more acidic solution. The resin production process continues until the resulting product is an oligomeric mixture that is still soluble. Condensation is halted by alkalinizing the medium.

1.3.3 Methylamines (Aliphatic Amines)

1.3.3.1 Current Production and Global Projection

Aliphatic amines or alkylamines are organic chemical compounds containing the amine functional group (-NH_2) attached to aliphatic radicals. These amines can be classified as primary, secondary, or tertiary, depending on how many alkyl groups (or alkyl substituents) are attached to the nitrogen atom. These compounds are widely used as intermediates in the production of various chemicals, pharmaceuticals, agrochemicals, rubber additives, water treatment chemicals, and surfactants, among others.

Methylamines, which include monomethylamine (MMA), dimethylamine (DMA), and trimethylamine (TMA), are a series of aliphatic amines used in various industrial sectors. These compounds are important chemical intermediates in the synthesis of a wide range of chemical products.

The global production capacity of methylamines is estimated at around 650,000 tons annually, with an annual growth rate of about 4.2% expected until 2032.

1.3.3.2 Uses of Methylamines

Particularly, dimethylamine (DMA), which has the highest demand, is used in the manufacture of N,N-dimethylformamide and N,N-dimethylacetamide, which have widespread applications as solvents. Additionally, it is used in the manufacture of agrochemical, pharmaceutical, cleaning, and surfactant products.

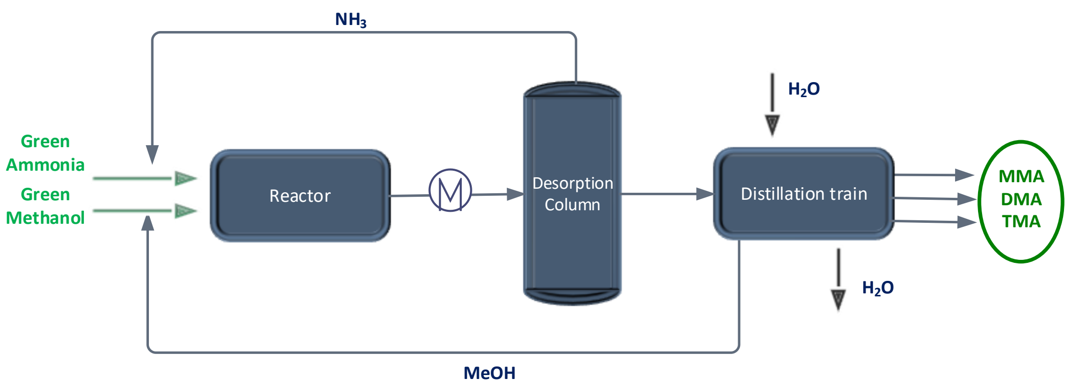
Monomethylamine (MMA) ranks second in terms of demand. It is used for the manufacture of solvents, dimethyl urea, and N-methyl-2-pyrrolidone, as well as for chemical synthesis or as a raw material for detergents.

Trimethylamine (TMA), which plays a minor role, is used in animal feed supplements, cationic starches, and ion exchange resins, dyes, and sensors.

1.3.3.3 Production Process

Historically, methylamines are produced from methanol in the vapor phase along with ammonia, using various variants of the so-called Leonard process. A simplified diagram of the methylamine production process is presented in Figure 6.

Figure 6 Methylamine synthesis process scheme



Source: Own elaboration

1.3.4 Melamine

1.3.4.1 Current Production and Global Projection

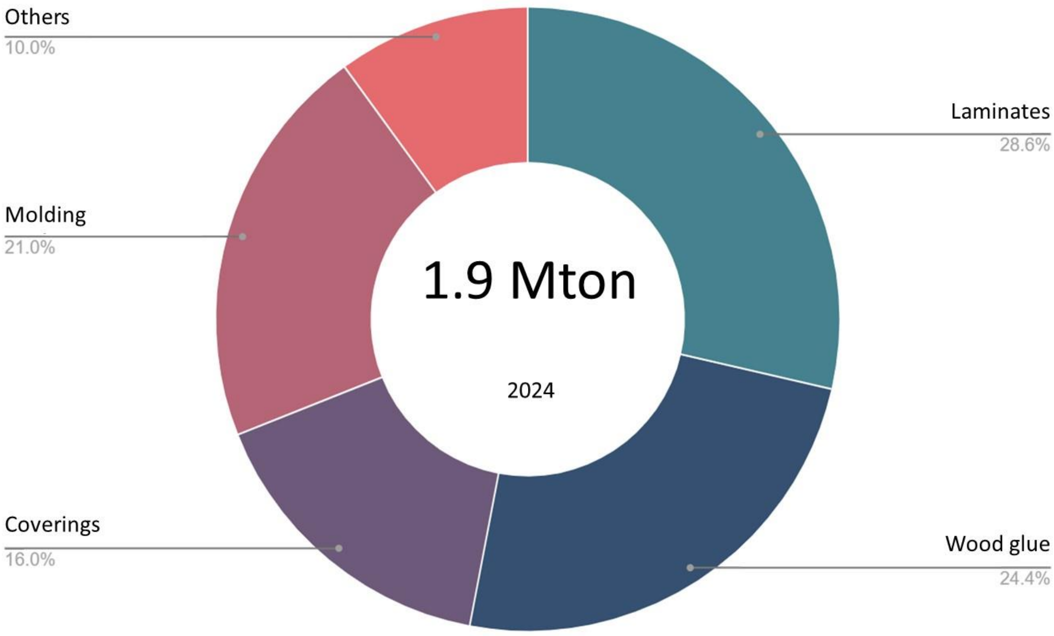
Melamine ($C_3H_6N_6$) is a white, crystalline solid that is sparingly soluble in water. Currently, the melamine market size is estimated at 1.9 million tons annually and is expected to reach 2.3 million tons by 2029, growing at a compound annual growth rate of 4.15% during this period.

1.3.4.2 Uses

Melamine demand is strongly influenced by construction and automotive manufacturing activities. The main applications are presented in Figure 7 and listed below:

- Surface Coatings: Melamine-formaldehyde (MF) resins are used for surface coatings in automobiles, metal containers, metal furniture, coil coatings, and electrical appliances.
- Laminates: Laminates are made by pressing paper or fabric saturated with MF resin under pressure and temperature onto a core material. Laminates are used in cabinets, furniture, flooring, and various types of panels.
- Molding Compounds: Melamine-formaldehyde molding compounds can be produced by compression or injection molding and are used to make dinnerware, appliance housings, and cases. Melamine-formaldehyde is also used in the automotive industry for manufacturing wheel covers, dashboards, lights, and door handles.
- Wood Adhesives: Melamine-modified wood adhesives are used in various wood products, such as plywood, particle board, medium-density fiberboard (MDF), truck and wagon floors, furniture doors, and wood trays.
- Other Uses: Include flame retardants, paper and textile treatment, as concrete additives, and many other small-volume applications.

Figure 7 Global consumption and uses of melamine



Source: Own elaboration

1.3.4.3 Production Process

Melamine is industrially produced from the decomposition of urea at temperatures in the range of 390-410°C. The overall reaction is endothermic and requires 649 kJ per mole of melamine, starting from molten urea at 135°C.

