The Costs of More Sustainable Castings Can we Afford the Change?

Lucas Pelchen(✉) and Sebastian Müller

Institute of Casting Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 81, 90762 Fürth, Germany
lucas.pelchen@fau.de

Abstract. Rising costs for fossil fuels and the need to reduce emissions in the production of castings are subjecting foundries worldwide to increasing pressure to act and innovate. Due to fierce global competition in this sector and high investment costs for alternative technologies, foundries are therefore under high pressure to transform, while at the same time having limited financial resources. This article examines the economic and environmental differences between a conventional industrial foundry process chain, a process chain based on a hydrogen (H_2)-fired melting furnace and an all-electric approach using conversion of H_2 to electricity within a solid oxide fuel cell. To ensure an unbiased comparison of the process chains introduced, the respective mass efficiencies are first determined using an absorbing Markov chain before calculating the mass-specific costs and emissions of each approach using a literature-based process model. The comparison of the setups shows negligible differences in terms of material loss and cost in the respective best case. However, significantly higher emission minimums are found for both H_2 approaches compared to the biogas-based conventional approach, especially for the use of green H_2. In summary, no significant economic disadvantages of the H_2-based approaches can be identified. Even considering that the economic comparison is biased in favor of biogas due to accounting measures, the environmental difference is comparatively small. The results indicate that the conversion of the foundry industry towards more sustainable H_2-based foundry process chains is in principle reasonable as well as affordable and should therefore be achieved in the medium term.

Keywords: High pressure die casting · absorbing Markov chain · energy demands · greenhouse gas emissions · hydrogen in foundries

1 Introduction

Like all energy-intensive industries, the light metal foundry industry, which relies on fossil energy production for 53% of its energy, is under increasing pressure to innovate due to the foundry's cost-intensive energy use and fierce competition for a limited amount of CO_2 certificates [1]. The modification of existing plant technology is cost-intensive and thus represents a potential risk in the economic competition of metal production.

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In conjunction with low achievable margins and the need to continuously maintain production operations as a result of supply commitments, a lack of innovation can thus arise [2, 3]. However, due to the rising costs of conventional process chains, the cost differential to more sustainable process chains based on renewable energy is increasingly narrowing. Therefore, a sound prediction of the expected costs for the more sustainable process chains represents a crucial factor for the economic success of the foundry industry. As energy efficiency has been a focus of research in recent decades, a variety of different methods for predicting energy consumption and process emissions for casting processes can be found in the literature. These range from approaches based on thermomechanical models [4, 5] and simulations [6, 7] to audit-based methods [8–13]. While simulations require a deeper understanding of the interactions and physical conditions in the process, audit methods demand a high organizational effort and sufficient industry participation. In the case of the established fossil fuel-based foundry process chain, a sufficient amount of data is available, showing that the range of energy required to produce aluminum castings worldwide is from 0.35 kWh/kg_{Cast} to 2.28 kWh/kg_{Cast}, depending on process technology and requirements, batch size and equipment. [9, 11, 14–16] The average value of this span – 1,315 kWh/kg_{Cast} – results in emissions per ton of aluminum casting between 0.109 $kgCO_2/kg_{Cast}$ and 0.909 $kgCO_2/kg_{Cast}$, depending on the emission factor of the natural gas combusted. [17] Based on the available literature, no approach could be found to predict energy consumption and process emissions for hydrogen-based casting process chains, which makes it much more difficult for foundries to decide to invest in this technology due to planning uncertainty. In this work, therefore, the energy consumption and emissions per kg of aluminum casting are calculated for two hydrogen-based process chains, one which burns hydrogen (C-route) and the other uses H_2 as an energy source for electric melting technologies (E-route). This information will help accelerate the foundry industry's transition towards more climate-neutral casting production.

