Renewable Metal Fuels as Sustainable Seasonal Energy Storage

Covering Winter Peaks of Heat and Electricity Demand

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ABSTRACT

Renewable Metal Fuels (ReMeF) have great potential to store renewable energy for several months. A thorough criteria evaluation of possible candidates was conducted, considering (1) abundance in the Earth's crust, (2) world reserves, (3) market price and its development, (4) energy density, and (5) potential increase in metal production. Aluminium, iron, and silicon are the most favourable candidates that can be safely stored, easily transported, and recycled to provide a sustainable closed-loop energy storage solution. Technology development to produce ReMeF without direct greenhouse gas emissions or CO_2-neutral is expected to reach full commercialization by 2030. In addition, several research institutes, EU research projects, and even start-up companies have been identified that are developing technologies for various small and large scale applications that generate heat and/or electricity via heat or hydrogen from ReMeF.

Keywords: *Long-term energy storage, Renewable Metal Fuels, Combined Heat and Power, Sector Coupling.*

1. INTRODUCTION

On an annual basis, 50% of the final energy demand (FED) in Europe can be attributed to space, water, and process heating. But in winter months like January, heat demand accounts for up to 65% of final energy demand in countries like Switzerland. The combination of increased heating demand and reduced renewable energy generation from solar in winter creates an energy shortage that can be met by seasonal energy storage options which transfer renewable "summer energy" into the winter. Considering that seasonal energy storage is defined by one storage cycle per year, high storage capacities to cover several weeks or months of demand are required. Therefore, large storage capacity, high energy density, and low capital cost are key criteria.

Renewable Metal Fuels (ReMeF) are energy carriers which can shift large quantities of renewable energy into the winter to cover local peak electricity and heat demand, which also has a stabilising effect on the electricity grid.

In focus are metals which act as winter-energy suppliers. Their suitability is determined by their availability, cost, and chemical properties, as well as the potential to achieve greenhouse gas (GHG) savings compared to import options or natural gas Combined Heat and Power (CHP) plants.

2. REMEF REDOX STORAGE CYCLE CONCEPT

As shown in Figure 1, renewable energy can be stored during periods of excess electricity by producing ReMeF in a centralized industrial facility (Power-to-Metal, charging process). By using CO_2-free technology to produce metals, only oxygen or water is emitted into the atmosphere.

Subsequently, the ReMeF acts as an energy carrier that can be easily stored for several months without loss. Like wood chips or pellets, ReMeF is transported to homeowners or industry to cover peak winter energy demand. By releasing the energy of the ReMeF (Metal-to-Energy, discharging process) via metal-water oxidation, which produces hydrogen and heat, electricity can also be produced by further conversion of hydrogen in a fuel cell system. Thus, both by replacing heat from heat pumps as well as by producing additional electricity, ReMeF can be used to stabilize the grid during peak demand periods. The reaction product of this Metal-to-Energy conversion is a metal-hydroxide that serves as the initial feedstock needed for the Power-to-Metal process, thus creating a closed-loop material cycle.

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Ideally, decentralized CHP solutions based on ReMeF could eliminate the need for gas- or oil-fired power plants and back-up systems in the medium and long term. For countries with a pronounced peak of heat demand in the cold season, the use of ReMeF in the building stock may provide the missing piece of the decarbonization puzzle to achieve a 100% renewable electricity and heat supply even in winter and to become independent of short-term supplies and dependencies on energy sources from abroad.

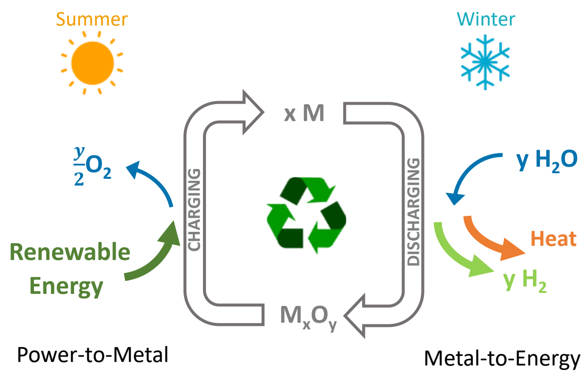

Figure 1 Renewable Metal Fuels (ReMeF) redox storage cycle.

