# Road-map for gas in the Norwegian metallurgical industry: greater value creation and reduced emissions

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## Vision and objectives

The basis of this road-map is a vision of a sustainable Norwegian metallurgical industry that will attain $CO_2$-neutrality by 2050. Expanding the use of gas in the production of metals will contribute to making this vision a reality. This road-map describes what we will need to do to increase the use of gas in metal production.

## Background

Greater use of gas would make metal production more environmentally friendly while improving the competitiveness of Norwegian metal producers. By "gas" we refer here to natural gas, biogas, hydrogen and flue-gases from the metal production industry's own and other industries' production processes. Gas can replace coal and coke or provide a basis for the development of new processes that are more energy-efficient and/or emit less $CO_2$. Using flue-gases would exploit a currently underutilised raw material; hydrogen or biogas combustion would reduce fossil-fuel emissions, while use of natural gas would remove $CO_2$ emissions from the volatile components of coal. Reducing the use of coal and coke would reduce global environmental footprints caused by coal-mining. The development of new processes could give Norwegian industry a competitive advantage.

One important but seldom mentioned factor is that carbon is a very undesirable component of the metals we produce. Carbon is utilised in the metallurgical industry for only two purposes: to remove oxygen from ores and to ensure that it can be transported away from the refining process in gas form. The metal production industry's consumption of carbon, and the $CO_2$ emissions that this consumption entails, are thus to a great extent a consequence of the processes rather than of the products involved.

Norwegian Industry's "The Norwegian Process Industries' Roadmap" describes a number of methods for reducing $CO_2$ emissions, such as carbon capture and storage (CCS), the use of biocarbon and BioCCs. The road-map that we present here focuses on the use of gas. It comes under the category of "other measures", which Norwegian Industry's road-map estimates could contribute 24% of the potential reduction in the emissions of $CO_2$ by Norway's industrial sector.

# Summary

In order to increase the use of gas in metal production, we will need to develop new – and to further develop existing – gas-based technologies, which will need to be adopted on an industrial scale. In order to provide a few examples, this road-map describes a number of potential technologies and their environmental impacts, stage of technological maturity and the degree of change required for their implementation. It also describes the conditions that must be met if we are to develop new technologies to increase the use of gas in metal production, as well as the necessary conditions for industrialisation.

The road-map describes the specific types of competence relevant to the use of gas that must be made available at our universities and research institutions, and which industry will have to be capable of utilising. The development and industrialisation of new gas-based technologies will demand greater research and development efforts that will depend on adequate government support. If we are to achieve the aims of the road-map, R & D projects with longer-term perspectives than is the case today will play a vital role, and possibilities for performing research on technologies at early stages of maturity but that have high potential must be created.

# Contents

# 1. Introduction

Increased use of gas in metal production can result in improved processes and products, while also reducing environmental impacts. This road-map describes some relevant technologies which could be part of a future scenario in which gas is an important raw material for metal production. It also describes how to get there. Such technologies will contribute to the further development of a sustainable process industry that will continue to be important for Norwegian employment and value creation.

Global warming is already a major challenge, and according to climate scientists, we have little time left to deal with it. Norway takes the climate challenge seriously, and is navigating towards achieving a global low-emissions society by 2050. Both the report from the Norwegian Government's Expert Committee on Green Competitiveness and industry's own road-map focus on how Norwegian industry can improve its competitiveness by reducing its own emissions. Industry is aware that there is a need to adopt an ambitious long-term technology-development process.

Metal production utilises reducing agents to remove oxygen from ore. In Norway, as in other countries, these are mainly based on fossil sources of carbon that contribute to $CO_2$ emissions, which have a negative impact on climate change. Change is essential if we are to reach our goal of doubling production while achieving negative emissions of greenhouses gases by 2050. To meet this goal, it will be necessary to implement carbon capture and storage (CCS) and/or carbon capture and utilisation (CCU), in addition to replacing fossil-sourced carbon with biocarbon, as well as various other measures. Gas-based technologies will play a vital role in reducing the emissions $CO_2$ by replacing fossil carbon with hydrogen, by using carbon extracted from natural gas to eliminate $CO_2$ emissions from coking, and by implementing the use of biogas and developing new processes that are more suitable for carbon capture and storage.

Gas technologies also have other advantages. Gas can reduce our dependence on critical raw materials, reduce energy consumption and play a role in the development of other more profitable processes. Gas often contains lower amounts of critical contaminants, and it is easier to purify than solid raw materials such as coal and coke. Using gas can therefore lead to cleaner products and less pollution. What is more, the use of gas will often involve completely rethinking century-old processes, increasing the chances of a "quantum leap" to entirely new processes instead of merely step-wise modifications and improvements.

Norwegian metal producers are already among the best in the world in terms of having the lowest possible $CO_2$ emissions and environmental impacts. Maintaining and increasing the market share of Norwegian metal producers is therefore good climate and environmental policy. By increasing their use of gas, Norwegian metal producers can improve the quality and profitability of their processes and products and strengthen their competitiveness, while they ease the way towards even greener metal production in the future.

Enabling the Norwegian process industry to achieve its sustainability goals will not depend on a single solution. Several technological developments and innovations, both large and small, will help to a greater or lesser extent. It is important that such efforts are launched soon, and that they proceed at a high intensity from the very beginning. In order to develop the long-term solutions that need to be adopted by 2050, development efforts must start today in parallel with shorter-term interim solutions. This road-map introduces some gas-based technologies for metal production, including some that are already well on the way to industrialisation as well as ideas that to date have scarcely been studied on a laboratory scale.

In order to realise these technologies, a number of conditions will need to be in place. Chapters 4 and 5 of this report address some of the most important of these, that are not under the direct control of players in the process industry themselves. It is therefore vital that decision-makers are involved. The best research results will not lead to industrial change if the appropriate conditions are not in effect.

Neither the costs of developing and implementing new technologies nor their profitability are discussed here. The information needed to describe business cases and profitability will emerge as part of the development process for each individual case. Taking the climate challenge seriously will not be without its costs, but it will be even more expensive not to do so in a timely manner. Those who manage to turn the challenge of reducing greenhouse gas emissions into opportunities for further development will be best equipped to meet competition in the years to come.

## 2. Background of the road-map

For several years, NTNU and SINTEF have been directing strategic efforts towards increasing the proportion of natural gas as a raw material in Norwegian metal production, with the aim of reducing $CO_2$ emissions, increasing value creation in Norway in connection with Norwegian natural gas, and in ensuring and increasing the competitiveness of Norwegian land-based industry. In 2014, SINTEF organised, as part of its internal NatGasMetal project, a workshop for Norwegian industry on the subject of "Increased use of natural gas in metal production". One of the topics covered by the workshop was a "Road-map for increased use of natural gas in metal production". Lots of useful input was received during the workshop, and on this basis the plans for, and the content of, a road-map were drawn up. These were presented at the 2014 Metallurgy Summer Meeting by Eli Ringdalen, and at the PROSIN Conference, also in 2014, by Nina Dahl. The road-map was not completed at that stage, but the work that had been done provided the basis for infrastructure project applications with strong industry support in 2014 and 2016.

In 2014 the focus was on the use of natural gas in particular. One important motivation here was to increase Norwegian value creation through increasing the use of natural gas by onshore industry. Since 2014, the focus on sustainability has sharpened, and concepts such as "Green competitiveness" and "The Shift to Greenness" have entered the general debate and have gained in importance for Norwegian industry.

In 2016, a new workshop that focused on the use of natural gas in metal production was organised by the KPN GasFerroSil competence project. This time, the focus was shifted more towards gas in general, and gas from other sources such as biogas, hydrogen and off-gases was included in the programme. Once again, an important item on the agenda was the preparation of a "Road-map for increased use of gas" to be based on the 2014 discussion.