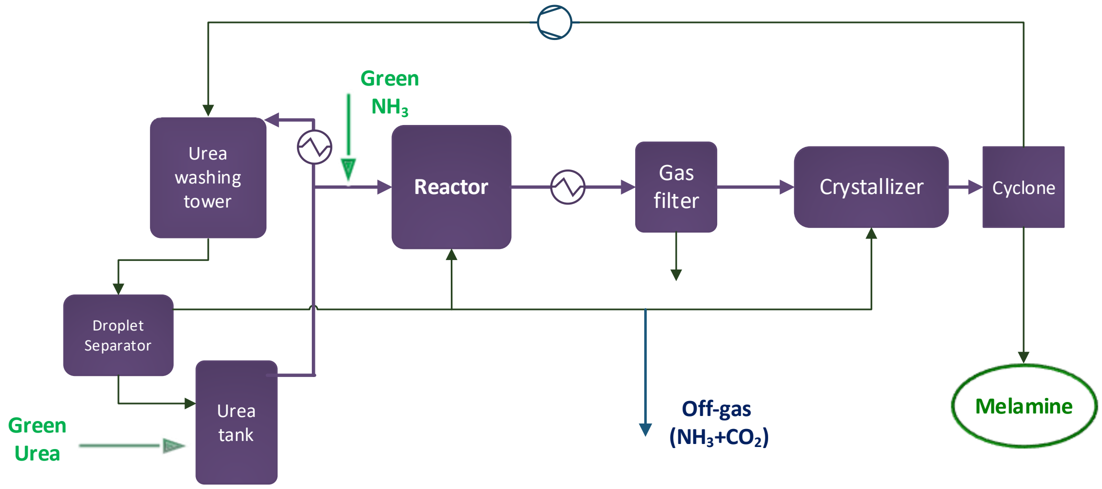
Production processes can be divided into two categories:

- Low-Pressure (<10 atm), Catalytic, see Figure 8
- High-Pressure (>80 atm), Non-Catalytic

Regardless of the type of process, three plant sections are identified:

a) synthesis
b) Recovery and purification of melamine
c) Treatment of residual gases

Figure 8 Melamine synthesis process scheme



Source: Own elaboration

Typically, this treatment involves the total or partial conversion of the residual gases (a mixture of NH_3 and CO_2) back into urea. Therefore, melamine production plants are often located near a urea production plant, from which they obtain their feedstock and to which they return the residual gases as raw material to produce more urea.

1.3.5 Polyoxymethylene (POM)

1.3.5.1 Current Production and Global Projection

Polyoxymethylene (POM), also known as acetal, polyacetal, and polyformaldehyde, is a semi-crystalline polymeric material that belongs to the group of engineering thermoplastics. It is noted for its low friction and wear characteristics, as well as its excellent balance between mechanical properties and chemical resistance.

The growth in global demand for polyoxymethylene (POM) has been almost constant for years, reaching 1.35 million tons in 2018. However, this growth is distributed very differently across regions. While the growth rate was 1.5% in North and South America, it was disproportionately higher in China (6%) and Asia (7%), due to the corresponding growth in electronics and automobile manufacturing in these regions.

The global POM market reached approximately 1.4 million tons in 2022 and is expected to grow at a compound annual growth rate of 4.4% over the forecast period to 2032, where it is projected to reach 2.15 million tons.

1.3.5.2 Uses

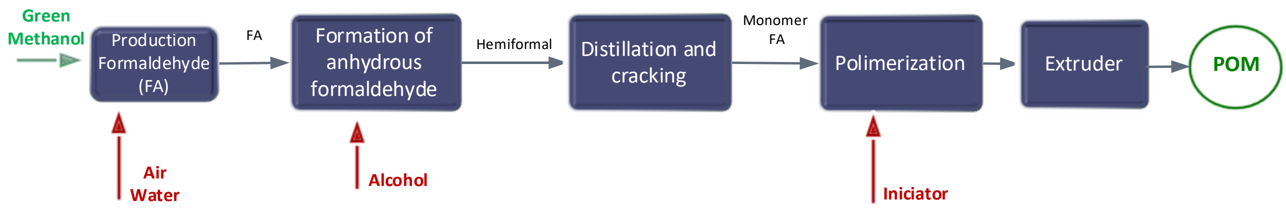
Polyoxymethylene (POM) has a balanced combination of favorable properties such as hardness, rigidity, toughness, spring elasticity, and resistance to fuels. POM is used in almost all sectors of industry and technology. The main areas of POM consumption are described below:

- Automotive Sector: Used in the manufacture of pump parts, gasoline meters, chains, clips, tank closures, water separators, lock housings, fan blades, speaker grills, fuel tank modules, and seatbelt parts.
- Electrical and Electronics Industry: Given POM's electrical insulation properties, it is used in the production of connectors, switches, and small gears.
- Consumer Goods: Used in various applications, such as zippers, buckles, handles, knobs, fasteners, and toys.
- Construction: Employed as a material in injection and extrusion molding. It has high ductility, strength, and rigidity.
- Others: Mechanical engineering and industrial applications; valves, pistons, bearings, gears, conveyor system components, and other precision mechanical parts requiring high strength, low friction, and dimensional stability. Medical technology; surgical instruments, drug delivery devices, orthopedic implants, dental components, and other medical equipment. Also used in pumps, valves, impellers, fittings, and other components that come into contact with chemicals, fuels, or corrosive fluids (Europlas).

1.3.5.3 Production Process

Polyoxymethylene is obtained by polymerization of high-purity formaldehyde via carbonyl bond opening C=O in gas phase. Figure 9 shows a scheme of the POM production process.

Figure 9: POM synthesis process scheme



Source: own elaboration

1.4 Case studies

From the set of candidate cases, and in conjunction with the counterpart, one case was selected for the methanol line and another for the ammonia line: the production of **formaldehyde for resins** and the production of **melamine**, respectively.

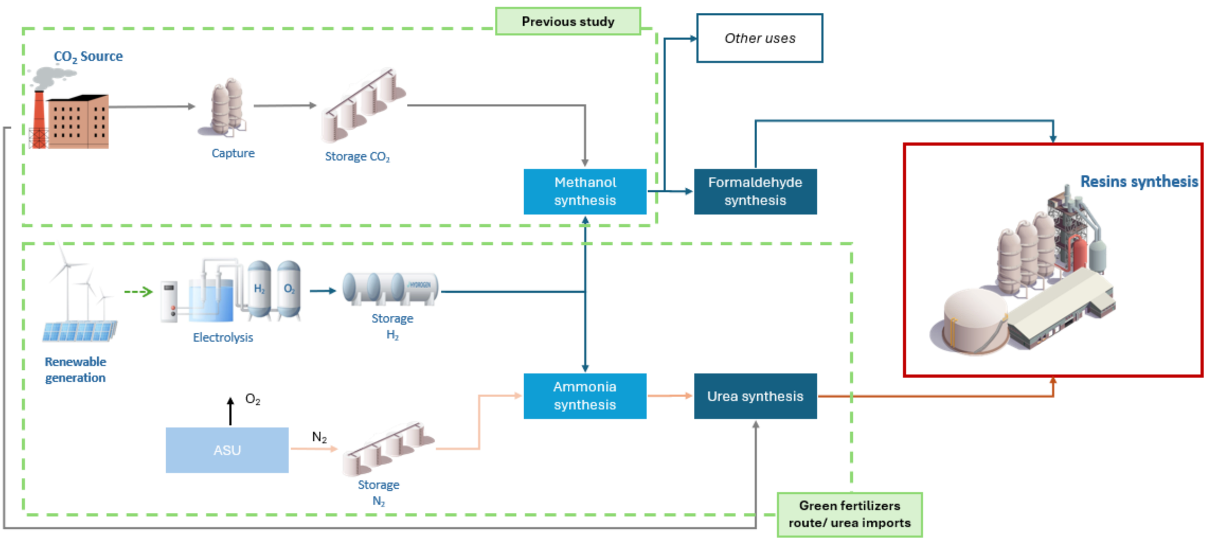
1.4.1 Formaldehyde for Resins

Characteristics, Uses, and Market Transportation. A combination of 85% urea-formaldehyde concentrate (UFC 85) and urea-formaldehyde resins (UF) was chosen, as they have different stability characteristics that impose limits in terms of transportation distances and market routes.