2 Methods

2.1 Definition of the Process Chain

The casting process chains and thus system boundaries investigated in this work comprise the melting of the aluminum ingots in a melting furnace, the holding of the melt at a target temperature by means of a holding furnace, the actual casting process, and the trimming of the casting at the casting line immediately after casting production. The electrically operated die casting cell and the electrically operated holding furnace are identical in all scenarios examined. These three scenarios – conventional setup (*setup 1*), C-route (*setup 2*) and E-route (*setup 3*) – thus differ only in the energy source of the first process step for melting the aluminum ingots in a furnace. The transition possibilities p_t from step to step are shown in the arrows between the corresponding steps (see Fig. 1) while the sum of the energetic demands of the respective setups are given under the corresponding title.

- *Setup 1: Conventional setup (Total energy demand: 1.315 kWh/kg$_{Cast}$)*

In conventional plants, the melting furnace is fired with natural gas, using special burners with integrated recuperators that recover the heat in the exhaust gases and thus achieve a higher average efficiency of about 74% [18]. Based on published data in existing literature, the industrial energy demand (including losses) for melting 1 kg of aluminum is estimated at 0.94 kWh/kg$_{\mathrm{Cast}}$, of which 90% is generated by natural gas [9, 15, 16]. Taking this distribution into account, the mean value for the fuel demand is 0.846 kWh/kg$_{\mathrm{Cast}}$, whereas the mean value for the electrical energy needed results in 0.094 kWh/kg$_{\mathrm{Cast}}$. In addition, holding at elevated temperatures as well as processing in the die casting cell consume an average of 0.065 kWh/kg$_{\mathrm{Cast}}$ and 0.310 kWh/kg$_{\mathrm{Cast}}$ of electrical energy. [1, 8, 10].

- *Setup 2: C-route (Total energy demand: 1.350 kWh/kg$_{Cast}$)*

The C-Route is based on burners that replace natural gas with hydrogen when firing the melting furnace, minimizing changes to the plant equipment. This results in an almost identical setup, which in turn means that both the burner efficiency and the proportion of electricity required for processing are very similar to those of the conventional setup. Due to the resulting moisture in the exhaust gases, a longer melt cleaning process should be considered for the melt prior to casting processing, resulting in a 1.5 times higher percentage of material waste and energy requirement during holding.

- *Setup 3: E-route (Total energy demand: 1.510 kWh/kg$_{Cast}$)*

The E-Route is an all-electric approach with an electric melting furnace powered either by electricity from a solid oxide fuel cell (SOFC) or from the electrical grid. To meet the foundries' need for a continuous, potentially off-grid energy supply, the option of generating electricity from H_2 is selected for this concept. This leads to a higher energy demand during melting due to the required conversion in the SOFC with an average efficiency of 60%. [19] However, due to the more efficient melting process, the final increase in energy demand is only about 1.23 times that of *setup 1* [6].

2.2 Absorbing Markov Chain Model

To describe the material flow within the different process chains, a model based on an absorbing Markov chain is used. This model consists of the three transient states *Melting*, *Holding* as well as *Die-Casting/Trimming* (represented by the indices 1–3) as well as the two absorbing states *Waste* (W) and *Casting* (C). In order to determine the final amount of aluminum that remains in the casting after trimming f_{Cast}, a corresponding transition matrix was created for each setup. Every matrix contains the percentage of aluminum mass flow from one state to another represented by p_{xy}, where x indicates the source and y the destination of the mass flow. f_{Cast} is then calculated by multiplying p_{12}, p_{23}, and