3. IDENTIFICATION OF RENEWABLE METAL FUEL CANDIDATES

Based on the periodic table of the elements and previous work by Bergthorson et al. (2018), interesting candidates were pre-selected for their usability as ReMeF according to the following criteria: (1) high availability of the metal, (2) low cost of the raw material, (3) high achievable energy storage density, (4) safety in handling (not explosive or too reactive), (5) high potential for closing the material cycle, (6) good reactivity during activation (power density), (7) simple and, if possible, loss-free storage [1]. Metals and their oxides that are toxic or too expensive are excluded. Based on a first screening, the remaining interesting candidates are *lithium, sodium, potassium, magnesium, calcium, titanium, iron, zinc, aluminium, silicon, and boron.*

In the last years, the price of lithium increased substantially from around 10’000 USD/tonne up to 80’000 USD/tonne due to the demand increase for electric vehicle batteries [2]. Therefore, lithium is excluded as a potential ReMeF candidate.

Boron is very attractive from an energy density point of view, with the highest volumetric energy density of 38.2 MWh/m3 compared to the other interesting candidates. It is mainly used in the glass and ceramics industry (approx. 50% of production), followed by agriculture (an essential nutrient for plants) and nuclear industries (neutron absorber). Boron is also an interesting candidate for use in other renewable energy technologies (magnets for wind turbines and electric motors). Therefore, demand keeps growing. It is produced only in Turkey and in the Mojave desert in California and there are no known new large-scale mining projects. Projections show that boron demand will exceed its supply by 2024 and is in need of additional capacity exploration already [3]. For this reason, it is not deemed a suitable ReMeF candidate today.

Sodium, potassium, and calcium are too reactive, and titanium and copper (abundancy 0.006%) are not reactive enough when in contact with water and are more expensive when compared to the other promising candidates [4].

For these reasons, *aluminium, iron, magnesium, manganese, silicon, and zinc* were shortlisted as promising ReMeF candidates and are considered further in the criteria evaluation.

The following key criteria are used to identify the most promising ReMeF candidates, weighted by the given factor in percent: (1) abundance in the Earth’s crust 10%, (2) world reserves 20%, (3) market price and its development 30%, (4) energy density 20%, (5) the potential production increase for ReMeF compared to today’s world market 20%.

It should be noted that the abundance and world reserves are both linked to the availability of the metal. The abundance refers to the amount of an element that exists in the Earth's crust, oceans, atmosphere, and other accessible natural resources (a natural occurrence). It is typically measured as a percentage or parts per million (ppm) by weight.

World reserves, on the other hand, refer to the estimated amount of an element that can be economically extracted from known sources. This includes both identified reserves (deposits that have been found and can be exploited with current technology) and undiscovered reserves (deposits that are likely to exist but have not yet been discovered). The estimation of reserves depends on factors such as the cost of extraction, market demand, and technological advances. While a certain element may be abundant, it may not have large world reserves if it is difficult or expensive to extract. In contrast, an element may have a small abundance but large world reserves if it is highly valued and economically viable to extract.

3.1. Abundance and World Reserves

Silicon (28%) is the second most abundant metal in the earth’s crust, followed by aluminium (8.2%), iron (5.6%), and magnesium (2.3%) whereas manganese (0.095%) and zinc (0.007%) are the least abundant of the selected metals [5].

