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# Qualitative comparison of on-site production of hydrogen and its synthesis products for steel processing industry

*Gabriela Zabik[a], Felix Birkelbach[b], René Hofmann[c]*

[a] *TU Wien, Vienna, Austria, gabriela.zabik@tuwien.ac.at, CA,*
[b] *TU Wien, Vienna, Austria, felix.birkelbach@tuwien.ac.at,*
[c] *TU Wien, Vienna, Austria, rene.hofmann@tuwien.ac.at*

## Abstract:

Decarbonizing high temperature heat in industrial processes is challenging as there are only few alternative fuels to reach the necessary temperatures. In steel mills the material must be heated up to 1250 °C before hot rolling of steel. Currently, this energy-intensive step is done in steel reheating furnaces fueled with natural gas. Synthetic fuels such as green hydrogen, synthetic methane and green ammonia are possible alternatives for substituting the current polluting energy carrier and in many future climate strategies considered as a crucial component for achieving greenhouse gas neutrality. In this paper, we present options for on-site production of synthetic fuels for steel mills and discuss them by a qualitative approach. Specifically, we investigate hydrogen, synthetic methane and ammonia. We consider state of the art technologies and apply them to a real-world use case from the steel processing industry in Austria. We point out the benefits of on-site generation of synthetic fuels as opposed to external supply in the case of steel mills. Depending on technology, we discuss possibilities for heat integration, implementation of carbon dioxide looping and efficiencies of the systems. We highlight the significant increase in the demand for electrical energy. Further, we discuss challenges of combustion in relation to nitrogen emissions, combustion behavior and effects on steel quality. Our results show hydrogen to be advantageous in many aspects when considering a fuel switch in steel mills with on-site generation. But also we identify synthetic methane as an interesting option that should be further examined.

## Keywords:

steel processing industry, on-site synthetic fuel production, hydrogen, synthetic methane, ammonia.

## 1. Introduction

The use of alternative fuels such as hydrogen, synthetic natural gas (SNG) and ammonia offers significant potential for decarbonizing industrial energy systems. These fuels can serve as an energy source for power plants or be utilized to produce heat directly for industrial processes. The first stage in generating synthetic fuels via the green route involves producing hydrogen from renewable electricity. The conversion of electricity into hydrogen is energy- and cost-intensive. Given that the demand for electricity in general will increase strongly in the future and given that the availability of renewable electricity is finite, it is crucial to carefully evaluate the most appropriate applications for these fuels. For high temperature processes exceeding 1200 °C, where electrification is not always a viable option, synthetic fuels can provide a suitable alternative and should be prioritized for these applications.

In Austria, the metal industry, particularly steel production, accounted for 61 % of the greenhouse gas emissions generated by the entire industrial sector [1]. Hot rolling of steel is one of the major energy consumers in the iron and steel production process chain, with energy consumption of around 1.5 to 3 gigajoules per ton of crude steel [2]. The main function of the hot rolling mill is to reheat steel blanks, called billets, above the recrystallization temperature and roll them thinner and longer through successive rolling stands. The billets are heated to about 1250 °C in industrial furnaces, mainly using natural gas as the primary energy source for heating [3]. The furnace for heating the billets is the major energy consumer in the rolling process and has a big impact on costs and emissions of the product. [2]

To date, only little literature is available concerning alternative fuels for steel reheating furnaces. Schmitz et al. [4] conducted a study on the reduction of $CO_2$ emissions from hydrogen-fired reheating furnaces, which considered the electricity generation mix. Their findings indicated a substantial potential for lower $CO_2$ emissions when compared to natural gas-fired furnaces. Similarly, Johansson [5] examined the economic feasibility of using bio-synthetic natural gas (bio-SNG) derived from biomass instead of LPG as a fuel source

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for reheating furnaces. The results of this study indicated that the use of bio-SNG was not economically viable. Niska et al. [6] investigated solid biofuels from forest products and found problems arising from ash deposition.

Potentials and challenges of alternative fuels with on-site generation are not explored. To determine the feasibility of on-site synthetic fuel production for steel mills, an evaluation must consider not only quantitative results obtained from simulations, but also qualitative factors such as combustion, safety concerns, technical feasibility or heat integration. This study seeks to assess the most suitable technologies for different alternative fuel productions, specifically hydrogen, SNG and ammonia, based on the aforementioned factors, and to identify the factors that influence the suitability of each option. It highlights the potentials and challenges associated with on-site generation of synthetic fuels and demonstrates the circumstances under which on-site generation is viable.

