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Electricity as an Energy Vector: A Performance Comparison with Hydrogen and Biodiesel in Italy

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Abstract

This study presents a comparative analysis of electricity, hydrogen, and biodiesel as energy vectors, with a focus on powering an aluminum smelter in southern Italy. It evaluates these vectors in terms of efficiency, land requirements for carbon-neutral energy production, and capital expenditure, providing insights throughout the entire supply chain (upstream, midstream, and downstream) into their feasibility for industrial applications. The research reveals that biodiesel, despite being carbon neutral, is impractical due to extensive land requirements and lower efficiency if compared to other vectors. Hydrogen, downstream explored in two forms as thermal power generation and fuel cell technology, shows lower efficiency and higher capital expenditure compared to electricity. Additionally, green hydrogen production's land requirements significantly exceed those of electricity-based systems. Electricity emerges as the most viable option, offering an overall higher efficiency, lower land requirements for its green production, and comparatively lower capital expenditure. The study's findings highlight the importance of a holistic assessment of energy vectors, considering economic, environmental, and practical aspects along the entire energy supply chain, especially in industrial applications where the balance of these factors is crucial for long-term sustainability and feasibility. This comprehensive analysis provides valuable guidance for similar industrial applications, emphasizing the need for a balanced approach in the selection of energy vectors.

Keywords

Electrification, Hydrogen, Energy Efficiency, Renewables, Decarbonization, Electricity

1. Introduction

In November 2023, the concentration of carbon dioxide in Earth's atmosphere reached an unprecedented high of 420.46 ppm, according to NOAA's Mauna Loa Observatory data [1]. This marked a significant increase from the 325-ppm recorded in January 1970. Such a rise is attributed to the excessive exploitation of carbon-based energy sources, accumulated over millions of years of Earth's evolution, disrupting nature's CO_2 equilibrium, where the direct and indirect consequences of this human activity are well-documented [2] [3] [4]: global warming, an increase in respiratory diseases, extreme weather events, coral bleaching, sea-level rise, desertification, and more. This man-made climate change is primarily driven by fossil fuel consumption, which accounts for 81% of global energy consumption and is responsible for 61% of global CO_2 emissions [5].

After years of scientific studies and public awareness campaigns, the international community has generally recognized the magnitude of this disruptive process, prompting governments to adopt strategic roadmaps for total decarbonization. This movement began in 1992 when 165 countries negotiated and signed the United Nations Framework Convention on Climate Change. The agreement was further reinforced by the 1997 Kyoto Protocol, endorsed only by 84 countries, and updated with the 2015 Paris Agreement, signed by 195 countries. These agreements have set common targets and shared responsibilities for a global problem.

In a bid to lead the world's decarbonization process, the European Union (EU) advanced beyond the Paris Agreement, and in December 2019, all 27 EU member states endorsed the European Green Deal. Defined by Ursula von der Leyen [6], President of the European Commission, as "Europe's man on the moon moment and new growth strategy", the deal aims at a first milestone targeting a 55% reduction on carbon emissions (compared to 1990 levels) within the continent by 2030, and the EU carbon-neutrality by 2050. It rests on four main pillars [7]: carbon pricing, sustainable investment, new industrial policy, and the Just Transition Mechanism (JTM). Despite the Covid pandemic, the EU has steadfastly pursued its climate change objectives. The Next Generation EU plan, Europe's Covid recovery strategy, places climate change at the heart of the economic recovery.

At the national level, Italy has developed the Integrated National Plan for Energy and Climate (PNIEC), outlining policies up to 2030 to efficiently meet EU goals. However, these policies require revision to ensure the achievement of the EU Green Deal targets, despite any forecast deviations. The Italian government plans to revise the PNIEC later this year, charting a path to 2030 and setting eco-energy trends up to 2050. This revision will emphasize the shift in the energy mix towards renewable sources (RES), with photovoltaics identified as a key technology due to its high development potential, driven by Italy's high levels of irradiation and the increasingly competitive cost of solar power.

This research embarks on an exploratory journey to unravel the complexities and potential of different energy vectors in the context of industrial application. It stands out in the realm of renewable energy research due to its unique approach, being the first study of its kind to compare electricity, hydrogen, and biodiesel in terms of efficiency, land size requirements, and capital expenditure (CapEx) for powering an aluminum smelter. The originality of this research lies in its comprehensive comparative analysis, which delves deep into the practicalities of implementing these energy carriers in a real-world industrial setting. Evaluating each energy vector across multiple critical parameters, the study provides a holistic understanding of their operational implications, a perspective that has been unexplored in existing literature. The practical application of this study to an aluminum smelter not only enhances its relevance but also paves the way for scalability in other industrial domains. This approach marks a significant stride in bridging the gap between theoretical energy models and the dynamic requirements of industrial energy systems, thereby contributing valuable insights to the field of renewable energy research.

The Role of Electricity as Main Vector for Carbon-Neutrality

As stated, the EU aspires to lead the global energy transformation, transitioning from a brown economy (based on environmental disruptive activities) to a circular and green one. In alignment with this vision, Italy is undergoing a significant energy transformation. The PNIEC outlines the guidelines to achieve the EU's energy targets, promoting decarbonization on both the supply and demand sides. A key element in all future energy scenarios is the emergence of electricity as the dominant energy carrier, with the European electricity grid envisioned as the backbone of the decarbonization process across all energy sectors. Electricity is a fundamental component of a climate-neutral energy system, owing to the maturity of renewable technologies such as wind and solar, and the inherent efficiency advantages of electric power. As seen in Figure 1, currently, renewables account for 40.7% of the total electricity demand in the EU-28, but only 22.5% of the total energy demand [8]. This disparity implies that, as of today, electricity is a greener option compared to liquid or gaseous energy carriers.