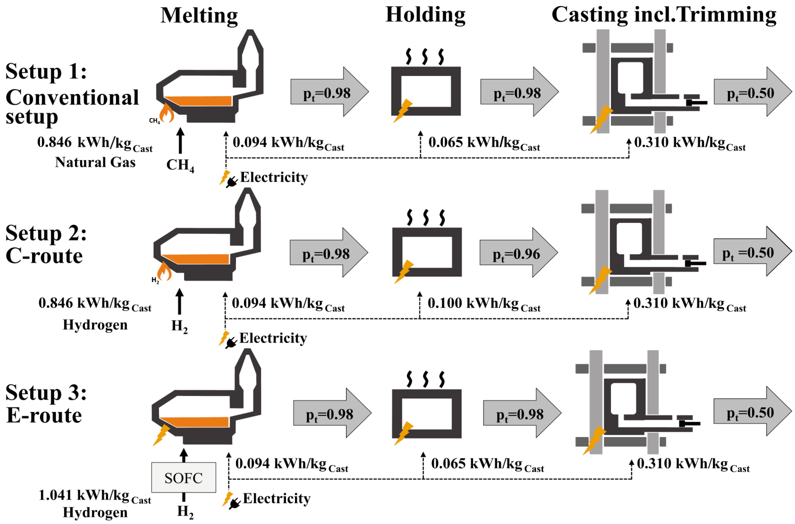

Fig. 1. Schematic overview of the investigated process setups

p_{3C} with 1 kg as nominal ingot quantity.

$$T_{Material} = \begin{pmatrix} p_{11} & p_{21} & p_{31} & p_{W1} & p_{C1} \\ p_{12} & p_{22} & p_{32} & p_{W2} & p_{C2} \\ p_{13} & p_{23} & p_{33} & p_{W3} & p_{C3} \\ p_{1W} & p_{2W} & p_{3W} & p_{WW} & p_{CW} \\ p_{1C} & p_{2C} & p_{3C} & p_{WC} & p_{CC} \end{pmatrix} \quad (1)$$

2.3 Investigated Energy Sources

Depending on the previously presented setups, different energy carriers are required for the process, resulting in a variety of energy costs and emissions in the process chain. The following table 1 provides an overview over the ranges of energy costs C_E and the corresponding emissions Em_E per kWh of the energy sources investigated in this paper. Despite the lower costs of directly using green electricity compared to green H_2 (see Table 1), the on-demand off-grid supply option makes the mixed scenarios more resilient, which is why these energy source combinations were selected for the study.

Table 1. Energy carrier and corresponding costs C_E and emissions Em_E per kWh

Energy Source	Cost range in $\frac{€}{kWh}$ **	Emission range in $\frac{g_{CO_{2eq.}}}{kWh}$
Biogas	0.03 … 0.11 [20]**	-19 … 435 [21]
Blue Hydrogen	0.05 … 0.09[22]	143 … 218[22]
Green Hydrogen *(Mains electricity)*	0.27 … 1.85[23]	694[23]
Green Hydrogen *(Electricity from own renewable energy sources)*	0.04 … 0.83[23]	44[23]
Green Electricity	0.13[24, 25]***	146[24]

* Storage costs are not included in this overview | ** Based on Data from 2021 | *** average german industry costs from 2020 [25] with average extra costs for green-option from 2017[24]

2.4 Definition of the Evaluation Criteria

Since the energy demand of an industrial foundry process strongly depends on the mass of the castings produced, the mass-specific costs c_i and emissions em_i were chosen for an objective evaluation of the three investigated setups. To calculate the mass-specific criteria for each setup i, the energy quantities e for each step s provided by an energy carrier j are multiplied by the respective cost factor C_E, or in case of e_i by the emission factor Em_E, for one kWh and added over the total number of process steps k as well as energy carriers n before being divided by f_{Cast}.

$$c_i = \frac{\sum_{s=1}^{k}(\sum_{j=1}^{n} e_j \cdot C_{E_j})}{f_{Cast}} \tag{2}$$

$$e_i = \frac{\sum_{s=1}^{k}(\sum_{j=1}^{n} e_j \cdot Em_{E_j})}{f_{Cast}} \tag{3}$$

3 Results and Discussion

3.1 Mass-Specific Efficiencies of the Investigated Setups

Due to the various transition probabilities for the described process chains, each setup has its own value for the mass-specific efficiency f_{Cast}, as shown in Table 2.