## 2. Use Case

A company from the steel processing industry located in Styria, Austria, serves as a use case. The steel mill processes delivered steel billets through hot-rolling, heat-treatment and mechanical processing. The main product is peeled bar steel for the automotive industry. The billets are heated to a rolling temperature of about 1250 °C using a walking hearth furnace powered by natural gas. The furnace is heated by numerous top and side burners, which enable homogeneous heat transfer along the length and width of the furnace.

The steel mill typically operates for one or two eight-hour shifts during weekdays, Monday through Friday. During idle times, the walking hearth furnace is ramped down to a user-defined temperature. The energy demand for the steel reheating is about 360 kWh per tonne steel. Detailed process control data of the furnace are available. The steel mill is located in a residential area and due to the presence of an outdated electric arc furnace, the maximum power connection to the steel mill is 30 MW.

## 3. Concepts for on-site generation of synthetic fuels

In this section, we investigate various options for on-site generation of synthetic fuels such as hydrogen, SNG and ammonia, and provide an in-depth analysis of the associated technologies, storage methods, combustion processes, influence on steel quality, safety considerations, costs and efficiencies. By presenting a comprehensive overview of these important factors, we aim to explore the potentials and challenges of on-site generation of these alternative fuels for steel mills.

### 3.1. Option 1: Hydrogen

The production of green hydrogen involves the electrolysis of water to split it into hydrogen and oxygen gases. Renewable electricity is used to power the electrolysis unit. There are three main electrolysis technologies available: alkaline water electrolysis (AWE), polymer electrolyte membrane (PEM) electrolysis and solid oxide electrolyzer cell (SOEC). These technologies differ in various aspects, such as their dynamics, efficiency, temperature and pressure levels, technological advancements, and lifetime. AWE are the most advanced electrolysis technology, but they cannot respond well to load changes. Response to load changes are the main advantage of PEM. SOEC is a high temperature electrolysis which can be coupled with an excess heat source. This results in a high efficiency; however, SOEC technology is still in development stage. [8] [9]

Storage of hydrogen is crucial for on-site generation and mainly serves to decouple the operation of electrolysis and steel reheating. Storage of hydrogen presents challenging problems due to its light weight and gaseous nature. Several hydrogen storage options are available, including compressed gas storage, liquefaction, absorption (metal hydrides) and adsorption storage. Liquefaction of hydrogen demands a high amount of energy, approximately 30 to 40 percent of the energy content of hydrogen [9], and is mostly used for high-purity applications in the chemical industry and aerospace applications [10]. Absorption storage have low sorption and desorption kinetics and cannot be operated very dynamically. Adsorption storage operate at very low temperatures and require a lot of energy. [9] Therefore, compressed gas storage is considered the most suitable for our specific use case.

Compressed hydrogen storage systems can operate at pressures up to 700 bar, which requires the use of compressors to attain the required ultimate pressure. The process of compressing hydrogen also causes a significant amount of energy consumption, equivalent to 13-18 percent of the lower heating value of hydrogen. [9]. Furthermore, the negative Joule Thomson effect of hydrogen must be taken into account. During compression, hydrogen undergoes a cooling effect, which raises concerns regarding the potential for pressure vessel materials to be damaged if the temperature drops too low. Conversely, when hydrogen is relaxed, it undergoes a warming effect [11].

Figure 1 shows the layout of an on-site hydrogen generation system. The setup includes an electrolysis unit, a compressor, hydrogen and oxygen storage and a reheating furnace. The oxygen produced as a byproduct

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during electrolysis is also stored and can be utilized for combustion. Moreover, the steel reheating furnace produces excess heat.