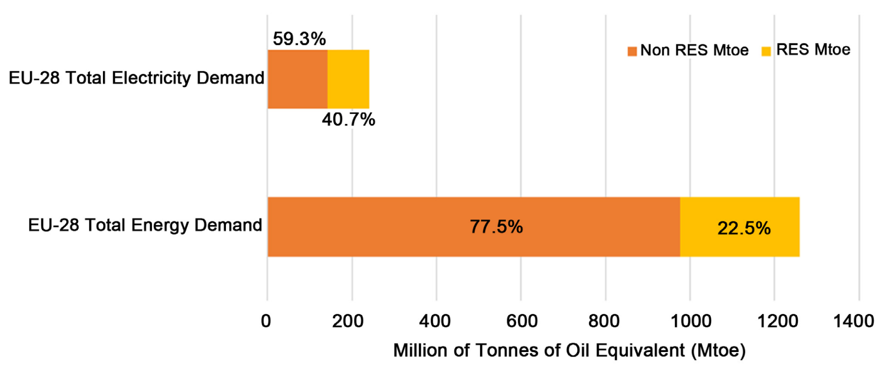

Figure 1. RES production incidence on EU-28 total electricity and total energy demand [8].

To maximize the decarbonization potential of electricity, it is important to increase its share relative to other energy carriers. This shift, commonly referred to as electrification, is not just about replacing one energy source with another, it's a strategic move towards reducing primary energy consumption and enhancing overall energy efficiency. Achieving long-term decarbonization goals hinges on this efficiency, integral to a holistic energy system. However, a deeper dive into the quest for carbon neutrality reveals more complex considerations. It's crucial to account for the carbon footprint of every component involved in the energy system, from the manufacturing of wind turbine rotors that produce clean electricity to the cables linking the grid and the computers orchestrating operations. These elements, often overlooked, play a significant role in the overall carbon equation. In a circular economy, such details cannot be ignored, as they substantially influence the net carbon impact. Therefore, the selection of an energy carrier is a decision with far-reaching implications. It's not just about the immediate emissions but also about the lifecycle carbon footprint of the entire system. This choice becomes a defining factor in the equation of total greenhouse gas emissions, underlining the need for a comprehensive and nuanced approach to achieving true carbon neutrality.

2. Methods

To gain a comprehensive understanding of the benefits and challenges associated with the electrification process, it is crucial to compare the characteristics and behaviors of electricity as an energy vector with other energy carriers. Our analysis will focus on a real project proposed by a multinational consortium of companies (whose name is withheld for privacy reasons) to be developed in Southern Italy. This project will serve as a case study to compare and evaluate the advantages and disadvantages of three primary green energy carriers: biofuels (specifically biodiesel), green hydrogen (via Power-To-Gas technology), and electricity (as an energy vector). It will provide a theoretical resolution and a performance evaluation of these vectors in a real-life scenario. The comparison will be based on three key parameters: the land area required for producing sufficient power using renewable energy sources (RES), the efficiency of the energy supply chain, and the initial capital expenditure (CapEx) requirements. To ensure an unbiased initial comparison, external factors such as existing infrastructures will not be initially considered. Therefore, it will be designed a standalone greenfield project where all external variables, both dependent and independent, are equalized for each energy carrier. This methodology will provide unbiased comparative data, facilitating a direct and more effective comparison.

Expanding on this foundation, the choice of an aluminum smelter as the focal point of our study is predicated on its status as one of the most energy-intensive industries. Aluminum smelting is a process that requires significant amounts of electrical energy to produce aluminum from alumina, making it an ideal candidate for assessing the impact of different energy vectors on industrial energy consumption. The high energy demand of aluminum smelters makes them highly sensitive to the efficiency, cost, and environmental impact of the energy sources they utilize. This sensitivity renders them perfect models for evaluating the feasibility and performance of biofuels, green hydrogen, and electricity in industrial applications. Furthermore, the selection of an aluminum smelter aligns with our objective to analyze energy vectors in a context where their differences in efficiency, sustainability, and economic viability are magnified. By examining an industry where energy is a critical input, we can more accurately assess the potential of each energy carrier to meet high-demand energy requirements while minimizing environmental impact and optimizing cost-effectiveness.

To ensure the robustness of our comparative analysis, we will employ a mixed-methods approach, combining quantitative data analysis with qualitative assessments of each energy vector's strategic implications for Italy's energy landscape. In conclusion, the choice of an aluminum smelter as a model for this study is not only appropriate but strategic, given its high energy consumption and the industry's relevance to Italy's economic and environmental landscape. This approach will allow for a detailed and nuanced comparison of biodiesel, green hydrogen, and electricity as energy vectors, providing valuable insights into their respective roles in supporting sustainable industrial processes.

2.1. The Project

An internationally recognized consortium plans to construct a 96 Ton/day aluminum smelter in Southern Italy, referred to as "the project". The electricity requirement for producing such a volume of aluminum is approximately 60 MW, based on an average consumption of 15 kWh/kg of aluminum [9], translating to 216 GJ. The consortium, committed to sustainability, mandates the exclusive use of renewable energy sources for their operations. Accordingly, they have identified a potential site for a RES plant, located 200 km from the factory. This site offers ample water resources, high solar irradiation (though limited wind potential), and requires minimal land modification.

Given the government's expectation for the consortium to secure land sufficient to power the smelter and considering the distance between the land and the smelter site, the consortium faces a crucial decision: they need to select an energy carrier that will minimizes their carbon footprint and aligns with economic viability. To this end, they have shortlisted three primary energy carriers for a comparative study: green hydrogen, biodiesel, and electricity. Each of these carriers will be evaluated based on their ability to meet the energy demands of the smelter efficiently and sustainably, considering the specific conditions and constraints of the project site (**Figure 2**).

