
# Hydrogen

## The key to a more sustainable manganese production

- Manganese (Mn) is the fifth most abundant metal in the Earth's crust, widely used in metal alloys and batteries, but difficult to produce.
- Current Mn production methods have high energy consumption and $CO_2$ emissions.
- Professor Jafar Safarian from the Norwegian University of Science and Technology (NTNU) developed the HAlMan process: a novel, sustainable way of producing Mn, ferromanganese, and manganese–aluminum alloys.
- The HAlMan process offers a cleaner conversion of Mn oxides to Mn metal or high-value alloys in the presence of hydrogen, while recovering energy.

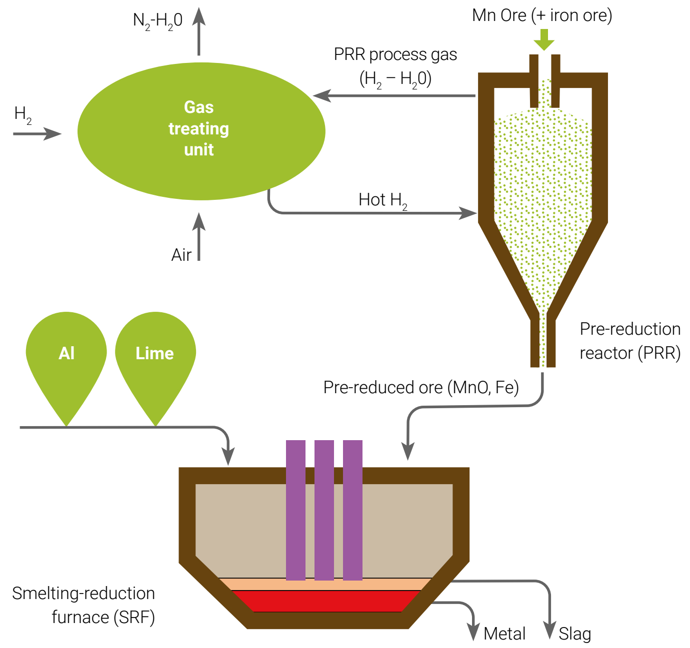
It is widely known that metals have many uses in our everyday life: in their pure form, for example as gold jewellery; or in the form of alloys (mixtures of metals with or without the presence of non-metallic substances). Some examples of alloys used for everyday activities are stainless steel or cast-iron pots and pans, white gold jewellery, or coins made of bronze. More recently, the use of various metals and compounds has expanded into battery making, which has made the demand for specific materials increase exponentially.

**Safarian developed a method to produce Mn and its alloys with significantly reduced energy consumption and $CO_2$ emissions.**

The process of sourcing specific metals to create certain alloys is not always straightforward, or even based on abundance. One metal that is becoming more and more difficult to obtain in the required tonnage is manganese. Manganese (Mn) is an element widely known for strengthening aluminum cans. It is also necessary for the production of steel and steel alloys based on iron and Mn. The oxide of manganese – manganese dioxide ($MnO_2$), is used to make batteries. Mn can be mined in the form of ore (oxides or carbonates) from readily available natural resources, with around 21 million tons of Mn ore mined in 2020. However, mining has caused environmental concerns around deforestation, contamination of soil and water streams, and disturbance of natural habitats. As such, there is an emerging need to come up with sustainable ways of producing Mn, especially given the tonnage required in industry.

### Traditional production methods

The traditionally used method to produce Mn or Mn alloys from Mn oxides ($MnO_2$ and $Mn_2O_3$) is via reduction of the oxide (meaning removing the oxygen) in a submerged arc furnace. Mn oxides need to be reduced to Mn metal, traditionally done through smelting Mn oxides with carbon to result in a carbothermic reduction. This results in an Mn-containing alloy (Mn ferroalloy), carbon oxides, and slag, which is the residual matter. This process can be




Modified from Safarian, J, (2022) doi.org/10.3390/pr10010027

Schematic of the HAlMan process for sustainable production of metals using hydrogen and Al sources.

quite energy intensive as it requires high temperature for several steps, resulting in 2-3 MWh per ton of metal. To put this into perspective, 1 MWh is the energy equivalent for the total energy needs of about 330 homes for one hour, so escalating this to the tonnage of Mn production results in an excruciating amount of energy required, and $CO_2$ emitted.

**The HAlMan method uses the produced energy to substitute energy requirements down the line, in this way closing the energy loop.**

Given the complex issues surrounding production of Mn and Mn alloys, including the energy consumption, carbon emissions, and waste products, researchers have been working on identifying more sustainable ways to produce this high-demand metal and its alloys. To this end, Professor Jafar Safarian at the Norwegian University of Science and Technology developed a method to produce Mn and its alloys with significantly reduced energy consumption and $CO_2$ emissions.