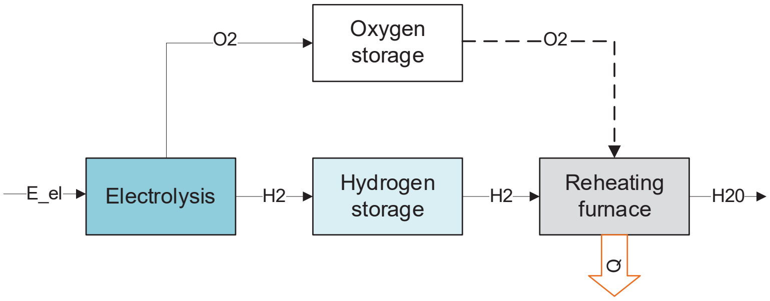

**Figure 1.** System hydrogen.

Hydrogen is well suited for generating high temperature heat due to a high flame temperature. However, there are significant differences between the combustion of hydrogen and natural gas. Due to its higher flame temperature, less fuel is required to generate the same amount of heat, resulting in less combustion air needed and lower convection within the combustion chamber. This must be considered in the process control when operating the furnace. [12]

Hydrogen can be burned with either air or oxygen. Combustion with air results in higher NOx emissions compared to natural gas combustion because the higher flame temperature (~2000 °C) produces more thermal NOx. Combustion with oxygen leads to lower energy input (approximately 30 %) and no NOx emissions; however, safety concerns regarding explosions and even lower convection due to the higher flame temperature (~2700 °C) make it challenging. Moreover, adaptation of the furnace is more expensive. [13] [12] [14]

Safe use and handling of hydrogen poses some unique challenges. Easy leaking, low ignition energy and possible damaging influence of equipment materials must be taken into account [10]. Scale formation on steel billets increases by 12 percent [15].

## 3.2. Option 2: Synthetic natural gas

Two main processes to produce synthetic natural gas (SNG) are catalytic methanation (CM) and biological methanation (BM). Methanation is a chemical reaction in which hydrogen and carbon dioxide and/or carbon monoxide, are converted into methane and steam with the aid of a catalyst or microorganisms. Catalytic methanation uses various metals as catalysts while biological methanation uses microorganisms as catalysts. Equation (1) shows the reaction equation for the synthesis of SNG:

$$CO_2 + 4\,H_2 \leftrightarrow CH_4 + 2\,H_2O \tag{1}$$

The CM unit typically operates within the temperature range of 300 to 550 °C and at a pressure of approximately 10 bar. The exothermic reaction involved in catalytic methanation generates a substantial amount of heat. The fixed-bed regenerator is the most commonly used reactor type for this process. In contrast, the biological methanation process operates at lower temperatures of 30 to 70 °C and at pressures ranging from 1 to 10 bar. Generally, larger reactor sizes are required to achieve high conversion efficiency. Both CM and BM units have good load response characteristics, although CM has a minimum load requirement of 40 percent and must maintain a standby temperature of 200 °C. The efficiency of the CM unit can be improved through heat integration. The catalyst used in CM is sensitive to impurities, whereas microorganisms utilized in BM are generally less sensitive. [16]

Figure 2 illustrates the arrangement of the system for SNG production. The SNG system consists of several components, including electrolysis, hydrogen and oxygen storage, methanation unit, and SNG storage. In addition, a carbon capture system is installed, which consists of an absorber and desorber. The CO2 separated from the flue gas is utilized for the methanation unit. Prior to absorption, the flue gas must undergo cooling through a heat exchanger, which generates excess heat. Oxygen can also be stored and utilized for combustion.

As previously mentioned, catalytic methanation produces excess heat, which can be employed for high-temperature electrolysis. The excess heat generated from the furnace can be utilized for the standby mode of the catalytic methanation unit or for high-temperature electrolysis utilizing SOECs. The excess heat produced during the operation mode of catalytic methanation can be also used for high-temperature electrolysis. Overall, the SNG system with carbon capture has the potential to utilize excess heat generated during various stages of the process to improve its overall efficiency. However, due to the two conversion steps involved, the process efficiency is lower, and additional space is required for the extra unit.