2.2. Theoretical Resolution

To effectively deliver the necessary power, the energy supply chain must encompass three key stages: production (upstream), transportation and storage

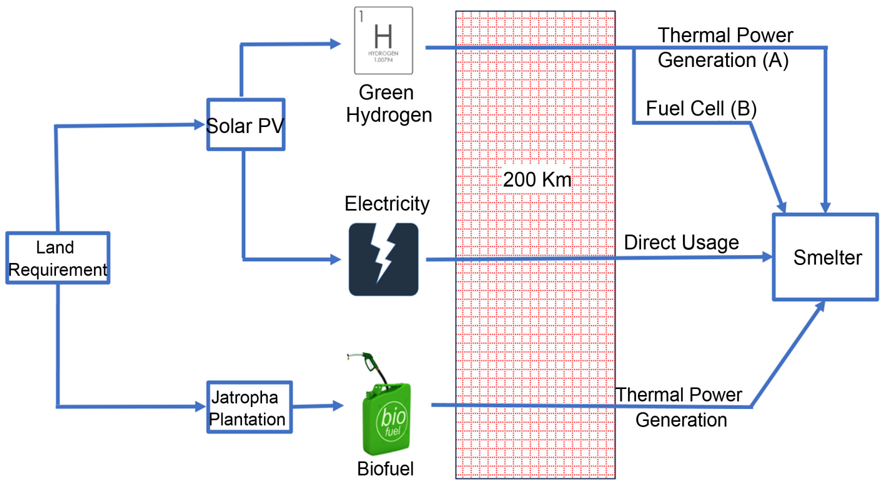

Figure 2. Visual representation of the theoretical framework.

(midstream), and delivery (downstream). Considering the inherent efficiency losses in the chain, the total energy production requirements and the system efficiency will be calculated using a backward principle, starting from the known downstream consumption at the factory, which is 60 MW, and running the needed calculations moving upward through the energy supply chain. The comparison of the three energy carriers (green hydrogen, biodiesel, and electricity) will be based on the following parameters:

1) Land Size Requirements: This parameter assesses the land area necessary for the project to develop its Renewable Energy System (RES) capable of generating sufficient energy to power the smelter.

2) System Efficiency: This includes both the total efficiency of the system (from production to delivery) and the partial efficiencies at each stage of the energy supply chain.

3) Initial Investment Requirements (CapEx): This involves calculating the initial costs required to construct the system that will produce and transport the energy to the smelter. The CapEx will be evaluated for each stage of the energy supply chain (upstream, midstream, and downstream) as well as the total investment needed.

These parameters will provide a comprehensive basis for comparing the feasibility and effectiveness of each energy carrier in the context of the project. The analysis aims to identify the best value-for money option for powering the aluminum smelter, aligning with the consortium's commitment to using renewable energy sources.

2.3. Greenfield Standalone Project

A detailed analysis of each energy carrier is required to assess their viability based on the three identified parameters: land size requirements, system efficiency, and initial investment (CapEx). Each energy carrier will be evaluated independently to ensure a thorough and unbiased comparison. This approach will provide a clear understanding of the practicality, sustainability, and economic feasibility of each option in the context of powering the aluminum smelter with an environmentally friendly energy.

2.3.1. Hydrogen

The biggest advantage of this gaseous element consists in having the highest energy density values per mass of all energy carriers (142 MJ/kg) [10] [11]. Applying the backward approach (downstream first), we need to calculate the quantity per hour of hydrogen required to power the facility. Once hydrogen arrives to the facility it needs to be converted into electrical power as per requirement, which can be done using two technologies: thermal power generation and fuel cell technology.

1) Downstream:

a) Thermal Power Generation (Option A)—Hydrogen: This option explores the use of hydrogen's thermal properties to generate heat, which in turn spins a turbine to produce electricity. Significant advancements have been made in this field by various Original Equipment Manufacturers (OEMs). A notable development is General Electric's announcement in 2018 of a combined cycle gas turbine, the 9 HA, with a reported efficiency rate of 64%. This turbine is designed to potentially operate on 100% hydrogen. While the simple cycle 9 HA turbine exhibits an efficiency of 43%, it reaches 64% in a combined cycle (gas + steam cycles). The decision to benchmark with the combined cycle 9 HA turbine is driven by the desire to utilize the most advanced technology available in the market, thereby maximizing efficiency. However, it's important to note that even with the 9 HA turbine's efficiency rate, approximately 36% of the total energy stored in hydrogen is lost in the conversion process. Thus, to obtain 216 GJ of electrical energy (as per request), our system would need to consume (chemical energy):

$$216\ \text{GJ}/64\% = 337.5\ \text{GJ}$$

In order to calculate the amount of hydrogen required to produce 337.5 GJ each hour with General Electric technology, we have to divide it by hydrogen energy density, equivalent to 142 MJ/kg (0.142 GJ/kg). Consequently, the system would need to be fed with:

$$337.5\ \text{GJ}/0.142\ \text{GJ/kg} = 2{,}377\ \text{kg} \quad \text{(hydrogen per hour)}$$

Once we found the needed amount of hydrogen to power our turbine, we need to calculate the price it will cost to build it. Combined gas turbines are built today at an average price of 972 €/kW [12], thus, building a 60 MW (60,000 kW) power plant would have an initial cost of about:

$$972\ \text{kW} \times 60{,}000\ \text{kW} = 58.3\ \text{M€}$$

b) Fuel Cell Technology (Option B)—Hydrogen: Another avenue for harnessing hydrogen's energy potential is through fuel cell technology, which has seen significant advancements in recent years. Fuel cells convert chemical energy directly into electricity, with heat as the only byproduct. This technology, which has achieved efficiency rates of up to 60% [13], represents a promising alternative for energy conversion. Fuel cells have been implemented in various applications, including some vehicles like the Hyundai Tucson, Toyota Mirai, and Honda Clarity. However, despite its high efficiency, the technology has faced challenges in widespread adoption in the transportation sector. Applying this technology to our project, we need to calculate the amount of hydrogen required to produce the necessary 216 GJ of electrical energy for the smelter, considering the 60% efficiency rate of fuel cells. To determine this, we will calculate the total chemical energy needed by the fuel cells to generate the required electricity considering the efficiency rate of 60%:

$$216\ \text{GJ}/60\% = 360\ \text{GJ}$$

Consequently, the fuel cell would need to be fed with:

$$360\ \text{GJ}/0.142\ \text{GJ/kg} = 2,535\ \text{kg} \quad \text{(hydrogen per hour)}$$

In terms of capital cost (or initial investment) for fuel cells, technology has been showing a downward trend in recent years. From an average of 7,150 € per kW in 2016 [14], the cost has decreased to approximately 5,541 € per kW as of the latest data [15]. Despite its high efficiency, fuel cell technology is currently not as economically competitive as other technologies, such as gas turbines. The pricing of fuel cells is influenced by various factors, including geographical location, the market price of electrodes (which is notably volatile), and economies of scale expected with increased production. Consequently, considering an average cost of 5,541 €/kW, the CapEx to build a 60 MW fuel cell power plant would be approximately:

$$5,541\ \text{€/kW} \times 60\ \text{MW} = 332.6\ \text{M€}$$

This calculation will yield the total initial investment required for establishing a fuel cell system capable of meeting the smelter's energy demands. It's important to note that while the upfront costs are significant, the long-term benefits and efficiency gains of fuel cell technology may offset these initial expenses. Additionally, the potential for future cost reductions as the technology matures and scales up should be considered in the economic analysis.