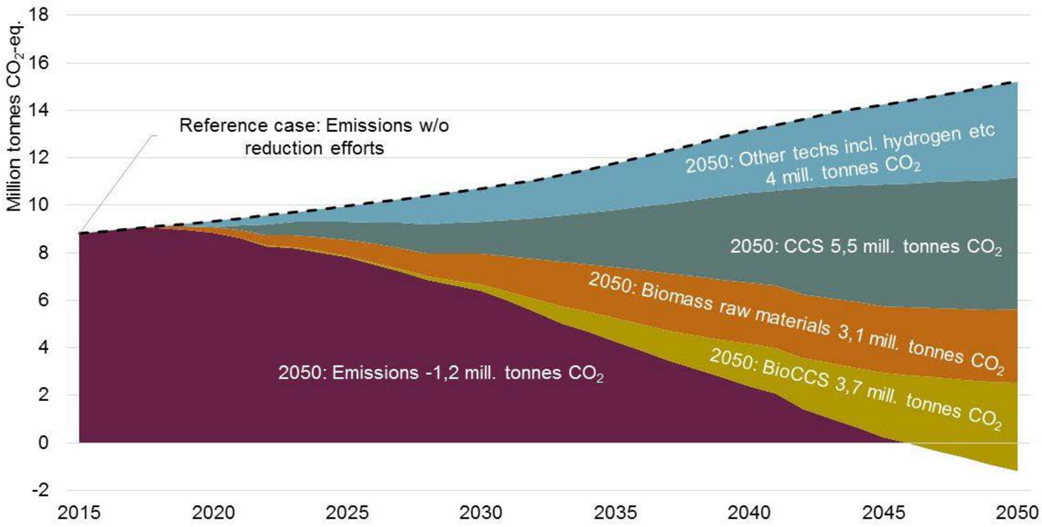


**Figure 1**: Emissions and reductions by type of emissions compared with reference track under conditions of robust industrial growth [Ref: The Norwegian Process Industries' Roadmap Combining Growth And Zero Emissions By 2050, English summary, 2016].

In May 2016, Norwegian Industry presented its "Roadmap for the Process Industry"[1], which offered a vision of a Norwegian process industry that produced zero emissions of greenhouse gases by 2050, without negative effects on the growth of the sector. This would require a reduction of emissions totalling 16.35 million tonnes $CO_2$-equivalent in 2050, in which the individual contributions to the reduction illustrated in Figure 1 are as shown below:

- Carbon capture and storage (CCS): 5.5 million tonnes $CO_2$ equivalent (34% of total)
- Biocarbon: 3.1 million tonnes $CO_2$ equivalent (19%)
- BioCCS; 3.7 million tonnes $CO_2$ equivalent (23%)
- Other measures: 4 million tonnes $CO_2$ equivalent (24%)

Such an ambitious vision will require a number of new technological solutions to be developed and implemented. Gas-based technologies will fall directly under the "Other measures" listed above.

Besides solid carbon, biocarbon production will also lead to fluid products such as biogas, which can also be included in gas-based technologies for metal production. The most important component of biogas is methane, which is also the main component of natural gas. In other words, a methane-based process can utilise biogas as a raw material in the medium term, replacing it with $CO_2$-neutral biogas in the future as sufficient supplies of the latter become available.

An important reason for launching this road-map is to help to reduce $CO_2$ emissions, but other advantages are also obtained by the use of gas in metal production. Access to raw materials is a challenge, particularly as much of the solid-phase carbon used in metallurgical processes comes from politically unstable regions of the world, and cannot simply be replaced without difficulty. Even though coal for the metallurgical industry comes to only a small percentage of world consumption, reducing this component will help to reduce coal extraction and the negative environmental impact of coal-mining. Both coal and coke contain a wide range of trace elements and impurities that negatively affect

[1] Norsk Industri: "Veikart for Prosessindustrien—økt verdiskapning med nullutslipp i 2050" (In Norwegian, English summary available as "The Norwegian Process Industries' Roadmap—Combining Growth And Zero Emissions By 2050"

both process and product, and that produce emissions. As a rule, gas contains fewer critical impurities than coal and coke, and it can be easier to purify than a solid material.

Gas-based technologies could become a means of improving competitiveness and increasing the profitability of Norwegian metal producers. Since Norwegian metal production is more environmentally friendly than the international average, maintaining and increasing metal production in Norway will have real environmental benefits.

Norwegian gas-based metal production processes will be one of several important solutions for ensuring sustainability and competitiveness, and that is the subject of this road-map. This “Road-map for gas in the Norwegian metallurgical industry” is presented as a supplement to Norwegian Industry’s “Road-map for the Process Industry”. The aim of the road-map is to emphasise the use of gas in metal production in particular, and to go into more detail regarding how the use of gas in metal production can help us to achieve the aims of Norwegian Industry’s road-map. The “Road-map for gas in the Norwegian metallurgical industry” does not go into detail in areas that do not directly touch on gas technology, instead referring to Norwegian Industry’s road-map.

The following chapters describe relevant gas-based technologies that have the potential to improve metal production, and offer an assessment of their potential, and of the chance that they will be realised by the metal production industry.

Also identified in the following are the other conditions that will need to be fulfilled if the road-map is to be realised. These are divided into two categories. In Chapter 4, “Prerequisites for technology development”, we describe the prerequisites for the development of new gas-based technologies that can be implemented by the metallurgical industry. Chapter 5, “Prerequisites for industrial use”, describes the conditions required to implement and industrialise these technologies once they have been developed.

# 3. Relevant technologies

## Introduction

In many cases, the wider use of gas in metal production will require other technological solutions than those that have been in use until now. In some cases, these are already available, but in many others, various amounts of research and development remain to be done. This may consist of incremental modifications of existing processes, new process stages or sub-processes, or completely new processes and plants.

Gas-based technologies can be used in metal production in many ways, such as pretreatment and pre-reduction of materials. In certain cases, gas can also replace solid carbon sources as a reducing agent and in that way play a role in reducing ore to metal. Another approach might be to use the gas as a source of solid carbon, while reduction during smelting would also be possible.

It is natural to start by focusing on the most readily available solutions, but in such a long-term perspective as 2050 – and with such an ambitious aim as zero greenhouse gas emissions – it will also be necessary to evaluate technologies that cannot be directly utilised in current processes or in existing plants. Precisely because the development of revolutionary technologies is such a demanding process, it will be necessary to adopt a long-term approach that ensures that these technologies will be available sufficiently far in advance to guarantee that we can meet our goals for 2050. Major long-term changes will be more attractive if developing them can also lead to improvements in current processes. Such interactions with existing technologies will also give us the opportunity to garner experience on the way, and thus make these technologies easier to implement. Wherever possible, therefore, the road-map identifies relationships between current and future technologies, and how such relationships can be exploited.

The following chapters present some potential gas-based technologies. These are intended to offer examples of possible uses rather than complete descriptions, whether in the form of a list of all possible technologies or complete descriptions of each individual case. Each technology is given a standard characterisation that summarises some of its most important features. The factors described in these summaries are the following:

- Environmental impacts: A quantification of environmental impacts will require a major effort, associated with considerable uncertainty. For this reason, they are described here merely in terms of keywords.
- Degree of change: This refers to the extent to which the technology is compatible with existing processes, or whether it will involve greater or lesser degrees of change or adaptation. These technologies are roughly sorted into three categories:
  - New raw materials. These will require only minor adaptations or adjustments to existing processes.
  - Adaptations of existing processes. These will require modifications of existing processes or new sub-processes.
  - New plants. Some processes will require complete restructuring, and their industrialisation will probably require new plant to be built.
- Technological Readiness Level (TRL): This is described on the basis of the EU Commission's definition. Here, we summarise it as follows:
  - TRL 0-4: from idea to testing and understanding of the mechanisms and principles involved, up to laboratory-scale demonstration.
  - TRL 5-6: Pilot testing on various scales
  - TRL 7-8: Commissioning of full-scale plant
  - TRL 9: Commercially available, well-established technologies

## 3.1 Pretreatment and pre-reduction

Metals are produced from oxygen-rich ores by removing the oxygen in a reaction with a reducing agent, usually carbon, at high temperature. In a separate process ahead of the reduction stage itself, the ore can be treated with hot gas. This heats and dries the raw material, in this way potentially lowering the energy consumption of the subsequent reduction process. During pretreatment, it is the energy content of the gas that is used to heat and dry the raw material. In pre-reduction, a reducing gas is used to remove some of the oxygen in the ore, so that the amount of carbon required in the subsequent reduction stage will be reduced. The gases most frequently used in pretreatment and pre-reduction are $H_2$ and CO, which can be obtained, for example, from metal production flue gases or production of biomaterials.

### Pretreatment and pre-reduction of manganese

Manganese (Mn) is produced by reducing ore that contains manganese oxides ($MnO_2$, $Mn_2O_3$ and $Mn_3O_4$), with carbon, to manganese metal and $CO_2$. The reduction process takes place in several stages, in which the higher-order oxides ($MnO_2$, $Mn_2O_3$ and $Mn_3O_4$) are reduced to MnO and thereafter by further reduction in the liquid phase to manganese metal. Pre-reduction involves heating, drying and partial reduction to MnO in a separate unit before the rest of the oxygen is removed and the metal is produced in a traditional smelting furnace, as illustrated in Figure 2.