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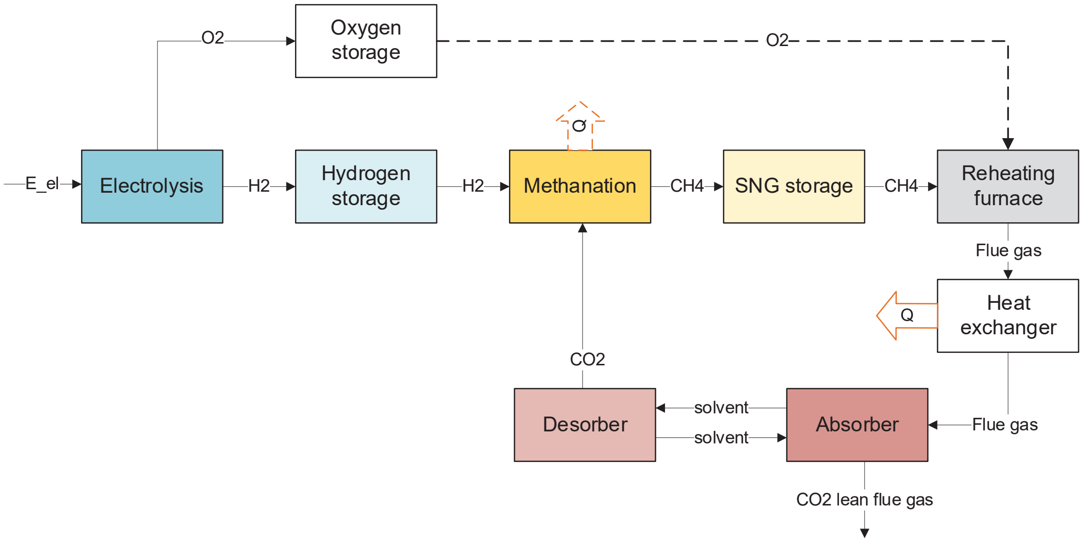

**Figure 2**. System SNG.

It is assumed that the combustion of SNG is similar to combustion of natural gas, and therefore no modifications to the furnace or process control are necessary.

SNG storage is less challenging than hydrogen storage due to the higher energy content per unit volume. Existing infrastructure for storage and pipeline transportation can be used for SNG. The pressures required for storage are significantly lower, resulting in negligible energy demands for storing SNG. Furthermore, lower storage pressures imply less strict safety requirements. The quality of steel and scale formation is not expected to differ significantly between natural gas and SNG.

## 3.3. Option 3: Ammonia

Ammonia today is mainly used for fertilizer, but is it an interesting option as an energy source for the future. Due to the high flame temperature, it is practicable to generate high temperature heat. Its main advantage is the easier storage of ammonia compared to hydrogen. For green ammonia, firstly hydrogen is produced through an electrolysis, additionally nitrogen is produced through an air separation unit and then hydrogen and nitrogen are processed into ammonia with the Haber Bosch process, according to Eq. (2): [17]

$$N_2 + 3\,H_2 \leftrightarrow 2\,NH_3 \tag{2}$$

More recently, ammonia is discussed as a fuel for generating heat for industrial applications. In the shipping sector it is seen as a promising alternative due to its stability and low transportation costs. However, ammonia combustion has disadvantages, including low burning velocity and high fuel nitrogen oxides production. To mitigate these issues, a blend of hydrogen or methane with ammonia can be used. Increased hydrogen proportion in the fuel mix leads to an increase in burning velocity, but also more NOx emissions. However, adding methane to the mix not only increases the burning velocity but also reduces the NOx emissions, making it a viable alternative.[18] [12]

Figure 3 shows the layout of the system ammonia. It consist of an electrolysis unit, hydrogen and oxygen storage, Air separation unit, Haber Bosch plant, ammonia storage and a reheating furnace. Excess heat is

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generated by the Haber Bosch unit as well as by the reheating furnace. As combustion of ammonia with pure oxygen is not performed, the obtained oxygen is not used within the system.