Table 2. Overview of mass-specific efficiency

Setup	1	2	3
f_{Cast}	0.48	0.47	0.48

As a result of the longer holding time due to the more intensive melt cleaning, f_{Cast} is lowest at 0.47 in *setup 2*. However, the difference to *setup 1* and *3* with mass-specific efficiencies of 0.48 each is subordinate. This strongly suggests that in terms of material losses there are no significant disadvantages of the more sustainable routes compared to the conventional industrial setup.

3.2 Setup-Specific Emissions

Based on the mathematical relationships from (3), the mass-specific emissions shown in Fig. 2 were calculated for the different setups, taking into account the data given in Table 1. Here, the conventional setup on the basis of a biogas combustion with 0.109 kg_{CO2}/kg_{Cast} achieves the lowest minimum emissions of all three setups. The minimum value for green H_2 is about twice as high at 0.236 kg_{CO2}/kg_{Cast} and is exceeded by the values for blue H_2 with a minimum of 0.414 kg_{CO2}/kg_{Cast}. In particular, green H_2 and biogas thus show a considerable range, which complicates the comparison to some extent and suggests that biogas is partly more sustainable than the use of green H_2 in foundries. However, the minimum emissions for biogas are only achieved when specific biogenic feedstocks are used as input materials and if the most favorable accounting measures such as waste heat and fertilizer credits are applicable. It must be assumed that these conditions are not met for the majority of industrial consumers, since the specific input materials are not provided in sufficient quantities for an entire industry and are usually only available locally and not sorted by type. On the other hand, considering the average emission value for biogas with 0.446 kg_{CO2}/kg_{Cast} instead of the minimum value, the potential of green H_2-based plants is clearly shown by almost halving the emissions. It should also be emphasized that the comparatively high emissions of green H2 mainly result from the assumption that grid electricity is used for electrolysis. Thus, if electrolysis is carried out with electricity from renewable energy sources, which is becoming increasingly likely due to current technological possibilities and preferences of society, the use of green H_2 in foundries is significantly more sustainable than keeping the conventional biogas-based plants.

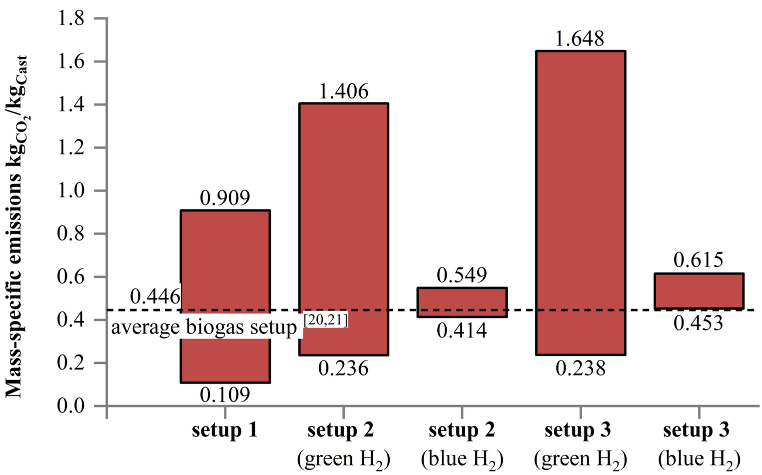

Fig. 2. Range of achievable emissions for different process setups in conjunction with corresponding energy sources for melting