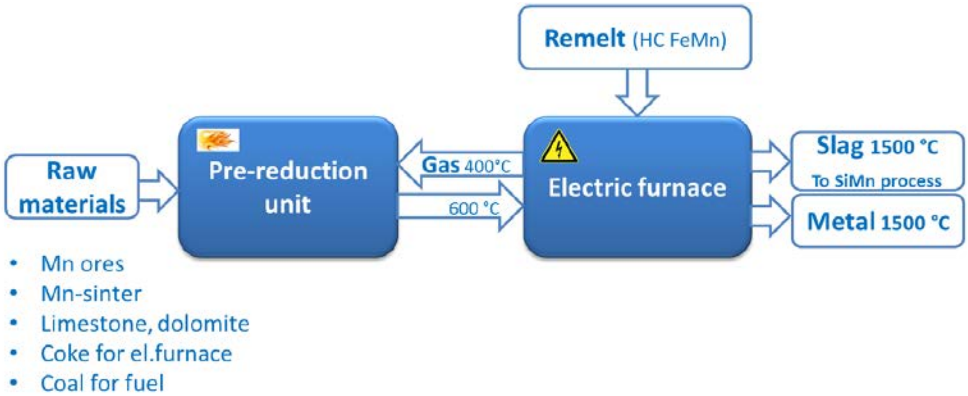


**Figure 2**: Diagram of manganese production process

In the most common process in current use, reduction takes place from high-order oxides to MnO and then from MnO to Mn metal in the same smelting furnace. Pre-reduction to MnO releases energy, which reduces the energy consumption of the furnace, but in industrial use, only about 40% of the theoretical potential is realised. Heating and drying require a great deal of energy, and by performing these processes in a separate pretreatment unit, the electricity requirements of the smelting furnace itself are reduced. An extra process stage often results in lower efficiency, with the result that total energy consumption increases, but a separate pretreatment unit enables other energy sources such as various types of gas to be used. This is particularly useful when electrical energy is not readily available or is very expensive, or when it is derived from non-renewable sources. The improved control of raw materials that results from sharing the process between separate units can reduce the energy requirements of the furnace and total energy consumption. The use of $H_2$ and $CO_2$-rich flue gases that are not currently exploited will reduce $CO_2$ emissions. Using biocarbon as a source of energy instead of coal or coke will also reduce fossil $CO_2$ emissions.

Pre-reduction of manganese ore is already under way on an industrial scale. Kashima Works in Japan pre-reduces ore using coal and gas in the process illustrated in Figure 2. The energy consumption of Kashima's furnace is 600 kWh/tonne of metal lower than for an equivalent process that does not utilise pre-reduction. Pretreatment of the ore offers a potential reduction in energy consumption per tonne metal at the furnace stage. When electrical energy is being generated from fossil fuels, this will reduce total $CO_2$ emissions.

Pre-reduction using only gas is not currently practised in industrial manganese production. Experience from the chromium industry, in which partly gas-based pre-reduction of chromium ore has been installed at a number of chromium smelters, could be used in the development of gas-based pre-reduction of manganese. This process is thus at a high level of technological readiness, and is capable of being installed at existing plants. Some gases could help to reduce $CO_2$ emissions, but the principal incentives would be the provision of flexibility in the choice of energy sources, the prospect of reducing energy consumption and the potential for improving existing processes.

**Environmental impact:** **Medium.** **TRL:** **5-6** **Extent of change:** **New unit at existing plant**

## Pre-reduction of ilmenite using gas

TiZir Titanium & Iron in Tyssedal in Norway produces the white pigment titanium dioxide ($TiO_2$) and special qualities of pig-iron, for use, for example, in wind turbines, in a two-stage process illustrated in Figure 3 below.

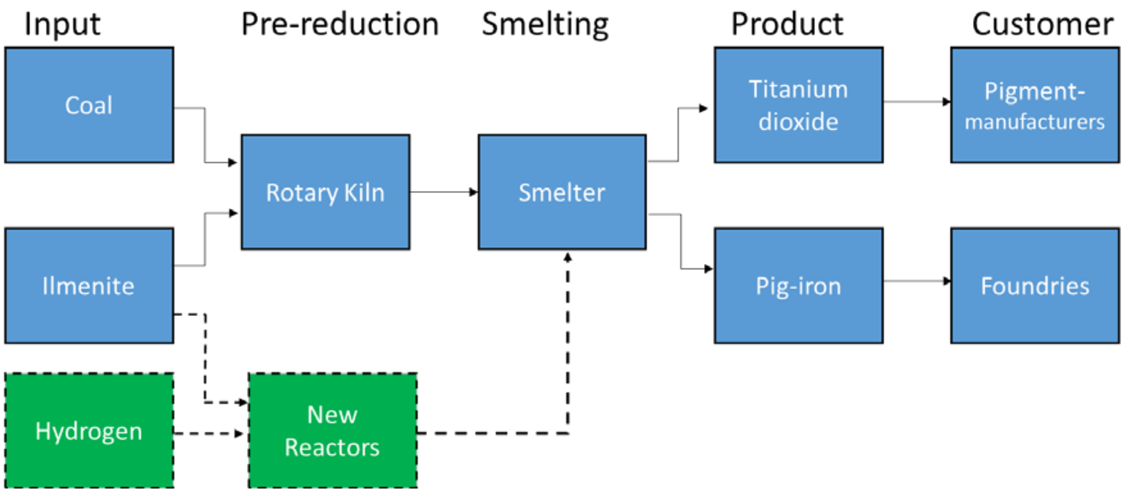


**Figure 3**: Diagram of TiZir Titanium & Iron's production process for titanium dioxide and pig-iron from Ilmenite (based on sketch, courtesy of H. Grande).

The ilmenite ore is first pre-reduced in a rotary kiln before the pig-iron and titanium oxide are produced in an electric smelting furnace. The pre-reduction stage uses coal as a reducing agent, in which heat is generated by combusting off-gas. TiZir Titanium & Iron is studying the possibility of switching to hydrogen as a reducing agent in a new pre-reduction process. The gas could potentially be generated by electrolysis of water. Fossil carbon would only be used in the smelting furnace as a means of fine-tuning the final degree of reduction of the products. In this way, $CO_2$ emissions per tonne of $TiO_2$ could be reduced by as much as 90%. TiZir Titanium & Iron has come furthest among Norwegian metal producers in implementing gas technology. Below is an English translation of the description of their technology Norwegian Industry's "Road-map for the Process Industry":

> *TiZir will replace coal with hydrogen as a reducing agent in its titanium dioxide and high-quality pig-iron production process as it increases production. This will be done via a four-stage process.*
>
> *The first of the four stages, which is already under way, introduces new technology. It will be prepared for a future transition from coal to hydrogen, specific $CO_2$ emissions and specific energy consumption will be reduced, and production capacity will be increased without exceeding the limits imposed by the emissions permit. NOK 450 million will be invested in this stage, which is being supported by ENOVA to the tune of MNOK 122. Stage 2 (2017) will be a hydrogen pre-reduction demonstration plant. In 2019, stage 3 will be opened as a full-scale pilot plant and in about 2021 stage 4 will be a full production line with hydrogen pre-reduction and a new furnace.*
>
> *The current production plant utilises a cold smelter feed, which results in energy losses. The planned hydrogen-based process will employ a hot smelter feed. Using hydrogen instead of coal will reduce specific emissions from 1.73 to 0.18 tonnes of $CO_2$ per tonne $TiO_2$ (90 per cent*

*reduction), and energy consumption from 6.4 to 3.8 MWh per tonne $TiO_2$ (40 per cent reduction). Total $TiO_2$ production will rise from 195,000 to 655,000 tonnes a year, while $CO_2$ emissions will be reduced from 338,000 to 118,000 tonnes/year. In connection with the project, a new scrubbing system will also be installed to reduce both diffuse dust emissions and the dust concentration of scrubbed flue-gases.*

*Hydrogen will be produced from electricity-powered water electrolysis. The technology to be developed will be transferable to other types of production and to other industries.*

**Environmental impact: High** **TRL:5-6** **Extent of change: New unit at existing plant**

## 3.2 Reduction to metal in solid phase

If gas can be used to completely reduce oxides to metal, there will no longer be a need for solid carbon, and if the ore is sufficiently pure, nor will there be a need for separation in a smelting process, which will enable $CO_2$ emissions and energy consumption to be reduced. The extent to which a given metal is suitable for such a direct reduction process will depend on the stability of the oxide and of the reduction potential of the gas employed. The most relevant gases, i.e. $H_2$ and CO, and various mixtures of these, are already used in iron production. A more speculative alternative that is not currently used might be methane ($CH_4$). In theory, methane is a more powerful reducing agent than $H_2$ or CO, and it could be used on various different metals, but there are a number of practical challenges that will have to be overcome before methane can be adopted on an industrial scale.

