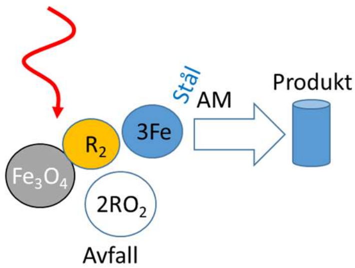
Project
AM-ORE

Energimyndigheten, Project no. 51021-1

Report on the ecological and economic potential

Version v1



Alexander Kaplan
Forskarämne produktionsutveckling
Avdelning för produkt- och produktionsutveckling
LTU

2021-05-19

Project AM-ORE

Report on the ecological and economic potential

v1

/Alexander Kaplan, LTU

Executive Summary

The project AM-ORE studies the possibility of direct 3D-printing of a steel-product when feeding with iron ore, where the reduction process takes place in the 3D-printer, by adding a reacting agent followed by removing an oxidized byproduct, Fe remaining. In this report the environmental and economic aspects are estimated. The first reacting agent actually studied is Si.

Direct reduction in a 3D-printer ideally requires:

340 kg Si / ton Fe
240 kg Si / ton Fe_3O_4

and produces as byproduct:

720 kg SiO_2 / ton Fe

Energy consumed in the process, ideally:

E_{Fe}= 4.14 GJ / ton Fe

Energy consumed by the system (However, plus further losses, to be estimated, like heat conduction, material losses, etc.):

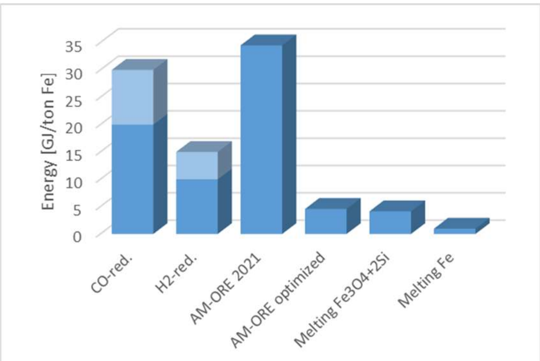
$E_{electrical}$ = 34.49 GJ/ton Fe, for today's systems and conditions.
$E_{electrical}$ = 4.58 GJ/ton Fe, for possible future optimizations.

This includes already the whole value chain, like manufacturing and transport.
Today just the steel-making, without the manufacturing chain and transport, consumes:

E = 20-30 GJ/ton Fe

The hydrogen reduction route would consume:

E = 10-15 GJ/ton Fe



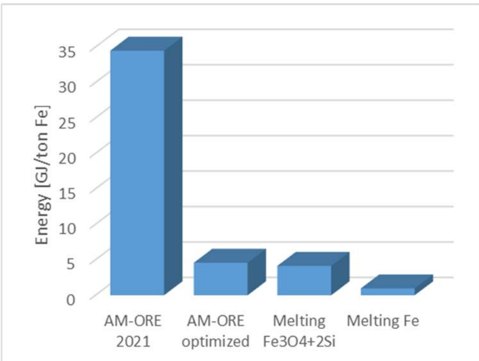


Fig. 1: Energy consumed per technique (left), only AM-ORE-technique and materials (right)

Estimations and explanations:

Costs

Estimation for investment:

- High power laser device 500 tkr/kW 3 mkr / 6 kW (per kW laser beam power)
- Whole system, including laser, automation, etc. 3 mkr for 1 kW; 6 mkr: 6 kW laser power

Investment depreciation usually for 3D-printing the by far dominant costs, before operator salary, consumables, energy, maintenance/repair, etc.

The production, throughput or building rate will be proportional to the laser beam power. The investment costs for high power lasers have decreased during the last decades and have much potential to further decrease. Costs for the overall system will differ, depending on either just upscaling many systems or instead developing larger efficient systems tailored to this application.

Greenhouse gas emissions

- 0 tons (zero) CO_2-equivalent per ton metal produced

The process does not produce CO_2 or other greenhouse gases, provided the electricity does not.

Material consumption and waste

How much material is involved, per chemical element? Here Si (e.g. Si-powder) is assumed as reacting agent, as a starting point, because of a number of promising aspects.

The target reaction Fe_3O_4+2Si = 3Fe+2SiO_2 requires a mixture of stoichiometric mass shares.

In the mixture Fe_3O_4+2Si,

- 58 wt-% is Fe (derived from the molecular weight/atomic mass),
- 20 wt-% is Si,
- 22 wt-% is O.

For 1 ton of Fe, 1.38 t of Fe_3O_4 and 335 kg Si are needed, or 240 kg Si per ton Fe_3O_4.
717 kg SiO_2 per ton Fe result as byproduct from the reduction.