Deciding which technology to use is both an economic and an efficiency decision, as it is necessary to understand how long the system will take to compensate for the initial investment difference between the two technologies.

2) Midstream

Moving up into the midstream, to feed the power plant, the system will need to transport 2,377 kg/hour of hydrogen for option A, or 2,535 kg/hour for option B, traveling 200 km from its production site. Even though, as stated, hydrogen has the highest energy density values per mass, we also stated that it is the lightest element of all. Therefore, on a volumetric scale, the situation is reversed (8 MJ/Liter in its liquid form), having its energy values per liter much lower than those of other elements [16] (**Table 1**).

Table 1. Energy per liter.

Energy carrier	Energy per liter
Hydrogen (liquid form)	8 MJ/Lt
Gasoline	35.2 MJ/Lt
Diesel	37.3 MJ/Lt

A hydrogen pipeline remains the most efficient method to transport the gas to consumers [17] and would be the preferred option for the project. However, pumping hydrogen presents unique challenges due to its low density and its tendency to permeate through most common metallic compounds [17]. As a result, a hydrogen pipeline must adhere to different standards compared to conventional gas pipelines, leading to increased capital expenditure (CapEx). For comparison, constructing a 20-inch diameter natural gas pipeline costs, on average, €1.85 million per kilometer, whereas a hydrogen pipeline of the same diameter averages €2.12 million per kilometer [18]. Therefore, the CapEx for constructing a 200 km pipeline for the project (where a 20-inch diameter would be adequate for both Option A and B) would be approximately:

$$2.12\ \text{M€/km} \times 200\ \text{km} = 424\ \text{M€}$$

For this section of the project, the energy consumption required to operate the pipeline will be disregarded, as it has a minimal impact on both the economics and the overall efficiency.

3) Upstream

Preamble: before digging into PV calculations, it's important to note the variability in recoverable sunlight across seasons: during winter, the average recoverable sunlight is lower than in summer, potentially necessitating an auxiliary source of electrical power to meet production requirements. Conversely, in summer, the recoverable sunlight hours exceed the average. To address this problem, the company plans to negotiate an arrangement with the local power distributor based on the annual average recoverable sunlight. The proposed arrangement entails the redistribution of surplus electricity produced during the summer months to the local power distributor, followed by the repurchase of electricity in the winter to address the deficit. This method is designed to achieve an equilibrium in energy supply across all seasons, obviating the necessity for large-scale hydrogen storage solutions. Furthermore, it fosters a carbon-neutral operation by ensuring that the quantity of renewable energy sold to the power distributor is equivalent to the quantity repurchased later in the year. This equivalence is maintained regardless of the carbon intensity of the production methods used for the electricity bought back. Hence, the renewable energy contributed to the local grid effectively offsets the carbon footprint of the energy consumed, even if the latter is generated through carbon-intensive processes.

In the upstream phase, it is necessary to size the production site to produce 2,377 kg of hydrogen per hour for Option A, or 2,535 kg per hour for Option B.

Given the lack of consistent winds and the presence of suitable solar irradiation levels at the chosen site, hydrogen will be produced using solar photovoltaics (PV). In some instances, solar PV fields allocate a portion of their power to green hydrogen production while feeding the remaining energy into the grid, thereby reducing the levelized cost of hydrogen (LCOH). Calculating the initial investment (CapEx) for such a plant is challenging due to the limited number of existing examples worldwide. However, it is known that the major components of CapEx in building a green hydrogen plant are the solar panels and the electrolyzers.

For optimal economics, the PV panels should be directly coupled with the electrolyzers [19], treating the solar PV field and the hydrogen production plant as a single integrated system. Therefore, an average price will be estimated by summing the initial costs of a solar PV field (sized to produce sufficient energy for the hydrogen plant) and the cost of the electrolyzers used in the plant. The process of converting electricity to hydrogen is approximately 65% efficient [20], with an electrical consumption of 48.95 kWh/kg [21].

Regarding electrolyzers, both PEM (Proton Exchange Membrane) and alkaline types are commonly used in the electrolysis process. However, PEM electrolyzers are 50% to 60% more expensive than alkaline ones, despite offering similar performance [20], and will therefore be excluded from this analysis. Calculating the cost of an alkaline electrolyzer is complex due to the highly volatile market prices, which range from a minimum of 415 € per kW to a maximum of 830 € per kW [20].

Given an annual average of 1,500 hours of recoverable sunlight, which equates to about 4.1 hours per day [22], the plant needs to generate sufficient hydrogen during these hours to sustain the smelter continuously for 24 hours. This necessitates producing hydrogen at a rate 5.85 times higher in the 4.1-hour window to meet the daily system requirements. Additionally, to ensure both a consistent output flow and a supply buffer for routine and unexpected maintenance, a storage facility capable of holding a 24-hour supply will be constructed and integrated with the system.