### Direct reduced iron (DRI)

Iron is one of the few metals that in theory can be completely reduced to its metallic form in the solid phase by means of synthesis gas (Syngas), which is a mixture of CO and $H_2$. It has been used since the 1970s for industrial production of “Direct Reduced Iron” (DRI). Global production is rising, and is now more than 70 million tonnes a year. Even though there are no Norwegian producers of DRI at present, the technology is still relevant. For several years, the potential of the Ironman project at Tjeldbergodden was studied. The plan was to use Norwegian natural gas and Swedish or Norwegian iron ore to produce extremely environmentally friendly iron, while drastically increasing the value of the export flow of natural gas from Norway. The project failed to attract investors and is currently inactive.

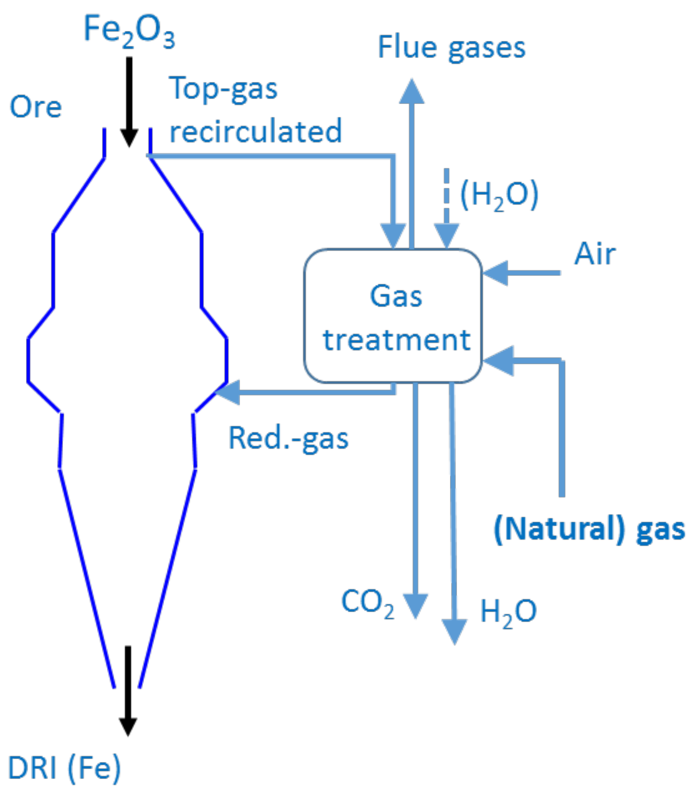


**Figure 4**: Outline of the DRI process

DRI is also important because it represents an already realised gas-based metallurgical process. A number of different technologies have been developed and are already in use, and one of them is illustrated in Figure 4. This process offers a good basis for the development of new processes, and it might be possible to transfer or adapt several of the technologies involved so that they can be used in the production of other metals.

DRI production is also indirectly relevant for iron-ore producers. RaNaGass was a four-year research project that investigated the prospects for processing Norwegian iron ore sufficiently to make it suitable for DRI production. The project was successful, but a continuation of its activities has been abandoned for the time being, due to the low global price of iron ore.

DRI as a technology has great potential for reducing global $CO_2$ emissions. Production of iron in a blast furnace generates emissions of around 1.9 tonnes of $CO_2$ per tonne of iron produced., while for DRI production using natural gas emissions are about 0.5 tonnes of $CO_2$ per tonne of iron, i.e. about 75% lower. World-wide production of steel in 2014 was 1500 million tonnes, 1150 million tonnes of which were produced from iron in blast furnaces. The large volume of production, in addition to the fact that gas-based DRI production accounts for less than 5% of global volume, means that there is a great potential for reducing $CO_2$ emissions by increasing the use of DRI in iron production.

**Environmental impact:** **High** **TRL:** **9** **Extent of change:** **New plant**

## Reduction to metal using methane as a reducing agent

When methane is heated it becomes unstable and decomposes into solid carbon and hydrogen gas:

$$CH_4 \rightarrow C + H_2$$

In theory, decomposition starts at around 500° C, a temperature that is too low for ore reduction. In practice, however, we find that methane can be kept in a metastable state to much higher temperatures than this, in fact hot enough to enable certain metal oxides to be reduced. At such high temperatures, methane gas is unstable and thus has a significant reduction potential. Reduction can thus take place at lower temperatures than when traditional reducing agents such as coal and coke are used, thus reducing energy consumption. If biogas is used as a source of methane, the net emissions of $CO_2$ from the reduction process will be zero. One by-product from a process of this sort will be a valuable mixture of hydrogen, methane and CO gases.

Oxide reduction using methane has been demonstrated on a laboratory scale for chromium and manganese, among other metals. A technology that utilises methane in this way on an industrial scale will have to control the reduction process well enough to avoid decomposition of the methane gas. This will be a major challenge that requires a fundamental understanding of reaction mechanisms down to molecular level. In other words, the road to industrialisation is expected to be long, although it has high potential.

This concept has been studied by a number of of projects financed by the Research Council of Norway: for silicon production, in the ReSiNa and KiSelROx projects, and for chromium, in Coralsea.

**Environmental impact: Medium (natural gas); High (biogas) TRL:1-2 Extent of change: New plant**

## 3.3 Gas as a source of carbon

As described above, methane decomposes into hydrogen and carbon at high temperatures:

$$CH_4 \rightarrow C + H_2$$

The carbon that is created can be used as a substitute for coal and coke. Coal contains volatile components that produce significant carbon emissions which would be eliminated by the use of methane, as would the negative environmental impacts of coal-mining operations.

Carbon is already produced industrially via methane decomposition, and is commercially sold as carbon black. This road-map primarily examines the use of gas in the metal production process itself or in pre-treatment units in which the gas meets the raw materials, rather than on the use of externally produced carbon black.

Carbon deposited from gas has different properties than particles of coal and coke. In many cases these can be an advantage or even a prerequisite for the processes and technologies involved. For example, carbon from gas can be deposited in pores, thus covering oxide surfaces that can then be reduced, or form finely divided particles that do not need to be crushed before use. The hydrogen generated in the course of decomposition can also be utilised in the reduction process, or be sold as a by-product. A number of potential applications are described below as examples.

### Composite materials from carbon black derived from gas.

One way to utilise the carbon content of methane is to deposit it directly on the ore to produce a composite raw material that contains both oxide and carbon. Such a material could be used as a raw material in existing furnaces without major infrastructure modifications. A layer of carbon that completely covers the oxide surface would provide a very extensive area of contact between the carbon and the oxide. This could influence the reaction mechanisms, increasing yield rates and thus improving their return and reducing energy consumption.

The deposition of carbon from methane on oxides has been studied on a small scale in the KPN GassFerroSil project.

Agglomerated composite materials also provide an opportunity to exploit finely divided particles of less than about 5 mm that would otherwise be unusable. In combination with deposition of carbon from gas, this would provide a very extensive area of contact between the carbon and the oxide, which would be an advantage when high reaction rates are desirable. Here too, hydrogen, possibly mixed with methane, would be a by-product. The resulting composite products could be utilised in existing or future processes. The environmental gains would include higher rates of return on the raw materials and reduced coking emissions, while the use of biogas would reduce emissions of fossil $CO_2$.

**Environmental impact:** **Medium** **TRL:4** **Extent of change:** **New raw material for existing process**

## Densification of biocarbon-based charcoal

Non-fossil carbon (biocarbon) is often porous, which is a disadvantage when carbon needs to be mechanicaly strong and not excessively reactive, as is the case in manganese production. The pores in biocarbon can be closed by the deposition of carbon from methane, as illustrated in Figure 5. This could ease the transition to the use of biocarbon as a means of reduction.

**Figure 5**: Porous biocarbon can be blocked by depositing carbon in its pores.

Methane gas or other carbon-rich gas can be blown through biocarbon at a temperature that is sufficiently high to deposit solid carbon. A two-stage process, in which the pores are first partially closed with carbon derived from methane at 1000 – 1100 °C, and then completely by heat treatment at even higher temperatures, is another possibility. In both cases, good control of the gas flow before, during and after the deposition process is essential. This process has yet to be tested. Its degree of technical maturity is regarded as low. The process could also be integrated into the production of biocarbon.

**Environmental impact:** **High** **TRL:1** **Extent of change:** **New raw material for existing process**

## Carbon black derived from gas in electrode production

Carbon black from gas is a potential raw material for both the aluminium and ferroalloy industries. Anodes for aluminium currently consist of coal and tar pitch, mixed with recycled anode material. The carbon material in the anodes can be replaced by carbon and biocarbon. As oil refineries increase their utilisation of petroleum for high-value products, the quality of their tarry by-products used to make anodes is declining. Dilution with pure gas-derived carbon could help to achieve the purity needed for electrode production. A certain amount of carbon black is produced today by thermal decomposition of methane; this is known as thermal black. This offers good control of purity, and provides a compact carbon black microstructure that is suitable for low-porosity anodes.

