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Green Hydrogen vs Conventional Energy Sources: A LCA Case Study of Aluminum Casting

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Abstract. Aluminum components production is associated with significant greenhouse gas emissions due to both raw material extraction and energy-intensive manufacturing processes. In particular, the melting phase required high thermal energy and conventional energy sources (e.g. fossil fuels, national grids...) can result in relevant environmental impacts. This study evaluates the environmental sustainability of four different energy supply systems for aluminum die casting through a comparative Life Cycle Assessment (LCA). Four scenarios were analyzed: natural gas, national grid electricity, photovoltaic (PV) electricity with battery storage, and PV-powered hydrogen production with metal-hydride storage. A cradle-to-gate approach was adopted, including energy production, storage, raw materials extraction, tool manufacturing, casting operations and finishing. The environmental impacts were modelled using SimaPro, and Global Warming Potential (GWP) was calculated according to the Intergovernmental Panel on Climate Change (IPCC) methodology. The results show that renewable-based solutions represent the most sustainable alternatives, with impact reductions up to 62% compared with traditional approaches. PV electricity with battery storage achieves the lowest unitary impacts (0.15 kg CO_2 eq/kWh). Hydrogen produced from PV electricity also provides significant reductions relative to natural gas and grid electricity and offers high operational flexibility. The metal-hydride storage system shows slightly lower impacts than battery storage, due to its long service life and minimal hydrogen losses. These results highlight the potential of renewable energy and green hydrogen as alternative energy carriers for industrial production.

Introduction

Sustainability has become a key aspect of industrial manufacturing and enhancing the environmental performances of energy-intensive processes is crucial to support decarbonization and a sustainable development of many industrial sectors [1]. This trend is also driven by increasingly stringent European and international regulations, making sustainability a fundamental requirement for companies.

Aluminum components are characterized by low weight and good mechanical properties and are used for several applications in transport, packaging, aerospace, and automotive sectors. However, aluminum components production chain is associated with relevant greenhouse gas emissions; this is related to both raw materials extraction and energy intensive production processes. As a matter of fact, it is estimated that more than 3% of world energy is used for aluminum melting [2]. Within the aluminum market, the casting process is widely used to produce near net shape components. In this process, aluminum ingots and scraps are melted at about 700°C and then injected into a steel mold at high pressure. This step is one of the most critical aspects in the aluminum economy as it is associated

with high energy use [3]. The energy demand, as long as the emissions of traditional energy carriers, results in significant environmental impacts. In fact, thermal energy required for melting is typically supplied by natural gas furnaces or by electric resistance furnaces powered from the national grid. In turn, national energy mixes still rely largely on fossil fuels, while the use of renewable energy sources is often limited [4]. Consequently, even when a significant share of secondary aluminum is used, new products are associated with relevant greenhouse gas (GHG) emissions.
This issue highlights the need to evaluate the use of alternative energy routes from renewable sources. Among these, solar photovoltaic (PV) systems have spread in recent years also thanks to the reduction in installation cost and the possibility to integrate modules on industrial building roofs [5]. To effectively use PV energy in the manufacturing process, it is necessary to introduce energy storage solutions in the system to have flexibility and decouple generation from use. A possible solution is represented by battery storage, typically based on lithium-ion technology [6]. Batteries are characterized by high round trip efficiency, modularity, and capacity. This makes batteries optimal solutions in combination with electric resistance furnaces. However, production and End of Life of batteries is a critical aspect as extraction and disposal of constituent materials have relevant environmental impacts [7]. A possible alternative to battery storage is represented by green hydrogen. This gas can be produced starting from PV electric energy and using electrolyzes [8]. H_2 can be stored and combusted to provide thermal energy in gas-powered furnaces, and this makes it possible to use this gas in aluminum industrial production. Hydrogen can be stored in high-pressure vessels, but this approach presents several critical issues related to the management of high operating pressures, as well as safety risks and potential leakage [9]. An innovative approach is represented by Metal Hydride storage in which hydrogen is stored in solid state form thanks to reversible chemical bonds created between the gas and a metal alloy. Solid state storage avoids typical risks associated with high pressure vessels and is characterized by a high volumetric storage capacity, minimal hydrogen losses, and long cycle life [10].
Despite the growing focus on sustainability, literature lacks a systematic assessment of the environmental impacts of different energy carriers for industrial production, particularly in comparisons between traditional and innovative solutions. In this context, this work presents a Life Cycle Assessment (LCA) analysis of aluminum die cast products manufactured using different energy sources for metal melting. The objective is to determine whether innovative solutions can effectively improve the environmental performance of industrial production and to identify potential improvement opportunities across different systems.