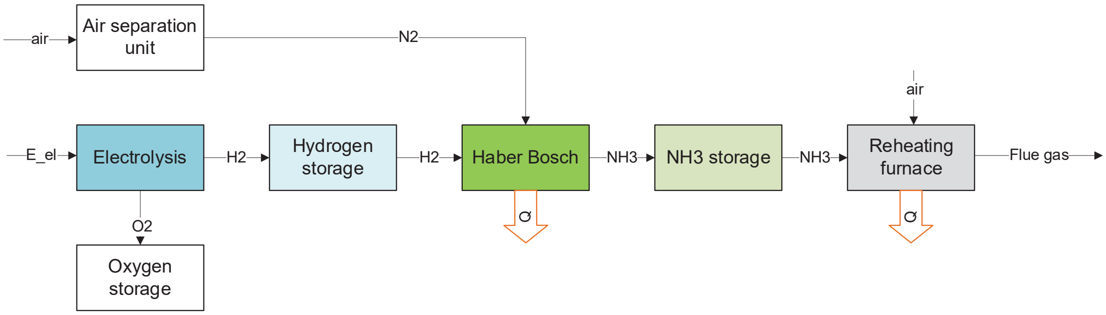

**Figure 3.** System Ammonia.

### 3.4. System specifications

While the focus of this paper is on qualitative comparison and analysis, basic evaluations of efficiencies, investment costs, and specific energy demand were also performed to provide a comprehensive overview of the subject and provide valuable insights. Consequently, Table 1 presents the summarized values for investment costs and efficiencies, which were utilized in further calculations.

**Table 1.** Investment costs and efficiencies of all components of the systems. [19]–[23]

| Component | CAPEX | Efficiency, % |
|---|---|---|
| AWE | 1400 €/kW$_{el}$ | 0.65 |
| PEM | 1800 €/kW$_{el}$ | 0.63 |
| SOEC | 2700 €/kW$_{el}$ | 0.81 |
| Compressor + H2 storage | 33 €/kWh$_{H2}$ | 0.85 |
| Hydrogen burner | 63.32 €/kW$_{therm}$ | - |
| Catalytic methanation | 750 €/kW$_{SNG}$ | 0.75*, 0.8** |
| Biological methanation | 1050 €/kW$_{SNG}$ | 0.78*, 0.9** |
| SNG storage | 33 €/kWh$_{SNG}$ | 1 |
| CO2 storage | 33 €/kWh | 1 |
| Carbon capture system | 40 €/t$_{CO2}$ | |
| Ammonia plant (ASU, Haber Bosch, NH3 storage) | 850 €/t$_{NH3}$ | 0.85 |

*in relation to the calorific value, **conversion efficiency

For calculations of the investment costs, the approximate capacities of the plants were determined through a small optimization problem (MILP) using data from our use case. These capacity sizes are summarized in the Table 2 were used for further calculations. In the case of SNG and ammonia, the hydrogen storage serves as a buffer between electrolysis and methanation unit and is smaller than the storage of the hydrogen system.

**Table 2.** Capacities of the plants.

| Plant | System hydrogen | System SNG | System ammonia |
|---|---|---|---|
| Electrolysis output | 7 MW | 8.75 MW | 8.25 MW |
| Hydrogen storage size | 35 MWh | 10 MWh | 10 MWh |
| Methanation output | - | 7 MW | - |
| SNG storage size | - | 35 MWh | - |
| Haber Bosch output | - | - | 7 MW |
| NH3 storage size | - | - | 35 MWh |

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# 4. Evaluation of concepts for alternative-fuel production

## 4.1. Qualitative discussion

There is no one-size-fits-it-all solution for substituting natural gas in steel mills. The suitability of the different alternative options depends on various factors. Important factors are space availability, location of the steel mill, environmental regulations, maximum power connection, integration of renewable energies, production schedule and energy demand for production. All these aspects will be discussed in the following.

The preconditions for on-site generation concepts include the sufficient space, a power connection capable of providing at least the same amount of power as the electrolysis unit, and the infrastructure to store hydrogen safely on premise. Additionally, integration with the company's renewable energy sources is advantageous.

For all alternative fuel options, out of the three electrolysis concepts, the Solid Oxide Electrolysis Cell (SOEC) exhibits the highest theoretical efficiency due to the availability of excess heat from the reheating furnace, which is at approximately 800°C without air preheating. However, the technology readiness level of SOEC remains below that of Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE). Furthermore, SOEC typically operates at a constant level, so it depends on the scheduling of the rolling mill and energy prices. The suitability of PEM electrolysis depends on the operation of the electrolyzer, which may require dynamic operation due to fluctuating renewable energies, energy prices or irregular production schedules. AWE, even though the most advanced electrolysis technology, is likely unsuitable for this particular application due to a lower efficiency and static operation.