Methane decomposition is an endothermic reaction that requires a continuous supply of energy. In carbon black production this is achieved by the combustion of hydrogen-rich flue gas. If the production of carbon black for anodes is incorporated into a smelter production cycle, its waste heat can be used to heat the carbon black reactor. This will make hydrogen combustion unnecessary, and the hydrogen can be treated as a by-product.

**Environmental impact: Medium (natural gas); High (biogas)** **TRL:2**
**Extent of change: New raw material for existing process**

## 3.4 Gas treatment of liquid metal

### Gas-based silicon refining

Silicon for use in solar cells needs to meet strict purity standards. Most solar-cell silicon is produced by variants of the Siemens Process, which is efficient but extremely energy-intensive. A great deal of effort has been invested in finding more energy-efficient purification processes, of which Elkem's process is a successful example.

An alternative method that has been studied is to use gas to clean the silicon melt. For example, boron, which is one of the most important elements that need to be removed, is eliminated by steam flushing. The boron dissolved in the melt is thereafter converted to boron hydride oxide (HBO) which is carried off in the flue gas:

$$[B] + H_2O_{(g)} = HBO_{(g)} + \frac{1}{2} H_{2\,(g)}$$

## 3.5 New processes

### Liquid metal as a reaction medium; a new process for manganese production

Methane can be decomposed in liquid metal, and by an arrangement as shown in Figure 6 we can obtain separate streams of hydrogen ($H_2$) and carbon monoxide (CO). If these are burned in a gas turbine or similar equipment with air or oxygen respectively, electricity can be generated with "pre-captured" $CO_2$.

Examples of areas that will require further study and/or research:

1. Methane injection: dissolution of C in melt
2. Hydrogen from cracking: $CH_4(g) \Rightarrow \underline{C} + 2H_2(g)$
3. Oxygen injection for $\underline{C}$ refining
4. CO from C refining $2\underline{C} + O_2(g) \Rightarrow 2CO(g)$
5. Addition of ore
6. Addition of solid carbon
7. Flue-gas from pre-reduction
8. Reduction of MnO using dissolved $\underline{C}$

The process outlined here can be described as "Production of synthesis gas ($CO+H_2$) with the aid of Mn smelt and separation of CO and $H_2$ into separate streams, and low carbon Mn as a by-product." The synthesis gas production stage corresponds to points 1 – 4 above; Mn production will depend on the other four points. Using the flue-gases for electricity generation or other combustion applications while CO is combusted with oxygen would represent a possibility for "pre-captured" $CO_2$. This would enable natural gas and Mn ore to be converted for example to electricity and manganese alloy without emitting greenhouse gases. This would depend on it being possible to deposit or utilise the $CO_2$ that is produced. In this case we are talking about quantities of gas equivalent to those produced by a gas-fired power station with a capacity of around 450 MW.

The produced hydrogen can of course be utilused for other purposes, ranging from pre-reduction of ilmenite to automobile fuel.

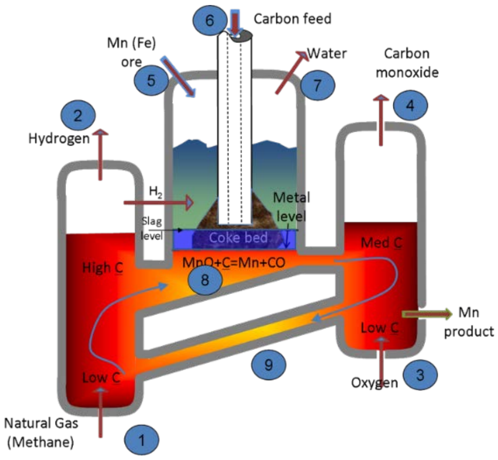


**Figure 6**: Outline of possible process for the use of metal smelt as a reaction medium.

In this way, carbon from natural gas diluted in metal can act as a reducing agent that produces only small amounts of pollutants, which can be used to reduce oxides.

**Environmental impact: Low** **TRL:4** **Extent of change: New plant**

## Reduction using solid carbon in $H_2$ or $CH_4$ gas mixtures

Carbon is used in traditional metal production to remove oxygen from the oxide (ore) to generate $CO_2$ gas, with the following general chemical equation:

$$2MeO_x + xC = 2Me + xCO_2$$

In a real-life situation, the reduction process does not take place through a direct reaction between solid carbon and an oxide, but via gas. Carbon monoxide and carbon dioxide “carry” oxygen and carbon between the oxide and a solid carbon-rich material such as coke or coal. Other gases such as $H_2$ or $CH_4$ can also be used for this “transport”. Both calculations and pilot studies suggest that metal production can take place more rapidly and at lower temperatures when $H_2$ or $CH_4$ are present in the gas mixture. This can reduce energy consumption, while opening the possibility of developing processes with higher yields.

Using methane could provide a basis for a new combined process. Methane can be decomposed to $H_2$ and C, and thus act as a source of both the carbon required for reduction and the hydrogen gas in which the reduction can take place. Since the hydrogen is not consumed in the process, it can be reclaimed from the flue gas.

**Environmental impact: Medium** **TRL:2** **Extent of change: New plant**

## SiC from SiO and $CH_4$

Silicon carbide (SiC) and silicon monoxide (SiO) are intermediate products of silicon production, and SiC is also a product in itself, being used as an abrasive, among other applications.

Hot SiO gas that meets cold methane gas is converted to SiC. This has been demonstrated on a small scale[2], but no attempts have been made to scale up the process, and the mechanisms involved have not yet been studied. Just as in several other cases, the gas could be a much cleaner source of carbon than coal, for example. This offers a potential opening for new processes that would produce highly pure SiC, suitable for use, for example, in the production of solar-cell silicon. An example is illustrated in Figure 7. It might also offer the possibility of higher yields of silicon. Since SiO production is the most energy-intensive stage of the production of silicon metal, improved yields would reduce energy consumption per tonne of silicon produced.

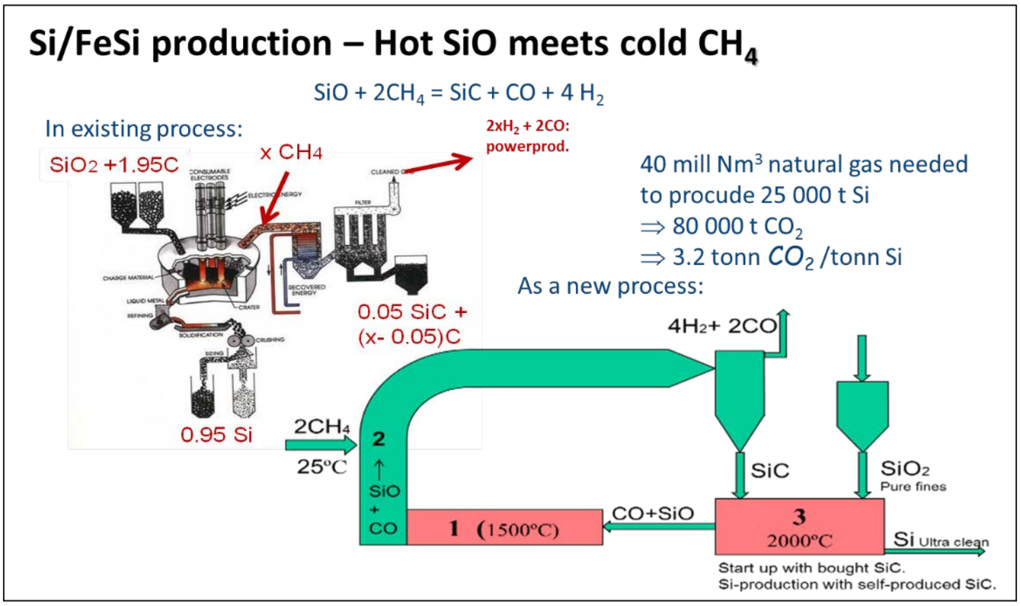


**Figure 7:** Diagram of how gas-based SiC production can be used to modify an existing process, or become an entirely new process.

We can also imagine using methane in existing silicon processes. For example, by blowing methane over the surface of the charge, we can cool the SiO-rich gas and produce SiC, which returns to the process, where it can further react to form silicon. A number of HSE challenges are related to this.