Methods: Life Cycle Assessment Analysis

The goal of the study is to evaluate the environmental sustainability of different energy supply systems for industrial applications. This assessment makes it possible to determine whether innovative solutions can deliver environmental benefits and identify potential areas for future improvement. To this end, a case study of aluminum casting was selected, and different energy sources for the metal melting process were considered.
To quantify and compare the environmental impacts of different energy supply in industrial applications, a Life Cycle Assessment (LCA) analysis was conducted. The analysis follows the methodology described by the ISO 14040-44 standards and it is constituted by four iterative phases:

1) Goal and scope definition: the goal of the analysis, the Functional Unit (FU) and the system boundaries (i.e. the phases considered within the study) are defined.
2) Life Cycle Inventory (LCI): the input and output data related to the phases considered within the system boundaries are gathered.
3) Life Cycle Impact Assessment (LCIA): the inventory data are translated into possible environmental impacts according to defined impact categories (e.g. Global Warming Potential, Ozone Depletion, Cumulative Energy Demand…).

4) Results discussion: the results are critically discussed to draw conclusions and identify criticalities and improvement possibilities.

The following phases are detailed in the next sections.

Goal and Scope Definition

The goal of this study is to compare the environmental impacts associated with innovative and conventional energy sources and carriers used for aluminum melting in casting processes. Hence, the Functional Unit is defined as the production of an aluminum component with a weight of 10 kg via die casting. Given the focus on energy sources, a "Cradle to gate" approach was selected to include all impacts associated with part production. More specifically energy production, storage and distribution, raw materials extraction, tools production, part casting, auxiliaries, and part finishing were included within the system boundaries. The part of service life and End of Life (EoL) were not included in the study as they would have been the same in the different scenarios and would not have changed the comparative analysis.
The investigated process consists of a conventional aluminum casting route. At first, a mix of aluminum ingots and scraps are melted in a furnace to approximately 700 °C. Gas or electricity powered furnaces were considered depending on the specific scenario (and the energy source). Impurities are removed, and the molten metal is transferred to the holding furnace and injected at high pressure into a steel mould. In turn, the mold is produced by a supplier from steel block through CNC machining (e.g. milling). The part hence cools down and solidifies before being ejected from the mold. A cooling system (e.g. water cooling) can be used to speed up the process. After ejection, runners and overflows are removed and finishing operations are carried out. Four different scenarios were considered in the analysis:

- Scenario 1: natural gas. In this scenario, the melting and holding furnaces are powered by natural gas (gas furnace).
- Scenario 2: national grid electricity. Aluminum is molten in a resistance furnace powered with electric energy from the national grid. Italian energy mix is considered.
- Scenario 3: Photovoltaic (PV) system with battery energy storage. Electric energy is provided by a roof installed PV system. To provide a stable power supply, the system includes a battery storage unit that acts as an energy buffer. A resistance furnace is considered also in this scenario.
- Scenario 4: PV powered hydrogen system with metal-hydride storage. PV electric energy is converted into hydrogen (H_2) through the Proton Exchange Membrane (PEM) electrolyzer operating at 30 bar. The gas is hence directed to a solid-state storage system based on metal hydrides which operates at the same pressure. This system is based on a reversible chemical reaction in which a metal alloy absorbs the gas, resulting in a stable metal hydride. During charging, hydrogen binds the metal structure and releases heat. As hydrogen is required by the user, heat is supplied to the system, leading to a release of the gas. Hence, H_2 can be used in a gas furnace similar to traditional natural gas.