UFC 85 is mainly used in the production of thermosetting resins and various organic and agricultural products. To produce UF resins, Urea Formaldehyde Concentrate (UFC 85) is generated as an intermediate. UF resins have reduced stability, so the potential market to supply is restricted to the regional market (Brazil, Argentina, and Paraguay); while for UFC 85, the potential destination market is global (mainly Europe).

Production Process. UF resin production is carried out using conventional raw materials; gray methanol and urea. To reduce emissions and enhance the use of green hydrogen and its derivatives in Uruguay, methanol and urea can be replaced by those produced using low-carbon methods. Figure 10 shows the simplified value chain diagram and analysis boundary for this study (red line).

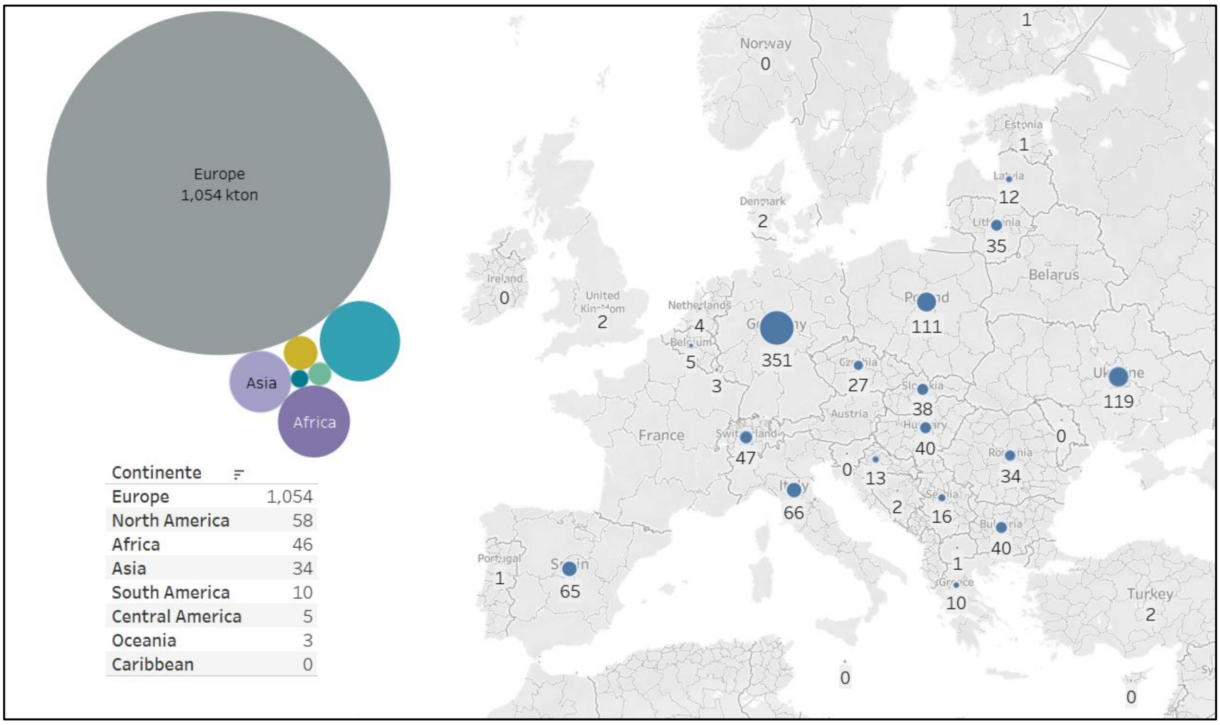
Figure 10 Low carbon Simplified UFC/ resins synthesis scheme and boundary of the study



Source: Own elaboration

Demand and Markets. The global UFC and urea-formaldehyde resin market is expanding, driven by various factors, including the growing demand for products made with plywood, particle board, and adhesives, as well as the increase in applications in the construction and furniture industries. Europe is established as the main destination for these exports, with Germany as the main importer. China and India are very relevant countries in the sector, both in production and domestic consumption. Figure 11 shows the dimensions of the global market for these products.

Figure 11 Global UFC and resinas UF imports, in kton/year



Source: Own elaboration

In the **regional market**, Argentina, Brazil, and Paraguay stand out.

Selling Prices. Both UF resins and UFC 85 concentrate are intermediate chemical compounds, and there are no homogeneous international price series as with basic chemical compounds such as methanol and ammonia. Instead, the information gathered is scattered, specific, and comes from different sources, presenting significant variations.

This is compounded by the inherent volatility of the market, influenced not only by variations in the cost of the main inputs (methanol, urea, and ammonia correlated with the price of natural gas) but also by the balance between supply and demand, disruptions in supply chains, among other factors. These combined conditions create a dynamic environment where price references show significant dispersion.

For this study, the prices considered are in the range between 600 and 700 USD per ton for resin and 800 and 1,000 USD for UFC 85, as these were the most commonly gathered from the analyzed sources.

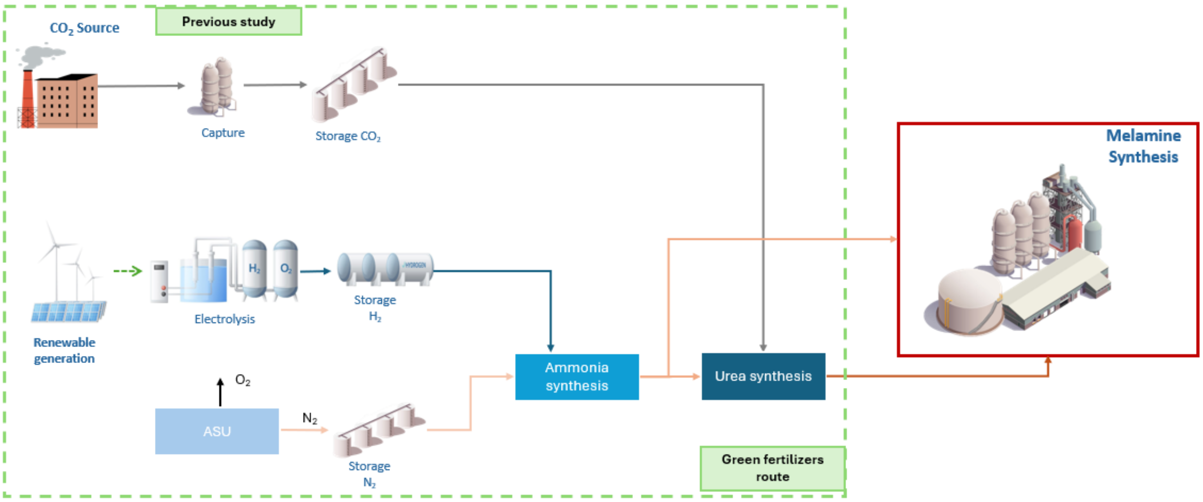
The global market has numerous key players who contribute significantly to the sector's growth, mainly driven by emerging economies.