**Environmental impact: High TRL:2-4 Extent of change: New raw material for existing process**

## Gas anodes for aluminium

Aluminium (Al) is produced by electrolysing aluminium oxide ($Al_2O_3$) in a salt-bath solution:

$$Al_2O_3 + 3/2\ C + \text{Energy} = 3/2\ CO_2 + 2\ Al$$

In the current process, the carbon source consists of carbon anodes that are consumed in the process. The smelted aluminium oxide reacts to produce aluminium and $CO_2$ in an electrochemical reaction. Inert anodes, which obtain all the energy used to reduce the $Al_2O_3$ from electricity, would completely remove the $CO_2$ emissions of the process, but the energy consumption would greatly increase. Several

[2] Monsen et al: Possible use of natural gas for silicon or ferrosilicon production; INFACON 13, Alamty, Kazakhstan 2013

years of research have not yet managed to develop an inert anode that is capable of surviving the extremely corrosive cryolite smelt. If porous anodes that are not consumed by the process, in which carbon is supplied in the form of methane gas that passes through the anodes as illustrated in Figure 8, are used, the reaction equation becomes:

$$Al_2O_3 + 3/4\ CH_4 + Energy = 3/4\ CO_2 + 2\ Al + 3/2 H_2O$$

This reaction uses about the same amount of energy as the current process, while the $CO_2$ emissions per unit aluminium produced are reduced by about 50%.

The challenges for gas anodes lie in anode technology, and in controlling emissions of hydrofluoric acid (HF). When hydrogen from methane reacts with fluoride salts in the salt bath HF, which is extremely corrosive and toxic, is generated. Studies have been performed on whether HF in flue-gas can be reacted with $Al_2O_3$ or $Al(OH)_3$ to form $AlF_3$, which can be returned for reutilisation in the salt bath.

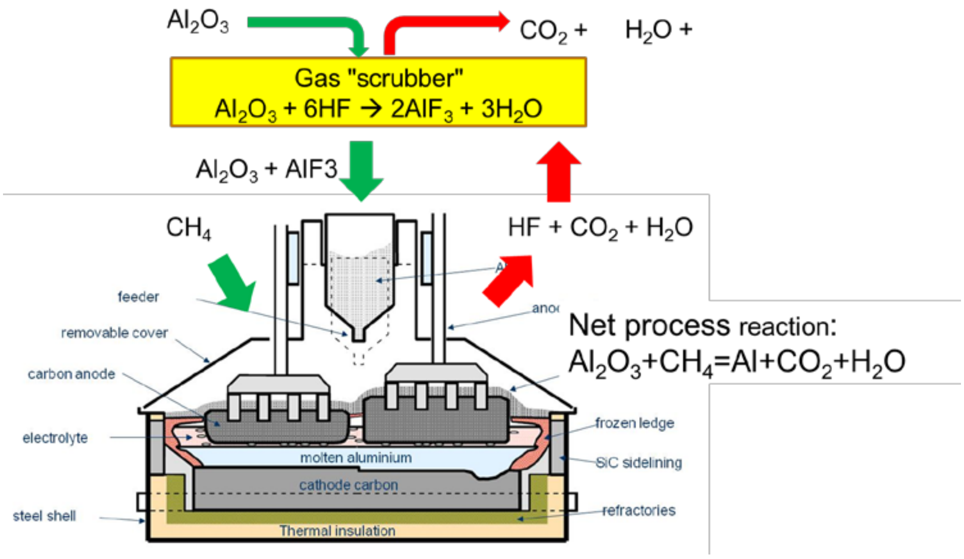


**Figure 8**: Gas anodes with scrubber for removal of HF from flue gas

The development of porous anodes will depend on a better understanding and control of the distribution of gas and electric current, and of the triple-phase reaction between salt-bath, electrode and gas phase. The anode material must also be able to withstand the highly reactive salt bath.

Gas anodes have been studied in the RCN-financed research projects FP Gas Anode and FP NovAl, and in SINTEF's internal strategic project NatGasMetal.

**Environmental impact: High** **TRL:2-3** **Extent of change: New plant**

## Co-location of different industries in industrial clusters

The joint localisation of different industrial entities opens up the possibility of using flue gases from one company's processes as a raw material for another. This can also be combined with power station operation and with CCS. The possibilities offered by co-location are illustrated in Figure 9. Co-location and clusters have been studied by the KPN GassMat and KPN FassFerroSil projects, which discussed clusters of the type known as "industrial symbiosis", in which the individual companies interact to their mutual benefit, in accordance with the same symbiotic principles as we find in nature.

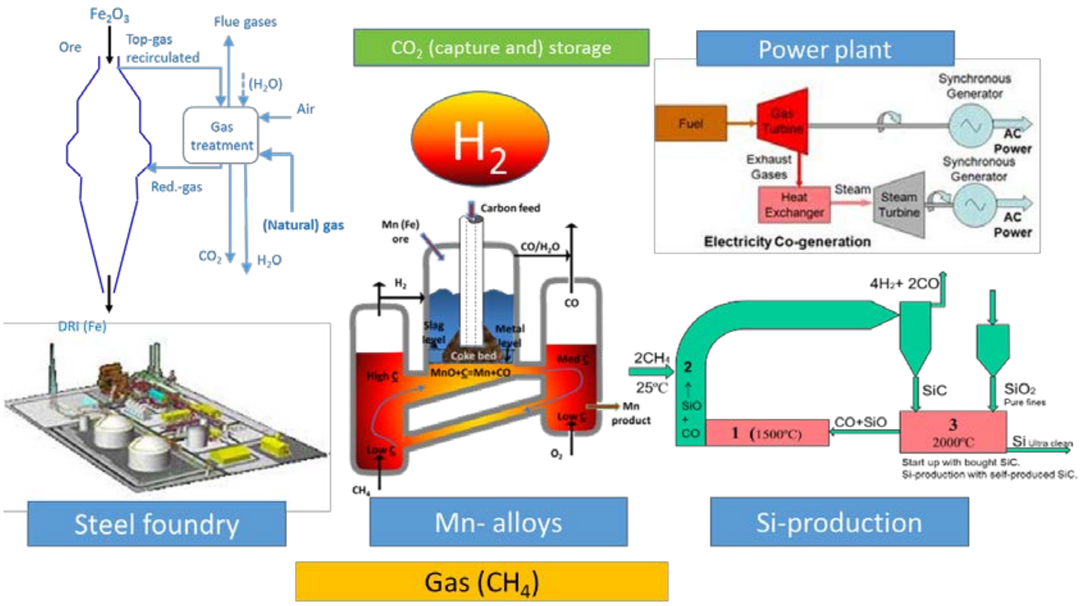


**Figure 9**:Possibilities produced by colocation of different processes.

The environmental impact and degree of technological maturity vary with the combination of processes involved, and are different from case to case. These are therefore not reviewed in this report.

Professor Marian Chertow of Yale University's School of Forestry and Environmental Studies, who has studied industrial symbioses for many years, points out that it is extremely difficult to construct such clusters; they need to grow or develop naturally in the course of a three-stage process[3]:

1. Formative stage involving numerous actors engaging in exchanges of materials and energy
2. Conscious recognition and intentional pursuit of network benefits
3. Institutionalization of beliefs and norms enabling successful collaborative behavior.

Like many other researchers in the field of industrial ecology, Chertow has studied the development of the Kalundborg Symbiosis Eco-industrial Park in Denmark, which is often described as the oldest and most advanced case of industrial symbiosis in the world. The story of Kalundborg Symbiosis started in 1961, when Statoil (at that time Esso) needed cooling water for its new oil refinery. Instead of using the local authority's drinking water supply, surface water was brought by pipeline from Lake Tissø. This solution was developed and carried out in collaboration with the local waterworks, and continued step by step in the course of time, as shown in Figure 10. The next step in the development of the industrial estate took place 11 years later, when by-product gas from the refinery was used by the gypsum producer Gyproc.