Bauxite is the primary raw material used in the production of aluminium and approx. 4 kg of bauxite is needed to produce 1 kg of aluminium. Today, world reserves of bauxite are estimated at 29’700 Mio tonnes leading to around 7’400 Mio tonnes of aluminium. But bauxite resources are way higher (between 55 billion and 75 billion tonnes) [6]. It should be noted that reported bauxite reserves can change over time, as more economically interesting deposits are discovered and mining technologies advance. Nevertheless, there are sufficient reserves to supply future demand. As of today, the aluminium industry would be able to more than double the amount of aluminium which was produced since industrialization.

Worldwide, the largest reserve of iron is in Australia (27’000 Mio tonnes), followed by Brazil (15’000 Mio tonnes), and Russia (14’000 Mio tonnes) [7]. The total iron content of all reserves is estimated to be some 85 billion tonnes. Meaning that the global quantity in circulation today (or rather the accumulated global production since 1943) could be doubled again.

Magnesium metal can be derived from seawater, natural brines, dolomite, serpentine, and other minerals. World reserves of magnesite are estimated at 2’400 Mio tonnes. But in general, reserves for this metal are sufficient to supply future requirements.

Manganese ore world reserves are estimated to reach 1’700 Mio tonnes (with an average of 40% manganese content). By far the largest reserves are found in South Africa. Demand for high-purity manganese is expected to increase 27-fold by 2035 due to the increase of electric batteries in vehicles. This number is based on a statement by GIYANI, the global supplier of high-purity manganese in China (90% of the global production) [8].

The source of silicon is silica in various natural forms, such as quartzite. Quantitative estimates of silicon reserves are not available. The reserves in most major producing countries are ample in relation to their demand.

The known world reserves of zinc have fluctuated slightly over the last decade and amount to 210 Mio tonnes in 2022 [9]. However, about 1.9 billion tonnes are identified as world zinc resources. According to the U.S. Geological Survey from January 2021, the accumulated global production of zinc amounts to 547 Mio tonnes (data from 1990 to 2019) [10].

3.2. Market price

In general, market price trends are subject to various factors that can impact supply and demand, such as economic conditions, geopolitical events, and changes in technology and industry trends. From 2018 until spring 2020, prices for the selected metals declined steadily [11], [12], [13], [14], [15]. But afterwards and until spring 2022, metal prices were on the rise. Since then, prices of most of the selected metals have steadily fallen and stabilized. In general, market prices increased from approx. 1’500 to 2’500 USD per tonne in 2018 to 2’000 and up to 3’500 USD per tonne in early 2023 where iron is the least expensive and silicon the most expensive.

3.3. Energy Density

The proposed ReMeF energy carrier must provide energy for several weeks or even up to several months. This means large amounts of energy are required which correlates to large storage volumes.

Therefore, storage media achieving high volumetric energy storage density are most favourable, because this ultimately reduces the required storage volume and space. Aluminium and silicon achieve the highest volumetric storage density; zinc and iron the lowest among the selected ReMeF candidates.

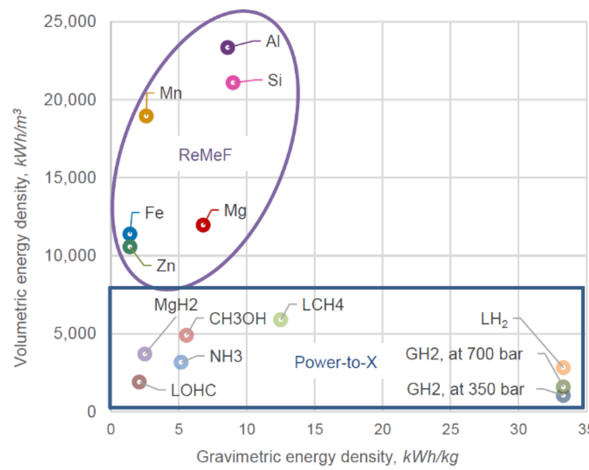

Figure 2 Gravimetric and volumetric storage density of ReMeF (solid) and other Power-to-X options (X as gas or liquid).