In all scenarios, auxiliary electric energy demands are supplied by the national grid. Hence, the main difference between the scenarios relies on the metal melting process. Figure 1 shows the system boundaries for the considered scenarios.

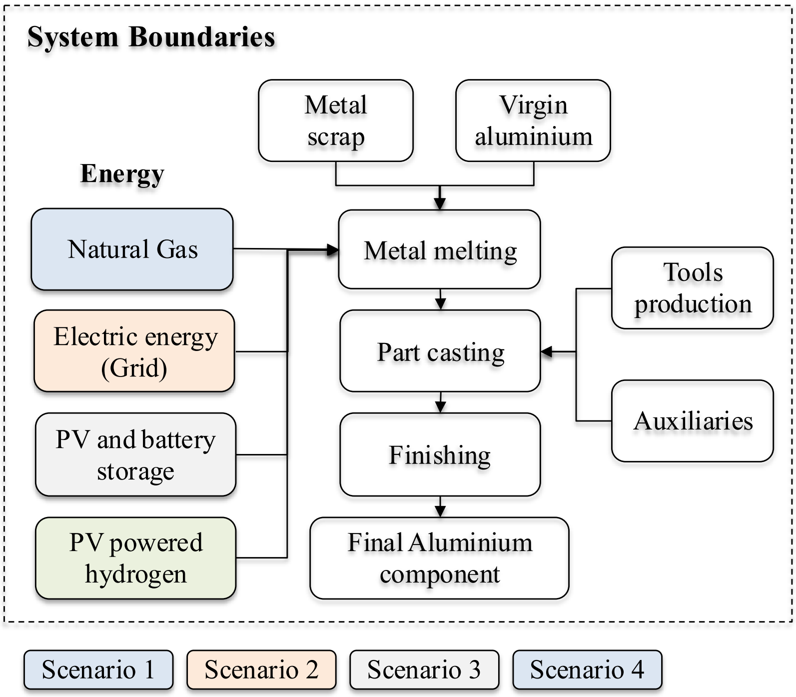

Fig. 1 System boundaries of the four scenarios considered in the present study

Life Cycle Inventory

Both primary and secondary data were gathered in the LCI phase.

The main input data related to aluminum casting was retrieved from relevant literature sources related to metal parts LCA [11,12]. Starting from the FU weight (10 kg) and the constituent percentages (virgin ingot and aluminum scraps, 40% and 60% respectively), the weight of each input material was calculated. Considering the FU weight a parametric approach was followed to estimate the energy consumption for the melting and holding furnaces, auxiliaries and mold weight.

Steel tool was considered for the casting process; raw steel input and milling process for mold production were considered. Both raw materials and milling impacts were retrieved from the Ecoinvent database. In addition, transport from the supplier to the final components manufacturer was considered. The impacts of tools production were allocated to the functional unit considering the number of parts that can be produced using one mold during its service life (up to 100’000 units according to). Impacts related to the casting process were considered the same for all scenarios with the exception of energy production and use.

The energy consumption required by the gas-powered melting and holding furnaces (Scenarios 1 and 4) was calculated considering the unitary energy requirements (0.67 kWh/kg and 0.13 kWh/kg respectively [11]) and the amount of material used for the production of the FU. The same approach was followed for the scenarios with the resistance furnace [13]. In this case, a higher efficiency can be obtained, and the unitary energy consumption is as low as 0.5 kWh/kg for metal melting.