To determine the appropriate size for the storage facility, it's necessary to calculate the volume of hydrogen required to fill the tanks:

a) Option A—tanks shall be loaded with 2,377 kg of hydrogen to sustain a 24 h cycle, having a total of:

$$2,377 \text{ kg} \times 24 = 57,048 \text{ kg}$$

b) Option B—with this option, tanks shall be loaded with 2,535 kg of hydrogen to sustain a 24 h cycle, having a total of:

$$2,535 \text{ kg} \times 24 = 60,840 \text{ kg}$$

In terms of costs, hydrogen tanks are very expensive due to its physical properties [23]. Moreover, high investment costs are associated with high-pressure gas tanks for compressed gaseous hydrogen storage, along with specific requirements for these tanks, especially in high-pressure storage scenarios. Additionally, even in low-pressure storage applications, the capital investment for storing 1 kg of hydrogen is around 780 €, underscoring the substantial investment necessary for hydrogen storage infrastructure, regardless of the pressure level [24]. Thus, this leads to the storage CapEx of:

a) Option A:

$$57,048\ \text{kg} \times 780\ €/\text{kg} = 44.5\ \text{M€}$$

b) Option B:

$$60,840\ \text{kg} \times 780\ €/\text{kg} = 47.5\ \text{M€}$$

Next, the PV site shall be designed. Considering a CapEx for solar PV of 690 €/kW (690,000 €/MW) [25], and with an average alkaline electrolyte price of 600 €/kW (600,000 €/MW):

a) Option A—to feedstock 2,377 kg of hydrogen per hour on a 24-hour cycle, the system shall produce approximately 13,914 kg of hydrogen every hour for 4.1 hours (recoverable sunlight), where the solar PV panels shall have to produce (calculated at 48.95 kWh/Kg):

$$\left(13,914\ \text{kg/h} \times 48.95\ \text{kW} \cdot \text{h/kg}\right)/1,000 = 681.1\ \text{MW}$$

The solar PV initial investment required is equal to:

$$681.1\ \text{MW} \times 690,000\ €/\text{MW} = 470\ \text{M€}$$

The alkaline electrolytes initial investment required is equal to:

$$681.1\ \text{MW} \times 600,000\ €/\text{MW} = 408.7\ \text{M€}$$

Total CapEx:

$$470\ \text{M€}(\text{solar PV}) + 408.7\ \text{M€}(\text{electrolytes}) + 44.5\ \text{M€}(\text{storage}) = 923.2\ \text{M€}$$

Land required is approximately 681 hectares (rule of thumb of 1 hectare per MW calculated on 4.1 hours recoverable sunlight).

b) Option B—to feedstock 2,535 kg of hydrogen per hour on a 24-hour cycle, the system shall produce 14,839 kg of hydrogen every hour for 4.1 hours (recoverable sunlight), where the solar PV panels shall have to produce (calculated at 48.95 kWh/Kg):

$$\left(14,839\ \text{kg/h} \times 48.95\ \text{kW} \cdot \text{h/kg}\right)/1,000 = 726.4\ \text{MW}$$

The solar PV initial investment required is equal to:

$$726.4\ \text{MW} \times 690,000\ €/\text{MW} = 501.2\ \text{M€}$$

The alkaline electrolytes initial investment required is equal to:

$$726.4\ \text{MW} \times 600,000\ €/\text{MW} = 435.8\ \text{M€}$$

Total CapEx:

$$501.2\ \text{M€}(\text{solar PV}) + 435.8\ \text{M€}(\text{electrolytes}) + 47.5\ \text{M€}(\text{storage}) = 984.5\ \text{M€}$$

Land required approximately 726 hectares (rule of thumb of 1 hectare per MW calculated on 4.1 hours sunlight).

Finally, calculating the overall system efficiency for both Option A and Option B is imperative. Assessing the efficiency of these systems is crucial due to its significant impact on financial considerations and renewable energy source (RES) requirements. The efficiency calculation is straightforward: we compare the amount of energy produced against the amount of energy consumed. This comparison allows us to determine the final total efficiency of the energy supply chain (Table 2):

1) Option A:

a) Energy produced – 349.1 MWh/3 (on a 24 h cycle) = 116.4 MW/h (116.4 MWh = 419.04 GJ)

b) Energy consumed – 216 GJ

c) Total efficiency – (216 GJ/419.04 GJ) × 100 = 51.54%

2) Option B:

a) Energy produced – 372.3 MWh/3 (on a 24 h cycle) = 124.1 MW/h (124.1 MWh = 446.76 GJ)

b) Energy consumed – 216 GJ

c) Total efficiency – (216 GJ/419.04 GJ) × 100 = 48.35%

2.3.2. Biodiesel

Biodiesel, a member of the biomass family, is a renewable energy source often mired in controversy due to concerns that its feedstock could endanger biodiversity [26]. However, its lifecycle is generally considered to maintain a natural CO_2 balance. The process involves converting the chemical energy stored in carbon-based materials (such as plants and food waste) into a usable form of energy. This conversion requires extensive arable land, significant irrigation systems, and specific incentive policies, making it unsuitable for certain locations. According to the Biomass Energy Resource Center [27], the efficiency of the biomass supply chain, from production to final electricity conversion, ranges between 20% and 25%. This efficiency is relatively low compared to other green energy sources.

1) Downstream:

In terms of downstream efficiency, biodiesel generators perform comparably to gas turbine generators. An ultra-supercritical plant, for instance, has an efficiency rate of about 44% [28]. Therefore, to generate 216 GJ of electrical energy, our biodiesel-based system would need to consume approximately the following amount of chemical energy:

Table 2. Hydrogen as an energy carrier in standalone project.

Option	Land requirement ha	System efficiency %	CapEx downstream M€	CapEx midstream M€	CapEx upstream M€	Total CapEx M€
A	681	51.54	58.3	424	923.2	**1,405.5**
B	726	48.35	332.6	424	984.5	**1,721.1**

$$216\ \text{GJ}/44\% = 490\ \text{GJ}$$

Having on average (according to the source of the fuel) an energy density per liter (not per kg) of 34 MJ/Lt (0.034 GJ/Lt), the generator will consume a total amount of:

$$490\ \text{GJ}/0.034\ \text{GJ}/\text{Lt} = 14,412\ \text{Lt} \quad \text{(biodiesel per hour)}$$

In terms of initial investment, this type of power generator has among the lowest CapEx, with an average cost of 660 €/kW (660,000 €/MW) [29]. To build the 60 MW generator needed for the project, the CapEx required would be around:

$$60\ \text{MW} \times 660,000\ €/\text{MW} = 39\ \text{M€}$$

2) Midstream:

Moving into midstream, a 24-inch pipeline for liquid fuels such as oil, diesel or biodiesel has an average CapEx of 3.03 M€/Km, higher than other gas pipelines due to its viscosity [18]. The total investment for the 200 Km pipeline needed for the project would be around:

$$3.03\ \text{M€}/\text{Km} \times 200\ \text{Km} = 606\ \text{M€}$$

3) Upstream:

In the upstream analysis, biodiesel can be derived from various vegetable oils, including melon, palm, soybean, sugarcane, and jatropha. Jatropha oil has emerged as a prime candidate for biodiesel production [30]. Its advantage lies in being a non-edible plant, thereby avoiding competition with human or animal food sources. This makes it a suitable choice for the project's plantation. Jatropha seeds, after three years of growth, yield oil ranging from 2.5 to 12 tons per hectare (ha) under irrigation [30]. Considering the biodiesel generator's consumption rate of 14,412 liters per hour, this translates to 345,888 liters per day and 126,249,120 liters annually. Given that biodiesel has a density of 0.87 kg/L, the annual consumption in terms of weight would be approximately:

$$(126,249,120\ \text{Lt}/\text{year} \times 0.87\ \text{kg}/\text{Lt})/1,000 = 109,837\ \text{ton}/\text{year}$$

To provide such quantities on a 10 ton/ha oil yield projection per year (based on an average of irrigated plantations), there will be a land requirement of:

$$109,837\ \text{ton}/10\ \text{ton}/\text{ha} = 10,983.7\ \text{ha}$$

The amount of land required for biodiesel production is prohibitively large and costly by European standards. Consequently, it would necessitate importing biodiesel, which would significantly increase the operational costs of the power generator and, by extension, the entire aluminum smelter. This could lead to considerations of relocating the project elsewhere or the necessity for government subsidies to offset the increased expenses. Consequently, there is no need to account for storage, as production in infeasible for European standards of land requirements (**Table 3**).

2.3.3. Electricity as Energy Vector

One key advantage of utilizing electricity as the energy vector for the smelter

Table 3. Biodiesel as an energy carrier in standalone project.

Land requirement ha	System efficiency %	CapEx downstream M€	CapEx midstream M€	CapEx upstream M€	Total CapEx M€
10,983.7	20 - 25	39	660	Not applicable	Not applicable

factory is the elimination of energy conversion losses in the supply chain process. Since the aluminum production process inherently requires electricity, this direct use of energy avoids the inefficiencies typically associated with energy conversion (except for any losses during electricity storage in the upstream process). Furthermore, bypassing the need for energy storage and conversion in downstream significantly reduces the overall capital expenditure and eliminates operational expenses related to storage, as the electricity is used directly. The primary downstream investment involves connecting the smelter to the transmission line (midstream), requiring setting up a 150 kV station with a high tension/medium tension (HT/MT) transformer and a connection line. In Italy, the average connection distance is about 5 km [31]. In practical scenarios, it's likely that such a station would already be in proximity to the grid, as systems are often designed with the foresight of energy demand. However, for the sake of uniform initial variables across all energy carriers, we will include the cost of constructing the station and the 5 km connection line in our downstream calculations. This is done with the understanding that in real-life scenarios, these facilities might not be necessary.

1) Downstream:

Based on Terna's average costs [31], the connection to the main transmission line can be calculated as the sum of the average cost of the 150 kV station, the average cost of the HT/MT transformer, and the average cost to construct a 5 km connection line (1 million euros per km):

$$3.5\ \text{M€} + 1.5\ \text{M€} + 5\ \text{M€} = 10\ \text{M€}$$

2) Midstream:

Moving into midstream, we incur in a physics' limitation when transporting electricity, explained by Ohm's law (please refer to Ohm's law literature for further knowledge). In essence, increasing the resistance in a transmission medium (such as a cable), while maintaining constant voltage, inevitably leads to a loss of current, primarily through heat dissipation. Since resistance is directly proportional to the cable's length, extending the transportation distance increases the cable's length and resistance, thereby reducing the current. To optimize electricity transportation, it's necessary to increase the voltage, reduce the current, and select the appropriate cable size and material for high conductivity. Fortunately, Ohm's law does not significantly affect the overall efficiency of transmission lines, which is estimated to be between 2% and 6% in the overall system [32]. Assuming an average energy loss of 4% over our 200 km transmission, the upstream production site must generate approximately 62.4 MWh of energy (60 MWh multiplied by 1.04) to compensate.

However, constructing a transmission line solely for 62.4 MW of power may not be practical, as the electricity grid typically extends across the region in a comprehensive manner. Yet, for the purposes of a fair economic comparison, we will include the cost of a transmission line in our analysis, while acknowledging that in a real-world scenario, an existing grid would likely be utilized. According to Terna's data, the average cost to build a high-voltage transmission line is around 1 million euros per kilometer. Therefore, for a 200 km distance, the construction cost would amount to approximately 200 million euros, which represents the total midstream CapEx for this project.

3) Upstream:

Preamble: Like hydrogen production, it's crucial to consider the seasonal variability in sunlight for PV calculations. As stated, winter has lower average recoverable sunlight, possibly requiring additional electrical power, while summer has an excess. To manage this, the company intends to negotiate with the local power distributor, selling excess summer power and buying back in winter to balance the annual average. As previously explained, this approach aims to ensure a consistent year-round energy supply, reducing the need for extensive hydrogen storage, and yet keeping a carbon-neutral process balanced throughout the year.

It has been estimated that to generate 62.4 MWh of energy using solar PV over a 24-hour cycle in the region, the plant needs to be designed to capitalize on an average of 4.1 hours of daily recoverable sunlight. This means it must produce sufficient energy during these 4.1 hours to both store and distribute it across the remaining 19.9 hours, ensuring a steady supply of 62.4 MW every hour. As a result, the plant requires an electrical energy storage (EES) system capable of storing enough energy to power the smelter throughout the entire day. While a storage system with a capacity for 19.9 hours would meet the basic requirements, it's important to also consider the needs for both routine and unexpected maintenance. Therefore, the system will be designed to ensure 24-hour autonomy.