Overall, gaseous hydrogen (GH2) has the lowest volumetric storage density. It should be noted that the data on energy density in Figure 2 do not consider any container or storage equipment. For example, compressed hydrogen storage systems typically achieve less than 10% of the hydrogen weight per system weight and therefore, from a system perspective, no more than 3.5 kWh/kg.

3.4. Potential metal production increase

It was assumed that 20% of the FED for heating and cooling could be allocated to winter peak demand that needs to be supplied from long-term stored energy carriers [16]. Furthermore, it was assumed that half of the target group would cover their winter peak demand for heating with ReMeF by 2050. Thus, the share of non-renewable winter peak demand (TWh per year) was estimated based on the following assumption:

$$Winter\ peak\ demand_{none-renewable} = FED \cdot 20\% \cdot target\ fraction \quad (1)$$

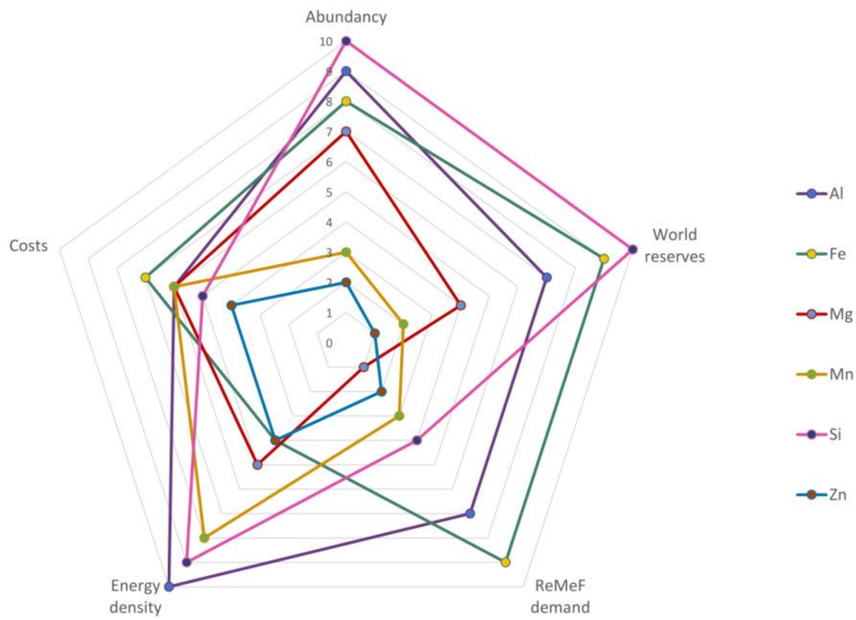

Figure 3 Criteria evaluation results of the promising ReMeF candidates: 0 – unfavourable, 10 - favourable.

Based on this assumed winter energy demand for ReMeF in 2050 and the gravimetric energy density of the ReMeF candidate, a total yearly additional production increase over the next 25 years (2025 to 2050) can be estimated.

If compared to the global production capacity in 2019, this results in a capacity increase of 1.2% for aluminium, 0.3% for iron, 48% for magnesium, 13% for manganese, 9% for silicon, and 36% for zinc.

3.5. Criteria evaluation results

Figure 3 illustrates the results of the evaluation described in 3.1 to 3.4 in a spider diagram.

Overall**,** *aluminium, iron and silicon* achieved the highest scores when the single criteria are summed up using the weighting factors as declared in the introduction of section 3 and are therefore identified as the most favourable ReMeF candidates.

4. PRODUCTION OF REMEF

Traditional metal extraction, in the case of iron (in the form of iron ore), aluminium (in the form of bauxite) and silicon (in the form of quartzite), relies on carbon feedstocks due to the high reactivity and abundance of carbon. This is because carbon is an excellent low-cost reducing agent, i.e., it can remove oxygen from metal oxides. In this case, carbon reacts with the metal oxides to form carbon dioxide (CO_2) or carbon monoxide (CO).