## The HAlMan process

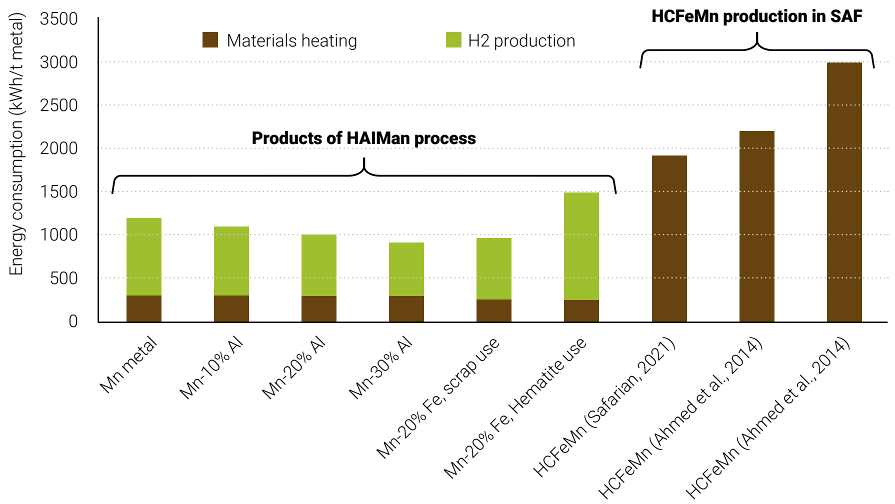
Safarian researches the use of hydrogen in metallurgical processes such as ironmaking, ferroalloys production, bauxite residue valorisation, and silicon refining for sustainable development. In the past couple of years, his work has focused on the development of a more sustainable production process for Mn and its alloys; in a recent publication, he explains how he achieved that. Safarian's proposed method is based on three key factors: the use of hydrogen for a step-reduction of Mn dioxide to MnO, use of aluminium or iron depending on the type of alloy desired, and the energy integration of processes, meaning energy gets recycled in process units, thereby reducing the requirements for additional energy. Safarian named the developed method 'HAlMan', an abbreviation of Hydrogen, Aluminum, and Manganese.

One of the main differences of the HAlMan process to other currently available methods is the use of hydrogen to produce MnO through 'removing' the oxygen from the Mn dioxide in Mn ore and 'adding' it to hydrogen – thus producing water, a much better byproduct than $CO_2$. After the hydrogen reduction process, MnO undergoes an aluminothermic reaction (heating MnO in a furnace with aluminum to create a reaction) to produce either pure Mn or manganese–aluminum alloys. If the desired product is a ferromanganese alloy, then a form of iron is added alongside the aluminum, or via another route. Given that the reduction reactions are exothermic, energy is produced in the form of a hot gas mixture of produced water vapor and unreacted hydrogen. The HAlMan method uses the energy produced to supplement energy requirements down the line, for example heating hydrogen to the temperature required for the reaction, or recycling unreacted hydrogen to the reactor, in this way closing the energy loop.

## Scalability and benefits of the HAlMan process

Safarian has validated the proposed method experimentally and illustrated the improvement in energy and emission saving computationally. Based on experimental results, the proposed method results to products of suitable purity while saving about 1.5 tons of $CO_2$. It also sees an almost 50% reduction on energy consumption per ton of ferromanganese alloy produced. Through previous research, Safarian showed that the byproducts, containing a percentage of Mn, MnO, and aluminum, can be treated to recover some of the metals, leading to an even more sustainable process.

Next, Safarian is looking to test the HAlMan process in a pilot study to confirm the results from the experimental and computational stages. The HAlMan process will be further studied in lab scale and pilot tested in a new Innovation Action project as part of the Horizon Europe programme (halman-project.eu) with the contribution of 18 partners from academia, research organisations, SMEs and industry. The project was initiated in January 2023 and will be implemented within four years.

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Energy consumption to produce metals by HAlMan process.

## Personal response

***How did you come up with the idea of developing this process?***

I love to research future sustainable metallurgical technologies, and this idea is a result of original thinking based on using fundamental knowledge. In addition, research activities into the use of hydrogen for metals production, manganese ferroalloys processes (my PhD research), and the valorisation of industrial waste such as aluminum scrap and dross for many years have been important.

***Could this process be used to produce different metals and alloys?***

Yes, the process is flexible and can be applied to produce different metal qualities and introduce even new types of bulk Mn alloys for further applications in industry.

***Which could be the limiting factors for scaling up this process to industrial implementation?***

The limiting factor may be convincing the industry to shift from the conventional process, developed from many decades ago, to a new process. The advantages of HAlMan process regarding sustainability are important and motivating.

***Can slag be repurposed or reused further than already discussed?***

The produced slag byproduct of the HAlMan process has significant amount of aluminum oxide (Al2O3), which is formed in the aluminothermic reduction step, and this Al2O3 can be recovered as a feedstock for Al metal production. A carbonate residue is generated along with alumina recovery from the slag, which is consumable/valuable. In recent years I have conducted significant research in this field.

***Between experimental and computational research, which one do you prefer and why?***

I think both are important and good research has a combination of both. I like experimental work and I do believe that any idea must be tested in lab. Computational research, however, is important to evaluate the results, plan for further experiments, analyse the process, etc.

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### Bio

Jafar Safarian is a professor in process metallurgy at the Department of Materials Science and Engineering at the Norwegian University of Science and Technology (NTNU), Norway. He researches the use of hydrogen in metallurgical processes such as ironmaking, ferroalloys production, bauxite residue valorisation, and silicon refining for sustainable development.

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### Further reading

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