[3] Chertow, M., and Ehrenfeld, J. (2012). Organizing Self-Organizing Systems: Toward a Theory of Industrial Symbiosis. *Journal of Industrial Ecology*, 16(1), 13-27. doi: 10.1111/j.1530- 9290.2011.00450.x

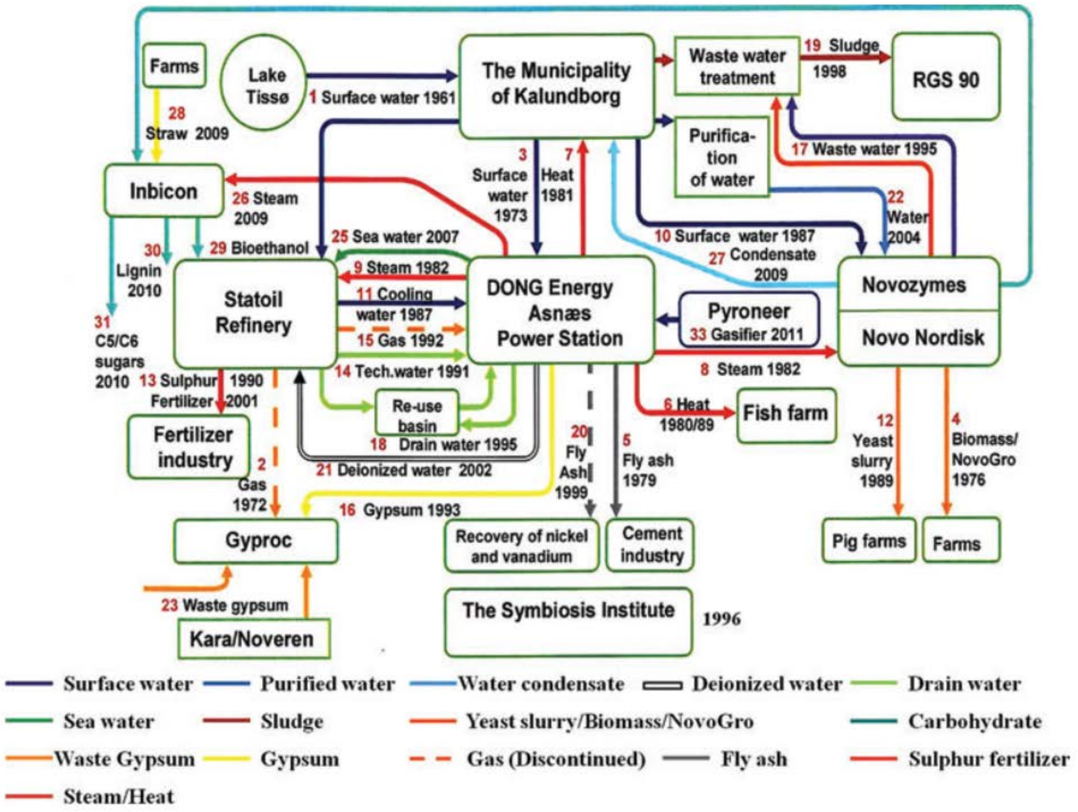


**Figure 10**: Kalundborg Symbiosis. Important exchanges of materials and energy are numbered from 1 to 33, and the numbered years indicate when each of them started. Subsequently removed connections are shown as stippled lines. The figure is taken from [http://www.symbiosis.dk/en/system] as modified by Chertow.

In 1989, about half of the currently active resource exchange projects were already under way in Kalundborg. It was about that time that the companies involved put a name to what they were doing, and started to call the process "industrial symbiosis", thus arriving at stage 2 of the Chertow process. They realised that they were working in accordance with the principles involved in symbiosis in nature, in which many species act together to their mutual benefit.

# 4.Prerequisites for technology development

Realisation of this road-map in the shape of increased use of gas in metal production will depend on the development of existing and new technologies, which in many cases will involve a significant element of research. Here, "technology development" refers to the development of an idea until it is sufficiently mature to be progressed to industrial use, i.e. until it can be demonstrated on pilot scale (TRL 6). In other words, technology development as we employ the term, will mostly take place in research institutions, although also in industrial research departments. Close collaboration among all these participants is essential for the development of technologies that can be realised on an industrial scale. In this chapter, we describe the most important prerequisites for the technology development that we need to take place. Even though the route from pilot scale to commercial operation is also largely a matter of technology development, in this road-map we have defined that aspect of the realisation process as "industrialisation". The prerequisites for industrialisation are described in Chapter 5 below. Even after realisation, research and development will be needed to continually improve processes, as the Norwegian metallurgical industry has been doing for more than one hundred years.

## 4.1 Competence

The most important prerequisite for all technology development is competence. We do not discuss the matter of basic competence here, but refer to Norwegian Industry's Route Map for the Process Industry and the government's Industry White Paper, which for example points out that necessary competence must be available at all levels of industry and the research sector.

In order to reach the goals of this road-map, we will need to focus on specific areas of expertise as prerequisites for technology development, which will involve the most important participants maintaining and continuing to develop their competence in metallurgical and process technology disciplines. These disciplines include, but are not limited to:

Thermodynamics:
Thermodynamics will be a basic area of knowledge for understanding gas-based metal production, just as it is for other processes. Expansion into new processes will require us to update our thermodynamic models of systems and databases.

Reaction kinetics:

Making improvements in processes requires a fundamental understanding of the reaction mechanisms involved. A necessary tool for such an understanding is a high level of competence in reaction kinetics and an ability to create kinetic models.

Properties of raw materials:
The properties of raw materials affect process design and operation. Competence in the areas of mechanical and electrical properties, and how these can be affected by pre-treatment (drying, agglomeration, etc.), are essential. Good methodologies for measuring and describing such properties are also important.

Fluid dynamics:
A knowledge of fluid dynamics is needed in order both to describe gas flows and in the design of reactors and processes, and such knowledge can also be a component of the process of modelling and understanding reaction mechanisms.

Gas-solid reactions:
A large proportion of the relevant reactions will be gas-solid reactions. This is true of most reduction reactions, as well as of catalytic effects in methane cracking.

Gas treatment:
This point applies not only to industrialisation and the construction of new plant, but is also relevant to the building of test-rigs in laboratory and pilot systems, and is essential for good HSE.

If we are to build up further competence in these areas, they will need to be given priority via strategic efforts and competence projects. Participation in international cooperative projects will give Norway access to international expertise.

Our research centres will need to be attractive enough to attract persons with high levels of competence in the above areas. In order to ensure recruitment to both industry and research, we will need to focus on the competence needed when training MSc students, and master's dissertation projects in relevant topics must be offered. It will also be necessary to possess up-to-date knowledge of current industrial production methods, equipment and technologies. This can best be ensured through close cooperation between universities, research institutions and industry.

## 4.2 Research and development

Long-term targeted research projects with time-scales of several years are required to develop the new technologies that we need. Different technologies have different requirements, but in many cases it will be necessary to start from basic research, with projects in which the research institutions play the main part. The role of industry will gradually increase as the technologies involved approach maturity, and the technology development stage will be completed by industry-controlled projects. How many research projects will be needed to reach that point, and how long they will last, will vary, but common to all development of ground-breaking technology is the necessity of working in a long-term perspective, for example a 10-year time horizon.

## 4.3 Research infrastructure

New technology needs new types of research infrastructure. Metallurgical processes take place at high temperatures of up to 2000 $^oC$, and all the gases involved ($H_2$, CO, $CH_4$) are combustible. In many cases, too, processing takes place under pressure. As the technologies mature, it will also be necessary to perform large-scale tests, often using large, heavy equipment. All this means that major demands are made of experimental equipment and how it is used and maintained. For several decades, SINTEF and NTNU have been building advanced laboratory equipment suitable for such experiments, besides developing the competence needed to use it. Continual maintenance, upgrading and modernisation of equipment so that it is always state-of-the-art is demanding.

In 2014 and 2016, applications were submitted for infrastructure for research on the use of gas in metal production. These applications were strongly supported by industry, and after 2014 were placed on the “Norwegian road-map for research infrastructure” under “major nationally important research infrastructures, that … are regarded as being worthy of support by the Research Council of Norway.” The applications also involved partners from industry and R&D on catalytic and chemical processes, reflecting the many similar needs of different disciplines for equipment. A common national infrastructure could act as a basis for future research cooperation, which would be relevant to future industrial clusters of companies in both the metal production and chemical process industry sectors.

Besides the major efforts such as the new investments described above, it will also be necessary for our R&D institutions to purchase new equipment and upgrade laboratories to make them capable of serving a metallurgical industry that is interested in gas-based technology. The HSE aspect and the ability to deal with relevant volumes of combustible gases are of particular importance.

## 4.4 Financing technology development

The technology development we need will require financial support beyond that which industry and the research sector themselves can supply. A number of financial instruments are currently available, largely via the Research Council of Norway, Enova, SIVA and the EU.

A potential challenge is that individual programmes may have different objectives and pull in different directions. The PILOT-E apparatus for environmentally friendly energy that was launched in 2016 could be a model worth emulating. PILOT-E operates a common application system. The projects that fall under the system are supported throughout their lifetime by several different sources of financial support, as long as they continue to provide positive results as they pass project milestones.

Progress from an idea to a new process or process change is often dependent on a research project that may have a longer time perspective than is usual for most financial support schemes. Norwegian Industry also points this out in its road-map, and is encouraging support for projects with durations of four to eight years. Short-term projects may lead to successful results not being followed up or realised. A pause between two project periods can lead to important expertise being lost to other research projects.