3.3 Setup-Specific Costs

The setup-specific cost per kg of casting was calculated using the costs from Table 1 and formula (2), with a significant difference in terms of the maximum cost for each setup (see Fig. 3). The lowest cost was calculated at 0.18 €/kg$_{Cast}$ for *setup 1*. However, the financial differences from the minimum of *setup 2* with 0.21 €/kg$_{Cast}$ for green H_2 and 0.23 €/kg$_{Cast}$ for blue H_2 are relatively small, as well as the minimum of *setup 3* with 0.21 €/kg$_{Cast}$ and 0.24 €/kg$_{Cast}$. While the maximum costs for biogas with 0.32 €/kg$_{Cast}$ and blue hydrogen are identical for *setup 3* and differ only slightly from *setup 2* with 0.30 €/kg$_{Cast}$ when using blue H_2 and for *setup 3* with 0.32 €/kg$_{Cast}$, the use of green H_2 causes significantly higher maximum costs of up to 4.14 €/kg$_{Cast}$. Considering these price ranges, especially the process chains based on green H_2 represent an increased financial effort compared to an existing industrial setup with biogas. This diversity of financial efforts for green H_2 is mainly based on electricity costs and electrolyser operating hours, which makes efficient management of the electrolyser urgent for competitive green H_2-based process chains. Though especially in the case of green H_2, the maximum costs of the more sustainable plants exceed those of the industrial plants, it becomes clear that the financial differences between the minimum costs for each plant are negligible. Since the price ranges for biogas are based on data from 2021 and a decrease in electrolyser costs is expected, which is based on economies of scale and increased price pressure due to more suppliers in this technological segment, a price parity of biogas and green hydrogen can be expected in the near future.

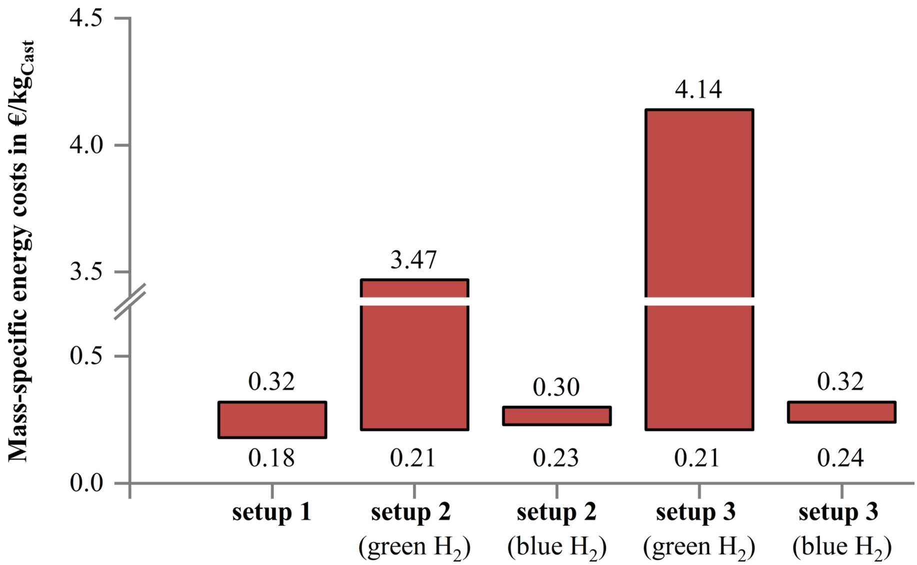

Fig. 3. Range of resulting costs for different setups

4 Conclusion and Outlook

The results presented in this work clearly underline that foundry process chains based on green H_2 are likely to become competitive with conventional process chains and are more sustainable than the industrial average in the non-ferrous foundry.

- Using green H_2 has the potential to nearly halving the mass-specific emissions to 0.236 kg_{CO2}/kg_{Cast} compared to the average of biogas firing with 0.446 kg_{CO2}/kg_{Cast}.
- Price parity can be achieved for both, green H_2 combustion and electricity generation, if the electricity for electrolysing is sourced from renewable energy sources.

The influences on alloy quality and in-process material losses need to be investigated in further studies using experimental test setups. Nevertheless, the results of this first evaluation indicate the distinct potential as well as the small financial differences between more sustainable H_2-based process chains compared to a conventional setup. This of course only applies if, from a macroeconomic perspective, sufficient H_2 capacity is made available. It is therefore to be expected that the success of a foundry in the future will depend not only on the technological quality of its products and efficiency of the foundry, but also on the skillful acquisition of energy.

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