1.4.2 Melamine

Characteristics, Uses, and Market Transportation. Melamine is a heterocyclic, crystalline, and colorless organic compound; widely used in various industries to create durable and heat-resistant thermosetting plastic products, such as plates, bowls, and kitchen utensils. Additionally, these resins are used in particle boards, enhancing their heat and moisture resistance; and in flame retardant materials (protective clothing like firefighter uniforms, wall and floor coatings) and also as acoustic and thermal insulation.

Production Process. It can be synthesized from various chemical precursors, with urea being the most common starting material. The process diagram is shown in Figure 12. During the manufacturing process, urea decomposes into cyanuric acid, which subsequently reacts to form melamine.

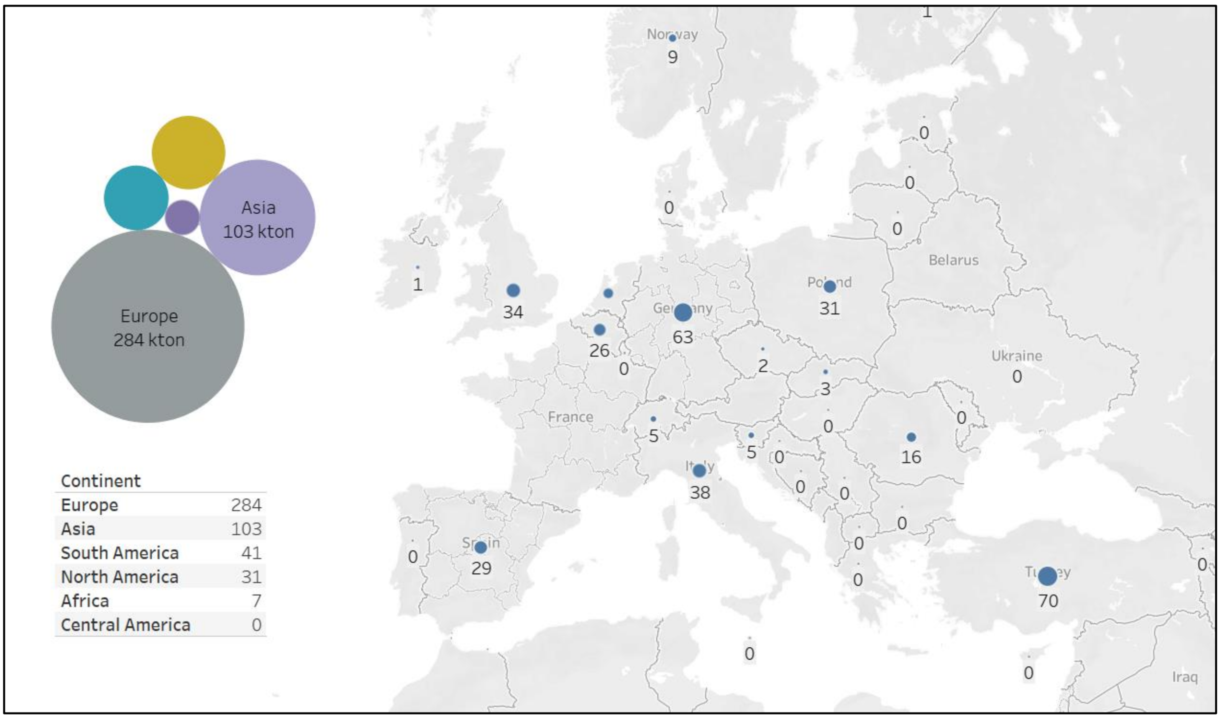
Figure 12 Low carbon melamine simplified synthesis scheme



Source: Own elaboration

Demand and Markets. Melamine is a market that expands and covers a wide spectrum of growing applications. Europe and Asia are established as the main destinations for these exports, with Germany and Turkey leading respectively. China plays a crucial role in the global melamine market due to its significant production capacity, high production levels, and great importance in the export market. Figure 13 shows the relevance of imports in Europe and Asia compared to the rest of the world, and also the importance of the main countries (Turkey, Germany, Italy, Poland, the United Kingdom, and Spain).

Figure 13 Global melamine imports, in kton/year



Source: Own elaboration

In the regional market, Brazil and Argentina stand out. In particular, Brazil is highly relevant in the regional market, being by far the main importing country of these products. The main source of these imports is China, followed by Singapore.

Selling Prices and Main Suppliers. As with UFC 85 and urea-formaldehyde resins, estimating the selling price of melamine is a complex task. This price is highly volatile, depending on the cost of raw materials (ammonia and urea), market dynamics (imbalances between supply and demand), disruptions in supply chains, and global economic conditions. For the study, a usual melamine price variation range between 900-1,400 USD/ton was considered. It is worth noting that China's predominant position in the market can create entry barriers and competition difficulties due to economies of scale.

1.5 Plant Sizing and Main Costs

1.5.1 Formaldehyde for Resins

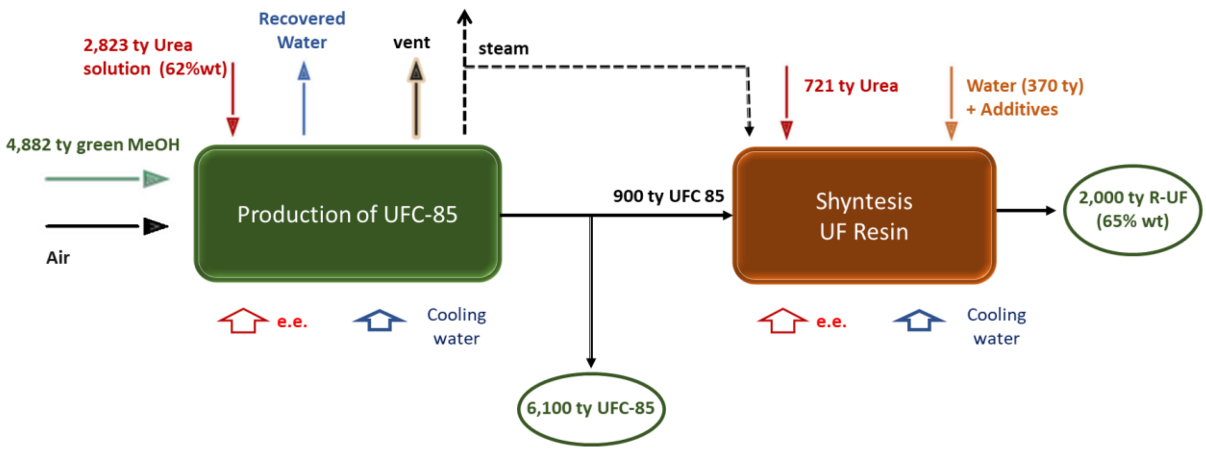
Scale of Operation and Conceptual Case Description. The conceptual design for a plant producing urea-formaldehyde concentrate (UFC 85) and urea-formaldehyde resins (R-UF) is developed. The proposed production is 6,100 tons per year of UFC 85 and 2,000 tons per year of R-UF. The products and production scale were established mainly considering:

- Size of the Potential Export Market, regionally (Brazil, Paraguay, and Argentina) and globally (Europe). Resin production represents 16.6% of the regional market, while UFC 85 reaches 0.6% of the European market.
- Distances and Logistics of Transportation.

Additionally, it has been verified that plants of the specified dimensions have been reported in open literature.