The past few years have seen a sharpening of focus on the financing of research projects with a relatively short distance to realisation and benefits, on the part of both the Research Council of Norway and the EU. Freer research funds are the object of extremely tough competition, as they are shared among all disciplines. There is a danger that there will be a "hole" in financial support for projects at earlier stages of technological maturity. Given that the "green shift" will need to be implemented over a time horizon of several decades, it is essential that industrially relevant projects at an early stage of technological maturity are also prioritised. On this basis, we are proposing a change in the direction of financial support schemes and means towards a longer time-frame. This will be an important prerequisite for the development of technology for use in metal production.

This can be realised through a separate Research Council programme for the Norwegian process industry. Norwegian Industry recommends such a programme in its Road-map for the Process Industry. We repeat and support this recommendation here, and add a further recommendation that such a programme work under a time-frame towards 2050.

# 5. Prerequisites for industrial use

The term "industrialisation" as employed here means that new or existing technology for increased use of gas in metal production is adopted by industry. The transition from technology development to industrial production is a gradual process. The final stages of technology development, i.e. pilot projects and the development of demonstration plants, are often carried out as part of the process of industrialisation. The conditions that are more concerned with basic technology development are described in the chapter on technology development. A number of important conditions will need to be met for gas-based technologies to be adopted for industrial metal production.

## 5.1 A living industry

The most import condition required for implementing the road-map is the existence of a healthy industry with the ability to develop and implement new technology. This means that the industry possesses the competence, freedom of action and necessary resources to make the effort required.

For this reason, it is imperative that conditions are suitable for a healthy industrial sector in Norway, as Norwegian Industry 's Road-map for the Process Industry describes. The report points out in particular that Norway needs to be an attractive host nation for investment in – and the development of – process industry, with "stable, long-term, globally competitive conditions and financial instruments".

## 5.2 Profitable, sustainable technology

If gas is to be an important input factor in metal production, current technology will need to be both profitable and sustainable. Establishing new plants and processes in Norway and increasing production are bound to be politically difficult if they are not environmentally sustainable.

On the other hand, new environmentally friendly concepts will not be implemented unless they are not only profitable, but more profitable than the alternatives. Large-scale projects such a replacing an existing process are associated with significant risk and need to have the expectation of real profitability.

Support and incentive schemes can help marginally profitable projects to be realised, although it is still important to maintain ongoing assessment of profitability throughout the technological development process.

## 5.3 Availability of raw materials

### Natural gas and biogas

The new processes and technologies described in Chapter 3 of this road-map do not distinguish between biogas, natural gas, flue-gases and other gas sources. The processes require gases or gas mixtures that are combinations of methane ($CH_4$) carbon monoxide, and/or hydrogen ($H_2$). How these gases and gas mixtures are produced is a secondary question in a purely process technology perspective. The most important component of both biogas and natural gas is methane, from which we can produce carbon, carbon monoxide and hydrogen. Natural gas, production industry flue-gases and biogas are all suitable raw materials for metal production. Hydrogen can also be produced from water with the help of electric power.

Longterm sustainability is dependent on renewable sources of gas, such as biogas. However, technology development will be seriously hindered if the implementation of gas-based technologies are held back until they become completely carbon-neutral. During a period of transition, natural gas and other sources of gases that help to reduce $CO_2$ emission will have to be used. The more widespread use of biogas and biomass can be expected to take place in several different branches of industry rather than in metal production alone. For biocarbon to bring the greatest benefits to society within a sustainable level of harvesting, it is important that it should be employed where it is most useful, and where there are no alternative sources of gas.

The use of gas not produced on-site will require a distribution system. In its road-map, Norwegian Industry writes that "a prerequisite for increased use of natural gas is that it should open the way for third-party access to the distributions systems that have been, and will be, built." Without such third-party access, the market will not function, regional monopolies will arise, and pricing will not be competitive. For biogas and biomass to be usable, a distribution network for these sources of energy will also have to be created.

### Other raw materials

Gas-based technologies will also be dependent on other raw materials besides gas, and in many cases these materials will involve conditions other than those imposed by those in current use. For example, there may be requirements regarding raw material purity, e.g. DRI for iron production. New processes may involve other, but similar, requirements to raw materials. A prerequisite for industrialisation is that the necessary raw materials are available in a quality that is compatible with process requirements, and at competitive prices.

## 5.4 Electrical energy

Norwegian metal producers use climate-neutral electric power from hydropower schemes. When this power is exported, it could perhaps be argued that seen in isolation, exports of hydropower reduce global $CO_2$ emissions, as the need for fossil-power generation in the receiving country is reduced. However, in a wider context this strategy may act against its own intentions, insofar as exporting hydropower will make Norwegian metal production less competitive and replace it with more polluting production elsewhere in the world, or that a larger proportion of the growth in production is taken by more polluting companies in other countries. The export of “solid energy” as metal is an alternative to power exports. The availability of electric power and the related conditions were discussed in Norwegian Industry ’s Road-map for the Process Industry.

## 5.5 Combined processes and cluster creation

Cluster creation is one possible way of achieving optimal exploitation of raw materials, energy and side-flows. Clusters offer benefits in the shape of geographical co-location, which in turn brings benefits in terms of shared availability of input factors such as raw materials, gas and electricity. Clusters can also represent even closer link-ups in the shape of combined processes in which processes can be optimised across sectors and products.

In both metal and chemical production, synthesis gas, which is a mixture of carbon monoxide and hydrogen, can be used as a raw material. Converting methane to synthesis gas is a cost- and energy-intensive process, and a joint synthesis gas production facility for metal and chemical production would have potential synergy effects.

It could become relevant to adopt CCS and CCU in connection with the metallurgical industry at some point in the future, in which case it would be natural to consider the co-location of several companies in order to achieve economies of scale via solutions of this sort.

A number of the possible technologies described in this road-map for metal production produce flue gases with high concentrations of hydrogen, carbon monoxide and methane. These are all valuable gases with the potential for use in other processes. Industrial clusters can ensure that such side-flows are optimally exploited. Establishing clusters demands long-term planning and adaptation, and in many cases the involvement of the authorities. As we have already pointed out, it is in any case likely that a successful cluster cannot simply be planned and built; it must be given the opportunity to grow and develop naturally.

## 5.6 Capital and risk

Even once all the other conditions have been satisfied, the industrialisation of new gas-based technologies in the metal industry could still be halted by their need for large capital investments, with the risks associated with these. In addition to other investors, industry and its financing institutions must contribute the largest share of the capital required.

The investment capacity of companies and other investors can be increased by the authorities providing measures that improve the relationship between risk and expected rate of return. Pure subsidies will reduce the total amount of capital required from the company. Public-sector financial aid can also take forms like support from ENOVA for energy-conservation measures, or support for first-time investors in new technology. Other potential measures include risk-free loans that limit possible losses in the event of an unsuccessful investment, or guarantees that minimise investment risks.

# 6. Conclusions

This road-map supports Norwegian Industry's vision of a sustainable Norwegian metal industry that will achieve carbon neutrality by 2050. The road-map identifies a number of potential gas-based technologies that could become a part of the realisation of such a vision. Gas-based technologies could play an important role in making metal production more environmentally friendly and Norwegian metal producers more competitive.

Gas-based technologies can help Norwegian metal producers increase their competitiveness and market share. The metal industry is a Norwegian export industry, and it is also important for many local communities. Since Norwegian metal production is among the most efficient in the world, with low emissions of greenhouse gases and other pollutants, further development of this sector would be a useful measure to take in order to meet our national environmental goals. Gas-based technologies can also help to make Norwegian metal producers even more environmentally friendly, thus further increasing benefits to the climate. By putting serious efforts into gas-based technologies, Norwegian metal producers could improve the profitability of their companies. A willingness to make long-term commitments and go in for radical restructuring is needed. People with relevant competence must also be recruited to the industry.

Norwegian universities and research institutions must join industry in performing a significant proportion of the research needed to achieve these goals. To put ourselves in a position to play this important role, strategic and competence-building projects on the use of gas in the metal industry will have to be prioritised, as must relevant types of equipment when we invest in research infrastructure. Norwegian universities will also need to graduate sufficient numbers of students with the right qualifications, in order for these to be available for recruitment to industry and the R & D sector.

For its part, the public sector can help by creating suitable conditions for Norwegian industry, and ensure that Norway will be seen as an attractive host country for existing and future land-based industry. The authorities can also contribute by ensuring that Norway possesses an adequate national infrastructure for access to, and distribution of, natural gas, biogas and other gases.

It is essential that the public sector should support and strengthen its financial instrument apparatus and make it easier for industry to finance industrially relevant projects at early stages of maturity. Measures that reduce investment risk in new technology in capital-intensive industries will also be essential. These could take the form of subsidies for environmentally measures, or of risk-free loans.

Gas-based technologies have great potential for making improvements in the metal production industry. For this reason it is essential that all the parties involved pull in the same direction and create adequate conditions for a green future.