**Hydrogen:** When considering hydrogen as a fuel for steel reheating furnaces, on-site generation presents several advantages. First, it eliminates the challenges associated with hydrogen transport. Additionally, the production of oxygen as a byproduct of the electrolysis process prevents the need for costly external oxygen supply. Oxygen use enables more energy-efficient production and reduces the required capacities for electrolysis and hydrogen storage. However, utilizing oxygen for combustion requires more extensive modifications to the furnace compared to air combustion. Nevertheless, existing steel reheating furnaces can be retrofitted for the use of hydrogen. Further, additional adaptations for process control and investigations of scale formation and steel quality are required. Using hydrogen as a fuel in steel reheating furnaces does not produce $CO_2$ emissions, as long as electricity is obtained from renewable sources.

**SNG:** Due to the two conversion steps involved, the process efficiency is lower, and additional space is required for the extra methanation unit. Nevertheless, the easier handling of the fuel and its combustion behavior, which is very similar to natural gas, represent the main benefits of this approach. The SNG system does not necessitate any modifications to the furnace or process control, and the quality of the steel and scale formation remain the same.

The SNG system, coupled with carbon capture, has the potential to utilize excess heat generated during various process stages to improve its overall efficiency. To evaluate the performance of the SNG concept, simulations that take heat integration into account are necessary. The performance of the SNG system primarily depends on production capacity and schedule, which enables efficient heat integration. In addition, the oxygen produced by the electrolysis can be utilized for combustion, representing another advantage of the on-site generation concept. When comparing catalytic and biological methanation, the latter method has the advantage of being less sensitive to $CO_2$ source impurities; however, the reactor needs more space.

**Ammonia:** The use of ammonia combustion for industrial applications, including steel reheating furnaces, remains largely unexplored. Also, there is a lack of research investigating the effects of ammonia combustion on steel. The use of ammonia as a fuel presents significant challenges in relation to NOx emissions and burning velocity, making it a less viable option compared to hydrogen. Moreover, as the primary advantage of ammonia over hydrogen is its ease of transport, and small-scale Haber Bosch plants are not common, on-site generation may not be advantageous. Additionally, the generation of nitrogen from an additional air separation unit, and the oxygen obtained from electrolysis that is not used pose further disadvantages. While ammonia combustion remains an interesting option for industrial applications, extensive research and development is required before its widespread use. Generally, it may be better suited for external supply.

## 4.2. Quantitative results

In this section, results of some basic calculations are presented. Figure 4 shows the efficiencies of the systems with all possible combinations of technologies. It is evident that the hydrogen system achieves the highest efficiency. The SNG system shows the lowest efficiencies, with no significant difference between catalytic and biological methanation. The system ammonia lies in between.

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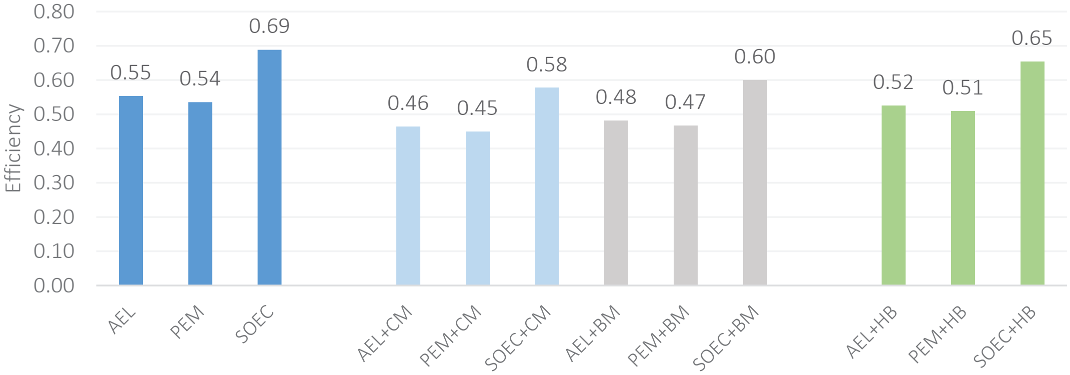

**Figure 4.** Efficiencies for the considered system configurations.

Figure 5 illustrates the total energy demand of the process chain for reheating of one tonne steel, for the different systems and depending on the combustion type (air/oxygen). Using oxygen for combustion can significantly lower the energy demand.