Energy production and supply were different amongst the four scenarios. Scenario 1 considers natural gas and its use was modelled using the Ecoinvent database. Scenario 2 considers electric energy use form the national grid; Italian energy mix was assumed and, as for the previous case, energy production was modelled using the commercial database. In Scenario 3, PV energy from modules installed on the roof of the manufacturer building was considered (Ecoinvent); Li-Ion battery with a capacity of 300 kWh was assumed for energy storage and its impacts were calculated considering the weight of the battery pack and the impacts per kg provided by Ecoinvent. A 90% round trip efficiency was considered for the battery [14]. The impacts of the storage system were allocated to the functional unit based on the total number of kWh managed by the battery over its lifetime (3000 charge–discharge cycles were assumed). In Scenario 4, the same energy production system as Scenario 3 (roof PV modules) was considered. Hence, electric energy was converted into gas hydrogen via PEM electrolyzer. For this Scenario, primary data were provided by the company involved in the analysis. An energy consumption equal to 7 kW was measured as well as the electrolizers productivity equal to 124 g/h. An efficiency of 59% was considered for the electrolyzer and it was calculated considering the electrolyzers productivity (kg H_2/h), their energy use and the gas calorific value (33.3 kWh/kg). Impacts associated with electrolyzers production were not considered within the system boundaries as would have determined almost negligible impacts (1-5% of energy production impacts) according to recent literature [15]. Hydrogen storage via metal hydride system was considered and modelled according to literature [16]; an allocation procedure analogous to the one applied to the electric battery was employed considering the storage system service life and the total weight of stored hydrogen. A 5% gas loss was assumed for storage.

Table 1 Main LCI data

Life Cycle Inventory		
FU part weight	10	kg
Virgin material	50%	
Die manufacturing		
Service life	100000	p
Steel mold	63.68192	kg
steel removed	74.00871	kg
Mold transport	200	km
Metal casting		
Melting furnace	0.673497	kWh/kg
Holding furnace	0.134699	kWh/kg
Electric tot energy	0.5	kWh/kg
Other Electricity Input		
Cooling water system	0.180556	kWh/kg
Finishing	0.333333	kWh/kg
Battery energy storage		
Battery capacity	300	kWh
Battery weight	3000	kg
Depth of Discharge	0.8	
Charge–discharge cycles	3000	p
Tot kWh lifetime	720000	kWh
Efficiency	90%	
Metal hydrides storage		
Tot hydrogen stored in lifetime	80000	kg
Tot energy stored used by user	2664000	kWh

The LCA dedicated software SimaPro was employed to model the defined scenarios and to conduct the LCIA phase. Global Warming Potential was hence calculated according to the methodology proposed by the International Panel on Climate Change (IPCC) and impacts evaluated in terms of kg CO_2 eq. This methodology was selected as it is one of the most relevant and most used in literature analyses for the evaluation of the environmental impacts of industrial production [9].