The use of carbon as a reducing agent in metal extraction has a long history and is supported by well-established technologies and infrastructure. Noteworthy, it is estimated that steel production accounts for around 4 to 7% of global CO_2 emissions today [17].

Therefore, ReMeF must not only be produced exclusively from renewable energy but also by sustainable technologies preferably without carbon as a reducing agent or with Carbon Capture and Storage (CCS) measures.

The most relevant carbon-free Power-to-ReMeF technologies being developed are the inert electrolysis for aluminium production, the direct reduction of iron using hydrogen, the molten oxide electrolysis for iron production, and last but not least the electrochemical reduction of silica in molten salt using inert anodes to produce metallurgical grade silicon.

5. WATER OXIDATION OF REMEF

Metal, such as iron (Fe), reacts with water and oxygen to form a corrosive layer (Fe_2O_3) which will grow over time. Aluminium and silicon, on the other hand, form a passivation layer. This passivation occurs naturally with metals that bond readily with oxygen. In this case, the passivation needs to be prevented or a promoter, such as an alkaline or base solution, is required to dissolve the oxide layer and start the oxidation reaction with water. At the same time, this passivation layer is a crucial advantage for long-term energy carriers because losses in standard conditions are very limited in this case.

The metal-water or metal-steam oxidation reaction typically yields heat and hydrogen which can be further used in an electrochemical conversion such as a fuel cell system. The oxidation reaction kinetics and energy yield are dependent on the chemical property (oxygen bond, impurities), the exposed surface of the metal, and the reaction conditions (temperature, pH, etc.). In general, ReMeF fully oxidizes if sufficient reactants, such as water or oxygen, are supplied and the passivating metal oxide layer on the surface is dissolved [18].

The reaction product obtained is again metal oxide or metal hydroxide, which is recycled in the Power-to-Metal process, creating a sustainable closed-loop energy storage solution.

It should be noted that post- or pre-consumer scrap with impurities can also be considered a valuable feedstock material for the ReMeF energy storage cycle [19], [20], [21].

6. CONCLUSION

ReMeF have an enormous potential to shift large quantities of renewable energy into the winter to produce heat, hydrogen, and/or electricity. Overall, aluminium, iron and silicon have been identified as the most favourable ReMeF candidates.

Metal companies such as ELYSIS, HYBRIT and ELKEM are actively collaborating with research institutions, industry associations and governments to meet their CO_2 reduction targets and accelerate decarbonisation efforts [22], [23], [24], [25], [26], [27]. Therefore, technologies for the CO_2-free production of aluminium, iron, and silicon are being developed and tested and expected to have reached full commercialization by 2030.

In addition, several research institutes, EU projects (REVEAL) and even spin-off or start-up company (apricot 366, metalot) develop technologies which use ReMeF as sustainable energy carriers providing renewable energy anytime and anywhere [24], [28], [29] ,[20], [29] [30], [31], [32].

Advantages of ReMeF over other Power-to-X energy carriers are (1) extremely high volumetric energy density, resulting in minimal storage costs and space requirements, (2) safe handling for metals that are non-toxic and feedstock material that is non-flammable, (3) easy storage and transport due to loss-free solid material storage that does not require pressurized or even cryogenic tanks, (4) flexible application since no CO_2 source is required when compared to synthetic fuels such as methane or methanol.

In addition, the temperature level of the heat produced by ReMeF is not strictly limited, because there are several technologies available to convert the chemical energy into heat and electricity: (1) low-temperature metal-water oxidation, (2) high-temperature metal-steam oxidation, also known as wet conversion, (3) metal-air reaction, i.e., direct combustion of metals with air, (4) electrochemical oxidation (metal-air battery). Therefore, small and large-scale applications are feasible, e.g., in building and industry for local on-demand energy production, stationary power generation, and even transportation.

AUTHORS' CONTRIBUTIONS

YI. Baeuerle: Conceptualization; Data curation; Investigation, Visualization; Writing – Original draft - Review and editing.

MY. Haller: Review and editing; Supervision.

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