Technology Selection. A FORMOX-type technology is selected to produce UFC 85 (this technology allows achieving the desired 85% concentration level). Urea-formaldehyde resin is obtained from a batch-type operation. Basic sizing of each main process equipment was performed, and the necessary investment and primary consumptions were evaluated. Figure 14 outlines the main input and output streams, and the mass balance. The UFC 85 production unit is fed with 4,882 tons annually of green methanol, which, along with process air (19,387 tons annually), is converted into formaldehyde. This is absorbed in a urea solution (2,823 tons annually, 62% wt urea in water) to yield 7,000 tons annually of UFC 85. Of this stream, 6,100 tons annually are marketed directly. The remaining 900 tons annually are fed to the UF Resin Synthesis unit as raw material for producing 2,000 tons annually of R-UF (at 65% wt). Additional feeding of 721 tons annually of urea is required. The studied process requires electrical energy for pumps and blowers, produces excess high-pressure steam, and needs cooling water.

Figure 14: Mass balance for the UFC 85 / R-UF process



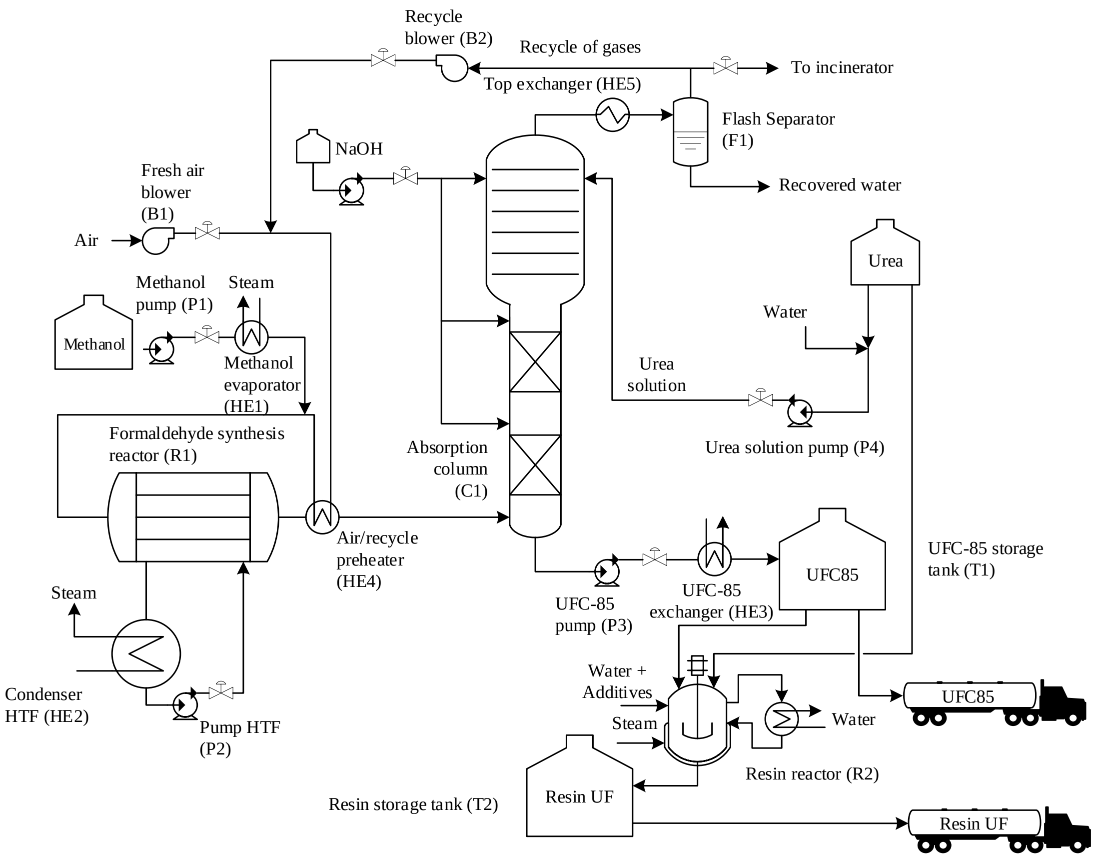
Source: own elaboration

Main Equipment Sizing. Table 1 details the equipment (see references in Figure 15), along with their characteristic parameters, required for the next stage of economic evaluation. The main equipments include fresh air blower, recycle gas blower, methanol vaporizer, multitubular reactor, HTF condenser, HTF pump, recycle air preheater, absorption column, flash separator, pumps, heat exchangers, and storage tanks.

Table 1 Included equipment in the UFC 85 and Resina UF plants

Equipment	Characteristic parameter	Observations
Fresh air blower (B1)	24.9 kW	
Recycling gas blower (B2)	55.7 kW	
Methanol pump (P1)	0.3 kW	
Methanol vaporizer (HE1)	6.4 m^2	Kettle type Thermal load: 124 kW
Multitubular reactor (R1)	339.3 m^2	Number of tubes: 4,000 dti = 1.8 cm
HTF condensator (HE2)	9.7 m^2	Thermal load: 772.2 kW
HTF pump (P2)	0.3 kW	
Air/recycle preheater (HE4)	358.4 m^2	Thermal load: 336.6 kW
Absorber columns (C1)	26.3 m^3	Stainless steel, 20 plates - bubbling dish (Sieve Tray)
UFC 85 Pump (P3)	6 kW	Reciprocating or piston cylinder, Stainless steel
UFC 85 heat exchanger(HE3)	31 m^2	Stainless steel
Urea solution pump (P4)	2.2 kW	
Column top exchanger (HE5)	134 m^2	
Flash separator (F1)	4.3 m^3	
UFC 85 storage tank (T1)	50 m^3	Stainless steel
Resin reactor (R2)	10 m^3	Stainless steel
Resin storage tank (T2)	50 m^3	

Figure 15 Process Diagram for UFC 85 / Urea-Formaldehyde Resin (UF) Plant



Source: own elaboration

Cost Calculation for Equipment and Consumables. For cost estimation, the NETL (National Energy Technology Laboratory) cost estimation method was used. This method involves evaluating the BEC (Bare Erected Cost), which includes the cost of equipment, accessories, and direct and indirect labor. The estimated CAPEX for the UFC 85 plant is 5 million USD. Added to this is the estimated CAPEX for the UF resin plant and the storage tanks for the products (UFC 85 and UF resin), estimated at 0.7 million USD, totaling 5.7 million USD. The main consumptions are methanol (4,882 tons annually), urea (1,750 tons annually), cooling and process water, electrical consumption, catalysts (details in Table 2).