Results and Discussion

Figure 1 presents the impacts per kWh delivered to the final user according to the four energy carriers investigated within the study: natural gas, electric energy from the national grid, electric energy from PV modules with battery storage and hydrogen produced starting from PV electric energy. This comparison shows the influence of the selection of energy systems over the environment performances of the aluminum casting process. The comparison is expressed per kWh of useful energy delivered to the melting process and this allows comparability across the different energy carriers, regardless of whether the energy is supplied as electricity (Scenario 2 and 3) or as thermal energy (Scenario 1 and 4). Among conventional solutions (Scenario 1 and 2), electricity from national grid has the highest impacts (0.28 kg CO_2 eq vs 0.38 kg CO_2 eq for natural gas and grid electricity respectively); this is mainly due to the composition of the Italian electricity mix (for which fossil based contribution is still significant) and distribution efficiency.
Solutions based on renewable sources (Scenario 3 and 4) represent the most sustainable alternatives, with impacts reduction equal to up 62% with respect to the traditional approaches. Photovoltaic electric energy with battery storage is the solution with the lowest unitary impacts (0.15 kg CO_2 eq/kWh); 53% of these impacts are associated with PV energy production while the remaining 47% is due to the battery storage system. To calculate the unitary impacts, the battery production footprint is allocated over the total amount of energy the system delivers throughout its service life (720,000 kWh). Despite this, battery production still represents a significant contribution; extending the battery service life would further reduce these impacts, leading to the very low unitary energy impacts mainly related to PV modules use.
The PV and hydrogen system, which can supply heat from gas combustion, shows higher impacts with respect to the PV and battery configuration (26% higher) but still remains significantly more sustainable than the two traditional solutions (i.e. 32%-52% reduction). Two main contributors can be identified also in this case: energy production and storage systems. The metal hydrides storage system has impacted slightly lower than those of the battery storage; similar allocation procedures were carried out, leading to impacts equal to 0.06 kg CO_2 eq (whilst the battery 0.07 were obtained for the battery). In fact, despite the relevance of the alloys used in the system, the long service life makes this storage solution sustainable [16]. In addition, hydrogen storage has high efficiency with only 5% losses. The main factor that contributes to increasing the impacts of the hydrogen system with respect to the battery one is represented by the efficiency of the electrolysis process in which electric energy is used to produce hydrogen (i.e. about 60%). Increasing the efficiency of the conversion is crucial to further improve the sustainability of this system. Despite that, this result confirms the advantages of renewable hydrogen that combines sustainability with flexibility. The highest efficiency is obtained as hydrogen is directly used in gas-based furnaces; in the case of reconversion of the energy carrier in electricity, higher impacts would be obtained due to the low efficiency of the reconversion stage.

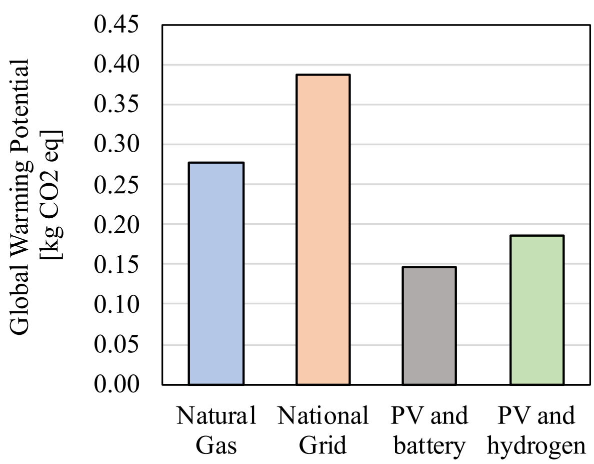

Fig. 2 Impacts per kWh available to the final user for the four considered energy systems

Figure 2 and Table 1 report the results of the LCA analysis for the casting process. As described above, the main difference between the four scenarios relies on the "Metal melting and maintaining" phase that considers different energy carriers. The other phases (raw materials, tools, accessories, and finishing) remain the same across different scenarios. The main contributor is represented by raw materials, accounting for up to 97% of total impacts (i.e. 93.937 kg CO_2 eq). This is due to the high unitary impacts of virgin aluminum (i.e. 22.4 kg of CO_2 eq). Lower emissions are expected as higher scrap aluminum percentage is employed; however, this aspect depends on the required quality of the final products and the specific industrial sector. For graphical clarity, the production of raw materials is not reported in Figure 2.