335 kg Si / ton Fe
240 kg Si / ton Fe_3O_4
717 kg SiO_2 / ton Fe

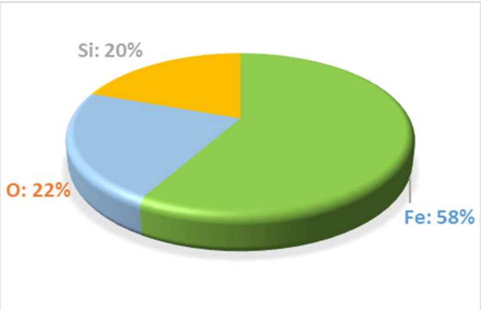


Fig. 2: Mass shares (wt-%) of the respective chemical elements required for the target mixture

<u>Energy consumption</u>

How much energy is consumed by this technique, per weight?

While certain losses need to be added, the energy consumption of the ideal process is a good starting point for orientation. In the ideal process, the iron ore and the reacting agent (here: Si) need to be molten and a net shape Fe-product of corresponding mass results, plus the byproduct (here: SiO_2). Melting means heating of a volume/mass to melting temperature plus latent heat of melting.

Melting of the two components requires the following specific energy:

Fe_3O_4	1.65 GJ/t
Si	2.79 GJ/t
(Fe	1.19 GJ/t)

Since the stoichiometric mixture requires $Fe_3O_4+2Si = 3Fe+2SiO_2$, the combined energy is E_{mix}=(1.65+2·2.79)/3=2,41 GJ/t for this mixture.

Hence the above energy E_{mix} corresponds to the following energy required, related to the resulting amount of iron only (the resulting product):
E_{Fe}=2,41/0.58=4.14 GJ/ton Fe,
while then also having produced SiO_2.

Producing one ton of iron (as a final 3D-printed product) consumes ideally 4.14 GJ.

E_{Fe}= 4.14 GJ/t

This is the energy required for melting the chemical components. The 3D-printer process has energy losses by

- limited absorption A of laser light in the melt (reflection losses R, A+R = 100%)
- limited wall plug efficiency of the laser system

Typically, without any measures, for the most common laser systems (wavelength, about 1 µm) absorption is about 30%. It depends on the material (refractive index, temperature-dependent), wavelength, polarization, angle of incidence and surface conditions. From proper understanding and optimization, reaching 90-95% absorption could be possible, particularly from beam polarization.

Typically, modern (fiber) laser systems of the here relevant beam powers have a wall plug efficiency (laser beam power out divided by electricty in, including chiller unit) of 40%, tendency increasing. For the last two decades, high power (fiber) lasers are based on semiconductors and have high potential to become more efficient. Heat losses can be reduced further, by efficient semiconductor design. The theoretical limit (quantum efficiency) can be close to 100% for semiconductor-based lasers.

An absorption of 30% and wall plug system efficiency of 40% would require electrical energy of $E_{electrical}$=4.14/0,3/0,4=34.49 GJ/ton Fe.
Optimizations would keep it close to the above value. $E_{electrical}$=4.14/0,95/0,95=4.58 GJ/ton Fe.

$E_{electrical}$ = 34.49 GJ/ton Fe, for today's systems and conditions.
$E_{electrical}$ = 4.58 GJ/ton Fe, for possible future optimizations.

Process losses need to be added, like lateral heat losses, heating of the melt to higher temperatures, mass losses, etc.

Vice versa, also preheating is an option for a more energy efficient process, to be proven. If the process would operate in a hot environment, ideally just below the melting temperature, on the one hand the (simpler) heat for preheating is required, on the other hand the process just needs to provide the latent heat of melting, no more the amount of heating up.

The above includes already the whole value chain, like manufacturing and transport.
Today just the steel-making (CO-reduction), without the manufacturing chain and transport, consumes:

E = 20-30 GJ/ton Fe

The hydrogen reduction route would consume:

E = 10-15 GJ/ton Fe

Note: These figures from CO-reduction and H2-reduction are the indicative spread from selected international text sources, identified by LTU, but not exhaustive.

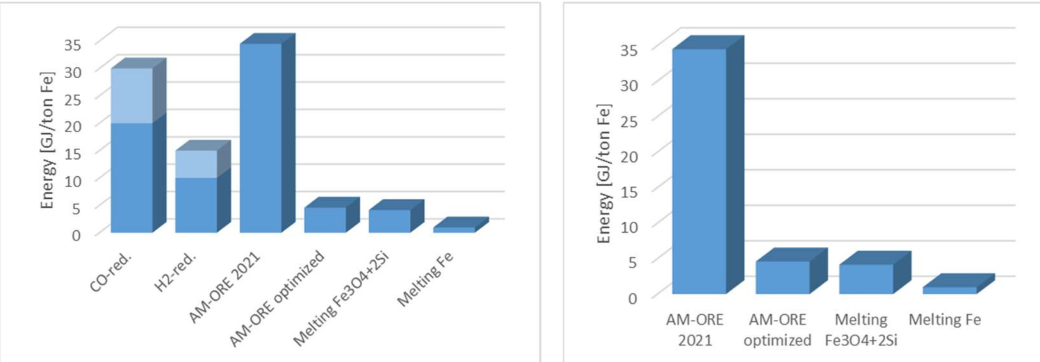


Fig. 3: Energy consumed per technique (left), only AM-ORE-technique and materials (right)

____