Table 2 UFC 85 and R-UF operating parameters

	UFC 85	UF resin
Methanol (ton/year)	4,882	-
Urea (ton/year)	1,750	721
Cooling water (m^3/h)	68	1.7
Process water (m^3/h)	0.13	0.044

Electric demand (MWh/year)	751	40
NaOH (kg/year)*	2,450	3.5
Catalyst (kg/year)**	680	

* Price NaOH = 0.35 USD/kg

**Catalyst cost = 30 USD/kg

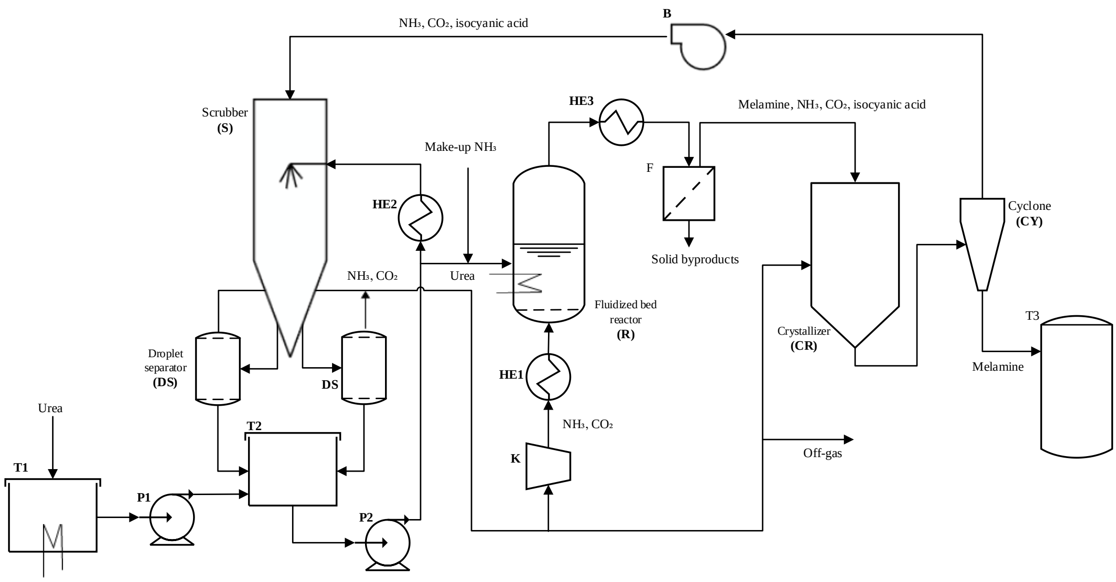
Additionally, fixed operation and maintenance expenses equivalent to 2% of the CAPEX value are considered.

1.5.2 Melamine

Scale of Operation and Conceptual Case Description. For the conceptual sizing of the process, a production capacity of 25,600 tons per year of melamine was considered, based on information from an industrial-scale plant and market considerations (the adopted volume represents about 5% of the global market).

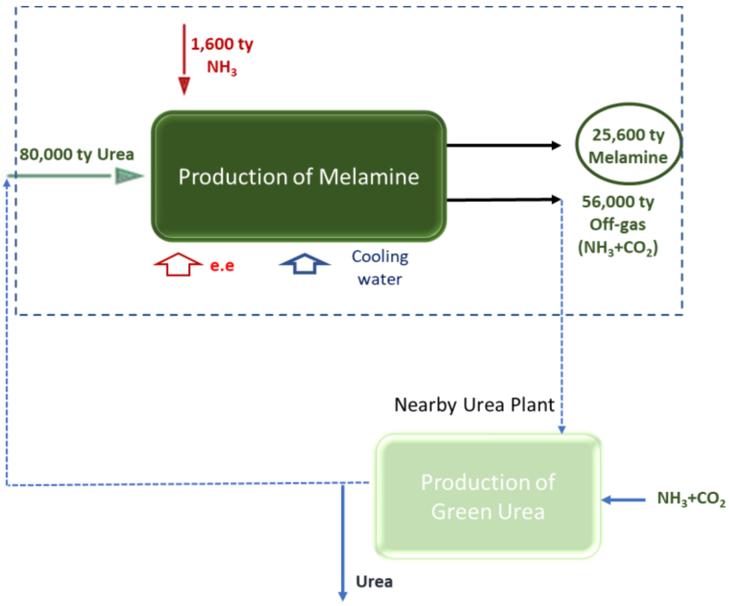
Technology Selection. The reference plant uses low-pressure technology, specifically the BASF process (Figure 16). The necessary investments for setting up the plant and the main consumptions (electric and services) were estimated. A diagram with the main input-output streams of the melamine production process is presented in Figure 17.

Figure 16: BASF melamine synthesis process



Source: own elaboration

Figure 17: Mass balance melamine synthesis process



Source: own elaboration

It is important to note that melamine production plants are designed to be integrated with a urea production plant to take advantage of the residual gas stream from the melamine plant containing NH_3+CO_2. This residual gas is reconverted into urea in the adjacent plant, significantly reducing melamine production costs while minimizing environmental risks.

The feed urea, along with the ammonia make-up, enters the process. 3.125 tons of Urea are required per ton of Melamine, therefore, for the production of 25,600 tons annually of melamine, 80,000 tons annually of urea are needed. Additionally, 1,600 tons annually of ammonia are fed to minimize the generation of by-products. The process output streams are powdered melamine and a residual gas stream of 56,000 tons annually containing NH_3+CO_2. This residual gas is converted into urea in the neighboring urea plant. This residual gas stream is equivalent to approximately 41,600 tons annually of urea.

This synergy between the melamine and urea plants significantly improves the economics of the process. A summary of the mass balance of the process is reported in Table 3.

Table 3 Mass balance for melamine process

	Input (ton/year)	Output (ton/year)
Green urea	80,000	
Ammonia	1,600	
Melamine		25,600
Residual Gas (NH_3+CO_2)		56,000

The process requires electricity for heating, pumps, compressors and blowers. Cooling water is also needed. No service steam is demanded.

Main Equipment Sizing. Granulated urea is melted in a vessel with electric heating and fed to the fluidized bed catalytic reactor. Alumina is used as a catalyst, and a mixture of NH_3 and CO_2, with the same composition as the residual process gas, is used as fluidization gas. Since the reaction is endothermic, the reactor must be continuously heated to maintain the desired reaction temperature. The gas leaving the reactor is a mixture of melamine, traces of by-products, and unreacted urea (in the form of its decomposition products: isocyanic acid and NH_3). The rest of the outlet stream consists of NH_3 and CO_2.

Downstream of the reactor, the gas mixture is cooled and filtered, with more than 98% of the melamine crystallizing as fine crystals. The residual gas stream (NH_3 and CO_2 mixture) is sent to an adjacent plant to resynthesize urea. When the residual gas is recycled as urea, approximately 1.5 tons of fresh urea are needed to produce one ton of melamine, which corresponds to a yield of 95%. When this urea recycling is not present, the yield drops significantly, to values below 50%.

Cost Calculation for Equipment and Consumables. The selected case study produces melamine (25,600 tons annually) and a residual gas stream containing NH_3+CO_2 (56,000 tons annually). It requires green urea feed (80,000 tons annually) + green ammonia (1,600 tons annually). The plant consumes electrical energy and cooling water. The estimated total CAPEX is 18.4 million USD.

1.6 CO_2 emissions

1.6.1 Formaldehyde for Resins

The carbon footprint for UF resin production is determined by the CO_2 equivalent of all greenhouse gas (GHG) emissions throughout its life cycle. In this case, the analysis includes emissions within the UFC and resin production process and the emissions from the production processes of its main inputs: methanol and urea.

The conventional UFC/UF resin production process produces 1.6 kg CO_2eq/kg UF. Conventional methanol is produced from natural gas and emits 0.8 kg CO_2eq/kg MeOH. If it is replaced by e-methanol, combining green hydrogen (produced with renewable electricity) with a biogenic carbon dioxide source, then the life cycle emissions have no net climate impact.

Similarly, conventional urea produced from ammonia based on natural gas as a raw material emits 0.73 kg CO_2eq/kg urea. The emission savings corresponding to urea synthesis are subject to the use of green urea as an input.

The emission savings if methanol is replaced by e-methanol is 3,905 tons CO_2eq/year. If both methanol and urea are replaced by e-methanol and e-urea, the emission savings is 5,709 tons CO_2eq/year.