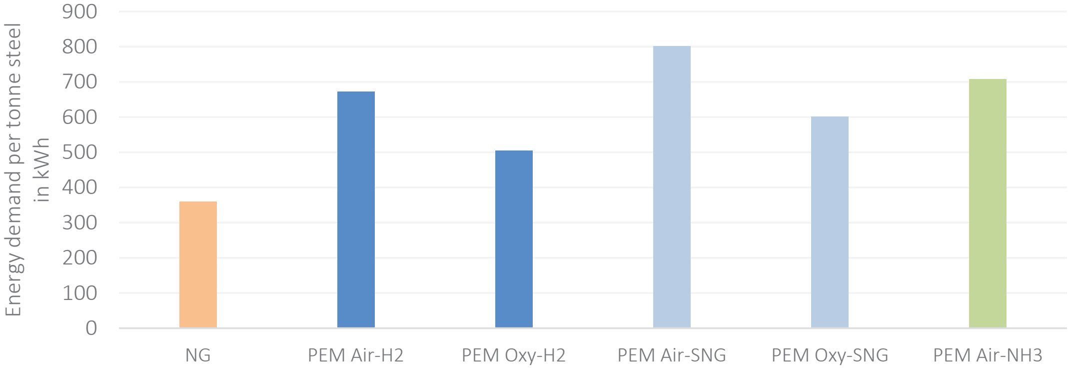

**Figure 5.** Energy demand per tonne steel reheated for air and oxygen combustion of different energy carriers.

Figure 6 gives an overview of investment costs for the different systems. The SNG system has the highest investment costs, primarily because of the additional costs for the carbon capture plant. Main investment costs in all systems are associated with the electrolysis unit, with SOEC being the most expensive one.

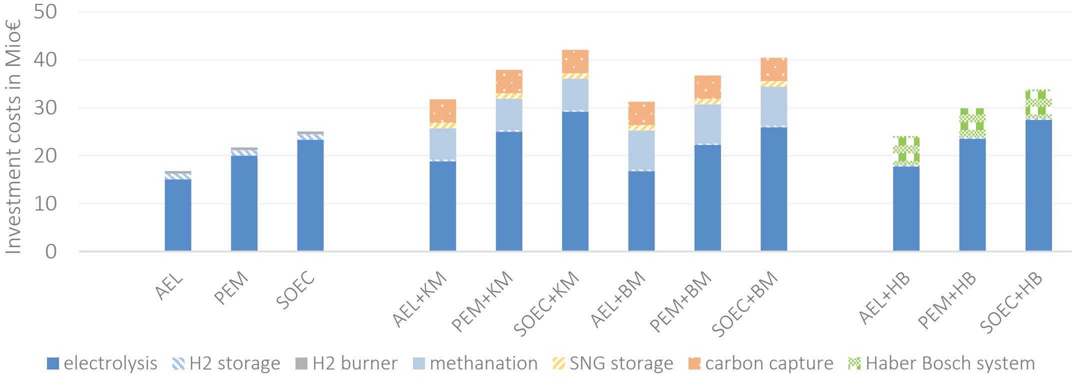

**Figure 6.** Investment costs for the considered system configuration.

## 5. Conclusion

In this paper, we presented concepts for on-site generation of hydrogen, synthetic natural gas (SNG) and ammonia, and conducted a qualitative comparison underpinned by basic estimates regarding investment costs and efficiencies. We discussed factors like combustion behaviour, heat integration, effects on steel quality. Our analysis revealed that on-site generation of hydrogen offers benefits related to transport, use of oxygen and low $CO_2$ emissions. For SNG, easy handling of the fuel and numerous possibilities of heat integration were identified as advantages. We found ammonia not to be suitable for an on-site generation concept. Also there are several challenges in combustion of ammonia, mainly related to low burning velocity and high NOx emissions. Overall, the production of synthetic fuels leads to a significant increase in electricity demand, requiring the company to have a sufficiently high power connection. If on-site generation will ever be economically viable will heavily depend of future natural gas prices and emission regulations.

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## Nomenclature

### Acronyms

| | |
|---|---|
| AWE | Alkaline water electrolysis |
| BM | Biological methanation |
| CM | Catalytic methanation |
| HB | Haber Bosch process |
| NG | Natural gas |
| PEM | Proton exchange membrane |
| SOEC | Solid oxide electrolyzer cell |
| SNG | Synthetic natural gas |

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