In choosing the most suitable EES technology, it's essential to consider the specific requirements of the system:

- Storing time within 24 hours
- Maximum power handled under 100 MW
- Roundtrip efficiency higher as possible
- Initial investment lower as possible
- Operational costs lower as possible

This criterion rules out certain technologies such as PHS (Pumped Hydro Storage), which is economically viable for power generation over 100 MW, AA-CAES (Advanced Adiabatic Compressed Air Energy Storage), where the absence of natural cave formations would significantly increase costs, and FESS (Flywheel Energy Storage Systems), typically used for power roundtrips within a few hours. Emerging options like ammonia and stacked blocks are still under research and won't be considered. This leads us to battery technology. Within the vast array of battery options, making the right choice can be challenging. Considering factors like low capital expenditure (CapEx), low operational expenditure (OpEx), scalability, and high safety standards, a Vanadium Redox Flow Battery (VRFB) emerges as a potential candidate.

Remembering that VRFB have the characteristics of energy and power separation, to size and calculate the costs of this battery there's the need to calculate how much power and energy will be required separately:

- **Power:**

  In terms of power output, the VRFB will need to discharge 62.4 MW.

- **Energy:**

  In terms of energy storage, the VRFB will need to be able to store enough energy to discharge 62.4 MW for 24 hours into the grid, meaning 1498 MWh in total.

The VRFB needs to be sized 62.4 MW/1498 MWh.

The EES costs are directly proportional to the power output required by the system, and the amount of energy to be stored (the amount of power to be released over time). On average, power will contribute 61% on the total costs of the battery, where energy 39% [33]. For power output the average cost is approximately 690 €/kW (690,000 €/MW) [25] [34], while for energy is 441 €/kWh (441,000 €/MWh). Consequently, the total approximated costs for the VRFB battery will be:

$$(62.4\ \text{MW} \times 690{,}000\ €/\text{MW}) + (1{,}498\ \text{MW}\cdot\text{h} \times 441{,}000\ €/\text{MW}\cdot\text{h}) = 703.7\ \text{M€}$$

Subsequently, we must determine the amount of energy that the solar PV plant should inject into the battery during production, considering the battery's roundtrip efficiency. The roundtrip efficiency of the Vanadium Redox Flow Battery (VRFB) is estimated to be between 75% and 85% [35] [36]. Using an average efficiency of 80% for this project, the total energy required to be injected by the solar PV plant is calculated as follows:

$$62.4\ \text{MW}\cdot\text{h}/80\% = 78\ \text{MW}\cdot\text{h}$$

This means that for every 78 MW charged onto the VRFB, the battery will release 62.4 MW. Knowing that the plant can only produce within 4.1 hours a day, the EES must be sized to accumulate energy in 4.1 h to be released in 19.9 h, providing 78 MW each hour in discharge. Consequently, each hour the plant will need to charge the VRFB with:

$$(78\ \text{MW} \times 19.9\ \text{h})/4.1\ \text{h} = 378.6\ \text{MW}$$

To complete production under the energy compensation base, the solar PV plant will have to produce another 78 MW of power each hour for 4.1 hours to close the 24-hour cycle. To conclude, the total amount of energy to be produced by the solar PV plant is the sum of the energy stored in the VRFB plus the energy needs during production time (4.1 hours) of recoverable sunlight:

$$78\ \text{MW} + 378.6\ \text{MW} = 456.6\ \text{MW} \quad \text{each hour}$$

Based on these values, the solar PV plant initial investment required will be equal to:

$$456.6\ \text{MW} \times 690{,}000\ €/\text{MW} = 315.1\ \text{M€}$$

To this, we need to add another 150 kV station with an HT/MT transformer, and a 5 Km connection line as per downstream, to connect the solar PV plant to the main transmission line (midstream). As stated before, this cost is equivalent to 10 M€.

The total upstream CapEx will be the sum of the cost of the VRFB + the cost of the solar PV plant + plus the connection line:

$$703.7\ \text{M€} + 315.1\ \text{M€} + 10\ \text{M€} = 1{,}028.8\ \text{M€}$$

The total land size required to produce 456.6 MW will be approximately 456 hectares (rule of thumb) (Table 4).

In terms of total efficiency, the project must produce 78 MW each hour, equivalent to 280.8 GJ, while consuming 216 GJ at the smelter. Thus, the total efficiency rate is:

$$\text{Total efficiency} - \left(216\ \text{GJ}/280.8\ \text{GJ}\right) \times 100 = 76.92\%$$

To conclude this analysis, Table 5 and Table 6 resume and put in comparison all three scenarios:

The next section provides a final analysis on the comparative assessment of biodiesel, hydrogen, and electricity as energy vectors for the aluminum smelter project.

Table 4. Biodiesel as an energy carrier in standalone project.

Land requirement ha	System efficiency %	CapEx downstream M€	CapEx midstream M€	CapEx upstream M€	Total CapEx M€
456	76.9	10	200	1,028.8	1,238.8

Table 5. Energy carriers in comparison in standalone project.

Energy carrier	*Land requirement ha	*System efficiency %	*CapEx downstream M€	*CapEx midstream M€	*CapEx upstream M€	*Total CapEx M€
H2 - A	681	51	58.3	424	923.2	1,405.5
H2 - B	726	48	333.6	424	984.5	1,721.1
Biodiesel	10,984	23	39	660	N.A.	N.A.
Electricity	456	77	10	200	1,028.8	1,238.8

*Numbers are approximated by defect.

Table 6. Hydrogen and biodiesel comparison with electricity as an energy vector in greenfield project.

Comparison with electricity as energy vector	Land requirement	Efficiency	CapEx
H2 - A	+49.3%	−33.8%	+13.5%
H2 - B	+58.9%	−37.7%	+38.9%
Biodiesel	+23,035%	−70.1%	N.A.

3. Discussion and Conclusion

What do these results suggest?

1) **Biodiesel—**Not a Viable Option

The extensive land requirements for biodiesel production render it impractical for this project. The necessity of nearly eleven thousand hectares for cultivation is a significant barrier in the European context. Importing biodiesel to meet the project's needs would likely escalate the operational costs, undermining the project's economic feasibility. Furthermore, the overall efficiency of the biodiesel supply chain, at a substantially lower −70.1% compared to electricity, diminishes its attractiveness as a sustainable energy solution.