This emission savings represents the equivalent CO_2 emissions of approximately 1,240 cars per year.

It is important to consider that formaldehyde is classified as a probable human carcinogen by the International Agency for Research on Cancer (IARC). Exposure to elevated levels of formaldehyde can have harmful effects on human health. Therefore, precautions and safety measures must be implemented when working with industrial-grade formaldehyde to minimize risks for both workers and the environment.

1.6.2 Melamine

The carbon footprint for melamine production is determined by the CO_2 equivalent of all greenhouse gas (GHG) emissions throughout its life cycle. The green alternatives proposed in this study are based on the same synthesis process currently used but fed with both green ammonia and green urea.

Similar to green ammonia, the conventional alternative is produced from the Haber Bosch process, with the difference that both the nitrogen and hydrogen supplied come from steam methane reforming (SMR). This process emits around 1.8 kg CO_2eq/kg NH_3. Similarly, conventional urea production from ammonia based on natural gas as a raw material emits 0.73 kg CO_2eq/kg urea.

Grey melamine plants, in addition to the reagents, have a natural gas burner for substance heating. In the case of green melamine, this heating could be done using renewable electricity, further reducing emissions compared to the grey alternative.

The emission savings if ammonia is replaced by green ammonia, urea by green urea, and natural gas for heating by renewable electricity is 39,806 tons CO_2eq/year.

This emission savings represents the equivalent CO_2 emissions of approximately 6,500 cars per yea[2]r.

1.7 Economic Analysis

The economic evaluation of the case studies was developed considering the necessary investments to materialize the projects (CAPEX) and the costs required for their operation and maintenance (OPEX). The value of one of the indicators usually employed in project evaluation to measure its competitiveness was estimated: the Levelized Cost of Product X (LCOX), whether it is urea-formaldehyde concentrate (UFC 85) or melamine.

It is important to highlight that the analysis corresponds to the conceptual stage in project development, and economic estimates are preliminary. A deeper analysis is needed to advance with a business case; in particular, precise information regarding potential demand, willingness to pay for low-emission products, and market routes should be gathered.

1.7.1 Formaldehyde for Resins

[2] Este cálculo está basado en las emisiones que produce un auto por año de 4,6 tonCO_{2eq}/año (https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle)

Base Case. To produce UF resin and UFC 85 in the base case, it is assumed the use of green-origin methanol, costing 886.7 USD/ton MeOH, and grey urea, with an estimated cost of 328 USD/ton urea, is considered.

With these considerations, a cost of 932 USD/ton UFC 85 is reached, placing it in the upper range of market prices. 65% of the total cost is attributed to the cost of green methanol, while the cost of grey urea represents 12% (Figure 18).

Performing the same analysis but assuming that urea synthesis is also decarbonized, the relative share of this input increases to 20%. In this case, the cost of methanol remains the most relevant, representing 59% (Figure 19).

The levelized cost of the final UFC 85 product reaches 1,055 USD per ton of UFC 85.

Figure 18 UFC85 costs share, urea cost (fossil) 328 USD/ton

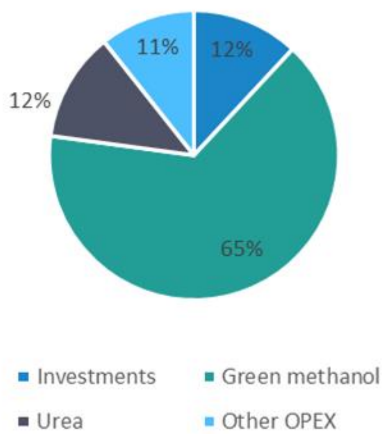
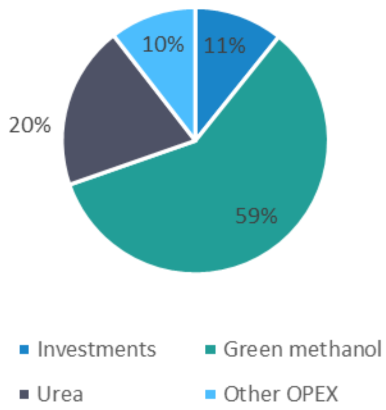


Figure 19 UFC85 costs share, urea cost (green) 590 USD/ton



Source: own elaboration

It should also be noted that, while the case study focuses on the resin and urea-formaldehyde concentrate plants, this process represents the final link in the green hydrogen value chain. It also requires significant upstream investments: in the renewable generation park, in green hydrogen production (electrolyzers), in the CO_2 capture plant, and in the methanol synthesis process, to which the value chain for producing green urea could also be added.

Sensitivity Analysis. To analyze the relationship between the cost of UFC 85 and the costs of its main inputs, methanol and urea, a sensitivity analysis was performed. In this analysis, the cost of methanol was varied between 500 and 1,000 USD per ton, and that of urea between 200 and 800 USD per ton.

The impact of variations in methanol cost on the levelized production cost of UFC 85 is much more significant than variations in urea cost. Indeed, a 100% increase in the levelized cost of urea impacts less than 25% on the cost of UFC 85. On the other hand, a 100% increase in methanol production cost represents an increase of over 60% in the final cost of UFC 85.

The values obtained for the levelized production cost of UFC 85 are presented in Table 4. When the costs of both methanol and urea are higher, in the range of those estimated for e-methanol and e-urea, the levelized cost of UFC 85 is placed in an uncompetitive range compared to current reference market prices for the same grey product. Assuming that UFC 85 is produced with e-methanol combined with grey urea, the levelized production cost estimates suggest it could be within the upper range of international price references for the conventional product.

Table 4 UFC 85 levelized cost: Sensitivity analysis

		Metanol					
		500	600	700	800	900	1000
Urea	200	514	606	699	792	884	977
	300	561	653	746	839	931	1024
	400	608	700	793	886	978	1071
	500	655	747	840	932	1025	1118
	600	702	794	887	979	1072	1165
	700	749	841	934	1026	1119	1212
	800	796	888	981	1073	1166	1259

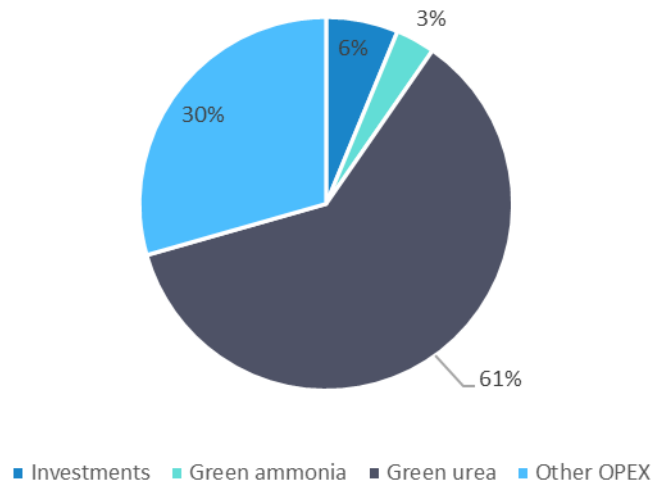
Source: Own elaboration

1.7.2 Melamine

Base Case. For melamine production in the base case, the use of both green-origin ammonia and urea, costing 760 USD/ton NH_3 and 590 USD/ton urea, is considered.

With these considerations, a cost of 1,472 USD/ton melamine is reached, placing it above the range of reference market prices. 61% of the total cost is attributed to the cost of green urea, while the operating cost (OPEX) represents 30%, mainly due to the high consumption of electrical energy (Figure 20).