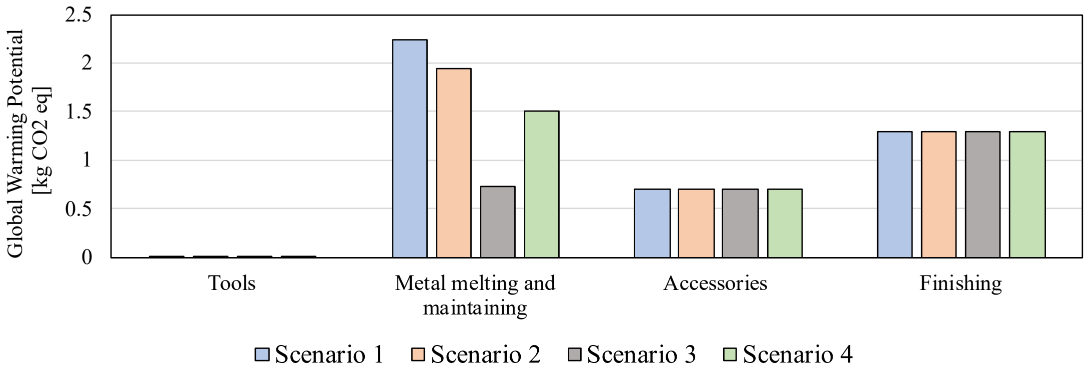

Fig. 3 LCIA results in terms of GWP and contributions of the production phases

Among the other phases, melting is the most relevant one and determines the advantages of one scenario over the others. As in Figure 1, the renewable energy solutions provide relevant impacts reduction with respect to the natural gas (Scenario 1) and national grid (Scenario 2) alternatives. However, in the case of aluminum melting, electricity from the national grid results in lower emissions than natural gas, even though the impact per kWh is lower for natural gas. This is because electric furnaces operate with higher efficiency, thereby reducing overall energy consumption and emissions. For the same reason, Scenario 3 offers even greater benefits than the other alternatives: it relies on electricity for melting (thus achieving high furnace efficiency) while also sourcing that electricity from renewable low-impact energy systems. Hydrogen still represents a promising solution; however, further improvements to the melting system may be required to enhance its overall efficiency.

Tools production determines negligible impacts; despite the relevance of the mold manufacturing process (accounting for 600.1 kg CO_2 eq), its impacts are allocated to many components, resulting in low carbon footprint for the considered FU. Accessories (i.e. the cooling system) and finishing operations are mainly related to electric energy use from national grid and account for about 2% of total impacts. Also for this energy consumption, more sustainable energy systems can be employed to further improve the sustainability of the four scenarios.

Table 2 Impacts contributions for the four scenarios in terms of GWP

	Tot	**Raw materials**	**Tools**	**Metal melting**	**Accessories**	**Finishing**
Scenario 1	98.181	93.937	0.006	2.241	0.702	1.295
Scenario 2	97.883	93.937	0.006	1.943	0.702	1.295
Scenario 3	96.677	93.937	0.006	0.737	0.702	1.295
Scenario 4	97.444	93.937	0.006	1.504	0.702	1.295

Conclusions and Future Development

This study investigated the environmental impacts of an industrial aluminum die casting process using different energy sources and carriers for the metal melting phase. Four scenarios were considered to represent traditional energy sources and renewable solutions: natural gas, electric energy from the national grid, PV energy with battery storage, and PV powdered hydrogen production. A cradle to gate approach was followed to focus on the manufacturing stages and energy use. The main results are summarized as follows:

- PV electricity with battery storage is the most sustainable option, reducing impacts per kWh by up to 62% compared with conventional solutions.
- Hydrogen produced from PV energy provides lower impacts with respect to traditional solutions and high flexibility. The metal hydride storage system is efficient and has low impacts; however, the overall system performance is sensitive to electrolizer efficiency.
- Electric furnaces are characterized by higher efficiency with respect to gas-powered ones. Hence, even if natural gas determines lower impacts per kWh with respect to grid electricity, the latter can be the most sustainable for metal melting.
- Raw materials account for up to 97% of GWP due to high unitary footprint of primary aluminum production. A higher recycled material rate is a valuable solution to reduce final products impacts.

Future studies could focus on improving the efficiency of conversion and storage technologies, continuously monitoring the sustainability of innovative scenarios. In particular, specific focus on hydrogen systems could further enhance their competitiveness relative to battery-based solutions. These aspects, along with process efficiency improvements, could contribute to a sustainable development of die casting.

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