2) **Hydrogen—**Challenges Outweigh Benefits

a) Efficiency Concerns:

Both hydrogen options (A: thermal power generation and B: fuel cell technology) demonstrate lower total efficiency than electricity (−33.8% and −37.7%, respectively). This inefficiency is primarily due to:

i) Multiple energy transformations within the hydrogen supply chain, leading to significant efficiency losses in accordance with the second law of thermodynamics.

ii) Lower efficiency in gas-to-power conversion systems, which further diminishes the overall energy output.

b) Capital Expenditure (CapEx) Analysis:

Although hydrogen's efficiency is lower, a reduction in CapEx could potentially make it more viable. For instance, Option A (thermal power generation) incurs an overall CapEx that is 13.5% higher than that of electricity, with most of this additional cost stemming from transportation (midstream). A decrease in these transportation costs could render this option more economically feasible than electricity, this is an important finding. However, for Option B (fuel cell technology), the situation is more complex. Beyond transportation expenses, the process of converting hydrogen to electricity using fuel cell technology also incurs high costs, rendering it an unsuitable option. Under a CapEx prospective, while green hydrogen energy supply chains currently have higher costs compared to electricity, advancements in technology could change this dynamic. At present, the higher CapEx associated with hydrogen diminishes its economic viability for this project.

c) Land Requirement Disadvantages:

The inefficiency of hydrogen-based systems necessitates significantly more land to produce the same amount of energy as electricity-based systems. Specifically, 49.3% more land is required for Option A and 58.9% more for Option B. This substantial increase in land requirement further challenges the feasibility of hydrogen as an energy vector for this project.

Given the challenges associated with biodiesel and hydrogen, electricity emerges as the most viable energy vector for the project. Its higher efficiency, lower land requirements, and comparatively lower CapEx make it a more suitable and sustainable option for powering the aluminum smelter. This study's findings suggest that, in a standalone greenfield project, electricity-based energy supply chains offer a more balanced and feasible approach in terms of economic and environmental considerations. The insights gained from this comparative analysis provide valuable guidance for similar industrial applications, emphasizing the need for a holistic assessment of energy vectors in the context of specific project requirements and constraints.

4. Limitations and Implications

This study embarked on a comparative analysis of electricity as an energy vector, focusing on its applicability, efficiency, and sustainability in the context of Italy's aluminum smelting industry. By examining electricity alongside alternative vectors such as hydrogen and biodiesel, the research aimed to provide a nuanced understanding of the most viable energy solutions for industrial applications. However, the study's findings are subject to several limitations that warrant careful consideration:

1) Geographical and Sector Specificity: The study's primary context, centered around Italy and the aluminum smelting sector, may not universally apply. Different geographical locations with varied regulatory, environmental, and economic conditions could influence the feasibility and efficiency of the energy vectors analyzed.

2) Selection of Energy Vectors: While the study meticulously compared electricity, hydrogen, and biodiesel, the exclusion of other potential energy vectors such as natural gas or green ammonia might limit the scope of findings. The evolving landscape of energy technology suggests that future research should incorporate a broader spectrum of vectors for a more comprehensive analysis.

3) Technological and Economic Assumptions: The analysis heavily relies on current technological capabilities and economic valuations, which are inherently fluid. Advances in energy storage, conversion technologies, and shifts in the global economic environment could significantly impact the cost-effectiveness and practicality of the preferred energy vectors identified.

4) Policy Dynamics: The study assumes a static policy environment, overlooking the potential for significant policy shifts that could alter the competitive landscape of energy vectors. Changes in environmental regulations, subsidies for

renewable energy sources, and international agreements on carbon emissions could influence the viability of the energy solutions proposed.

Nevertheless, the study's findings have several implications and possible future studies:

1) Strategic Policy Recommendations: To foster the adoption of efficient and sustainable energy vectors, policymakers and industry leaders must consider dynamic, forward-looking strategies that support the infrastructure development for electricity, especially from renewable sources, and the research and development of alternative vectors.

2) Future Research Directions: Although several ongoing studies, there is a pressing need for continuing supporting research for energy efficiency improvements, cost reduction techniques, and the exploration of untapped energy vectors. Such endeavors will not only refine the current understanding but also unlock new potentials for industrial energy utilization.

3) Sustainability and Corporate Responsibility: The study underscores the importance of integrating sustainability considerations into industrial practices. Companies should be encouraged to adopt energy solutions that align with environmental stewardship, economic viability, and social responsibility.

4) Educational and Awareness Initiatives: Amplifying awareness about the implications of energy vector choices through educational programs and industry seminars can equip future professionals with the knowledge to make informed decisions, promoting a shift towards more sustainable energy practices.

In conclusion, while this study contributes valuable insights into the comparative advantages of electricity as an energy vector for industrial applications, its limitations highlight the complexity of energy decisions. The implications drawn underscore the need for holistic approaches to policymaking, research, and practice in navigating the transition towards sustainable energy solutions. Further research that addresses these limitations can pave the way for more informed, effective, and sustainable energy strategies in the industrial sector and beyond.

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Conflict of Interest Declaration

The author declares that there is no conflict of interest regarding the publication of this paper. This research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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List of Abbreviations

PPM—Part Per Million
CO_2—Carbon Dioxide
RES—Renewable Energy Sources
PNIEC—Integrated National Plan for Energy and Climate of Italy
GHG—Green-House Gasses
P2G—Power-to-Gas
MW—Megawatt
kW—Kilowatt
kWh—Kilowatt-hour
kV—Kilovolt
kg—Kilogram
h—Hour
Lt—Liter
GJ—Gigajoule
MJ—Megajoule
Km—Kilometer
CapEx—Capital Expenditure
OpEx—Operational Expenditure
€—Euros
M€—Million Euros
LCOH—Levelized Cost of Hydrogen
PEM—Polymer electrolyte membrane
HT/MT—High Tension/Medium Tension
ESS—Electrical Energy Storage
VRFB—Vanadium Red-Flow Battery
PV—Photovoltaic
H2—Hydrogen Molecule
FCEV—Fuel Cell Electric Vehicle
PHS—Pumped Hydro Storage
AA-CAES—Advanced-Adiabatic Compressed Air Energy Storage
FESS—Flywheel energy storage system