Figure 20 Melamine costs share



Source: Own elaboration

As in the previous case study, it is noted that the melamine synthesis process represents the final link in the green hydrogen value chain. It also requires significant upstream investments: in the renewable generation park, in green hydrogen production (electrolyzers), in the green ammonia synthesis process, and in the biogenic CO_2 capture process to produce green urea.

Sensitivity Analysis. To analyze the relationship between melamine cost and the costs of its main inputs, urea and ammonia, a sensitivity analysis was performed. In this analysis, the cost of ammonia was varied between 300 and 1,000 USD per ton.

The cost of urea was estimated for each ammonia value. The values obtained for the levelized production cost of melamine are presented in Table 5. For ammonia costs higher than 800 USD/ton, the levelized production cost of green melamine exceeds the international price references for the conventional product.

Table 5 Melamine levelized cost: Sensitivity analysis

Amoníaco	300	400	500	600	700	800	900	1000
Urea	232	309	387	464	541	619	696	773
Melamina	840	977	1114	1251	1387	1524	1661	1797

Source: Own elaboration

1.8 Opportunities and Barriers

In general terms, the analyzed case studies could contribute to developing the route for hydrogen derivatives, such as green methanol and ammonia, in the medium and long term, transforming them into products with additional added value and multiple uses, mainly as additives in various industrial sectors. The analyzed products (urea-formaldehyde concentrate, UF resins, and melamine) can be classified as intermediate chemicals.

The definition of products and their production volumes considered the dimensions of the potential global (Europe) and regional (Argentina, Brazil, and Paraguay) markets, the stability of these compounds, their transportation logistics, and the production capacities of these plants worldwide. For the proposed scales, these plants could boost the export business of methanol for energy uses proposed in the roadmap for Uruguay and contribute to developing the green ammonia route for its use in fertilizers in Uruguay.

The economic analysis carried out at this conceptual stage indicates that the main cost drivers lie in the cost of their main inputs: green methanol, green ammonia, and green urea. The levelized production cost estimates suggest that it is still necessary to reduce the cost of these inputs to achieve parity with international (grey) reference prices, which, on the other hand, are volatile and show significant dispersion.

The penetration of these green products in international markets will critically depend on the willingness to pay of potential buyers.

Table 6 and Table 7 present the main opportunities and barriers identified from the analyses performed.

Table 6 Opportunities

Opportunity/Highlight	UF resins / UFC 85	Melamine
Emphasis on the role of green H2 derivatives in industry	Highlights the role of **green methanol** as a "building block" in the chemical industry	Highlights the role of **green ammonia** as a "building block" in the chemical industry
Temporality / Alignment with national priorities for the development of the green hydrogen route	Resins require the development of the value chain for the production of green methanol from green hydrogen. The project could be developed in the medium term.	Melamine requires the development of the green urea pathway. According to the guidelines of the H2 roadmap; suggests that the project could be developed in the longer term.
Complementarity with methanol as an exportable energy	Part of the expected production of green methanol for energy uses could be derived to develop the value chain from formaldehyde to resins	Not applicable
Complementarity with the development of the green fertilizer route	It is not essential to develop the value chain of green fertilizers (urea). Can be made with imported urea (gray or green in the future) since the processes do not necessarily have to be integrated.	Plants that must necessarily be integrated into the production of green urea to recycle waste gases (NH_3 + CO_2)
GHG Mitigation	0.815 tonCO_{2eq}/ton UFC 85 For the planned production volume, this represents emissions savings equivalent to 1,240 cars/year	1.555 tonCO_{2eq}/ton melamine For the planned production volume, this represents emissions savings equivalent to 6,500 cars/year
Transportation and port logistics	Urea formaldehyde concentrate (UFC) is a transparent and viscous material that contains 60% formaldehyde, 25% urea and 15% water. No difficulties have been identified regarding the danger of storage and transportation.	Melamine is manufactured and sold in the form of crystals. No difficulties have been identified regarding the danger of storage and transportation.
Required investment	6 million USD (7,000 tons per year of UFC 85	16 million USD (25,600 tons per year of melamine)
Income	6.6 MUSD/year	35.8 MUSD/year
Gross operating profits	0.8 MUSD/year	2.2 MUSD/year

Table 7 Barriers

Barrier	UF resins / UFC 85	Melamine
Economic and market	The main challenge is its cost, which depends mainly on the cost of the main inputs: green methanol for the resins/UFC and green urea for melamine. The range of estimated costs suggests that the cost of key green inputs needs to be reduced.	
Willingness to pay of potential offtakers	Routes to market and potential off takers still uncertain. The difficulty in identifying private off takers willing to pay a "green premium" would be a significant barrier.	
Financiamiento	Complex, unless concessional funds are available	
Value chain development	The resin synthesis process represents the final link in the green hydrogen value chain. In addition, it requires important investments upstream: in the renewable generation park, in the production of green hydrogen (electrolyzers), in the CO_2 capture plant and in the methanol synthesis process, to which the supply chain could also be added. value to produce green urea.	The melamine synthesis process represents the final link in the green hydrogen value chain. In addition, it requires significant upstream investments: in the renewable generation park, in the production of green hydrogen (electrolyzers), in the green ammonia synthesis process, and in the biogenic CO_2 capture process to produce green urea.
Stability	While the UFC 85 concentrate can be placed in transoceanic markets (Europe), the UF resin should supply the regional market due to its reduced stability.	Stable
Toxicity	The negative perception of urea-formaldehyde resins could affect demand and use in the industry. Consumers and regulators are looking for safer and more sustainable alternatives. This leads to the development and adoption of resins with lower or formaldehyde-free content.	Not observed
Technology/Value Chain Integration	The case analyzed represents approximately 30% of the volume of methanol that could be produced from the capture of biogenic CO_2 from a medium source, on the order of 0.26	The melamine plant must be built integrated with the green urea production plant.

	Mta of CO_2.	

1.9 Public Policy Recommendations

To promote a sustainable transition to a low-emission economy, it is recommended to:

Foster Framework Agreements with Importing Countries: Alliances and bilateral agreements with importing countries to promote long-term contracts with some price guarantees are crucial for making these projects viable. Use the diplomatic network to promote green hydrogen derivatives in international markets, facilitating negotiations and strengthening trade relations.

Prioritize Applications and Timing: The development of H_2 and its derivatives infrastructure for export requires a commitment to significant investments. Prioritizing applications is very relevant, which to start with, and at what pace to substitute. Although the analyzed case studies are positioned towards the end of the value chain, they can contribute to the diversification of green derivatives, leveraging synergies with methanol uses as energy and ammonia for nitrogen fertilizer production (urea).

Facilitate the Creation of Consortia and Associations: These consortia and associations can provide knowledge in different parts of the value chain and, together with state agencies, facilitate financing, mainly in the early development stages. One of the biggest challenges is the lack of a mature ecosystem of equipment suppliers, technological partners, investors, and buyers who can support decision-making for new investments. For this reason, creating agreements is relevant, which could present a great value-capture opportunity for these actors.

Promote R&D Activities and Human Resource Training: Developing projects for non-energy hydrogen derivatives will require new qualifications to carry them out and new support services that could be supported by universities to train qualified personnel.

Promote a Favorable Regulatory and Policy Environment: Develop and provide clear regulations and incentives for innovation (Uruguay already has programs in this regard where such ventures could be included).

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