



How to give a renewed chance to natural gas as feed for the production of hydrogen: Electric MSR coupled with CO₂ mineralization

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ABSTRACT

Recent years have seen a growing interest in water electrolysis as a way to store renewable electric energy into chemical energy, through hydrogen production. However today the share of renewable energy is still limited and there is the need to have a continuous use of H₂ for industrial chemicals applications. Firstly the paper discusses the use of electrolysis - connected to a conventional grid - for a continuous H₂ production in terms of associated CO₂ emissions and compares such emissions with conventional methane steam reforming (MSR). Therefore, it explores the possibility to use electrical methane steam reforming (eMSR) as a way to reduce the CO₂ emissions. As a way to have zero emissions, carbon mineralization of CO₂ is coupled - instead of in-situ carbon capture and storage technology (CCS) - to eMSR; associated relevant cost of production is evaluated for different scenarios. It appears that to minimize such production cost, carbonate minerals must be reused in the making of other industrial products, since the amount of carbonates generated by the process is quite significant.

1. Introduction

The transition to renewable chemicals production needs to be coupled with the implementation of novel infrastructures and technical solutions suitable for the exploitation of renewable sources as much as possible. An effective fashion to reduce the environmental impact of chemical industry is to convert the heating inputs conventionally deriving from fossils sources into electric ones. Indeed, power generation can exploit several renewable sources, by means of technology pathways already consolidated. Under the scenario of reaching a share of renewable energy of 100%, the electrification of chemicals production is aligned with the aim of reducing the emissions derived from this industry. Moreover, electric based chemical production, within the constraints defined by plant capacity flexibility, could also help in the absorption of grid power fluctuation just related to renewable power generation - such as from solar and wind sources (Van Geem et al., 2019). This contribution will be more and more relevant with the increase of installed renewable energy capacity, and will become essential in the case of a 80% share of renewable energy (Child et al., 2019; Weitemeyer et al., 2015).

Hydrogen is one of the chemical products with the higher global production capacity; it had a market demand of about 75 million tons in

2018. Indeed, it is widely employed for refinery applications as well as for base chemical production, such as ammonia and methanol. Further, hydrogen is deemed as an excellent chemical for energy storage (Lund et al., 2015; Blanco and Faaij, 2018), indeed it is characterized by: high energy density 122 kJ/g; - long term durability of storage; possibility to be converted into other chemical with high density to reduce storage volumes; - sustainable storage cycle, as matter of fact, it can be converted back into energy through fuel cell by producing only water as byproduct.

At first glance, water electrolysis seems the most effective solution in order to exploit renewable energy for hydrogen production. Since, such hydrogen production will not emit CO₂ and its production costs will be determined mainly by the depreciation of the capital costs (CAPEX). Nevertheless, these considerations are fitting only in the case of exploitation of power continuously produced from renewable sources - with the aim of H₂ production applied for industry consumption and not only as energy storage system. Indeed, the only renewable sources which can easily ensure continuous supply is the hydroelectric route (Barbato et al., 2014). In this case, assuming a value of 1 M€ for 1 MW_{el} electrolysis (Schmidt et al., 2017), the hydrogen cost of production would be roughly only dependent on CAPEX and related maintenance. Considering about 10% for depreciation, between 2 and 3% of CAPEX for

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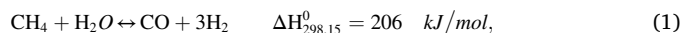
annual maintenance (Peters et al., 2003), an electrolysis efficiency value of 4.5 kWh/Nm³ (Bertuccioli et al., 2014) - meaning 222 Nm³ - and 8000 working hour per year, a range of hydrogen production of between 0.07 and 0.09 €/Nm³ can be calculated. This value would actually be competitive with the conventional cost of production (Iea and hydrogen production, 2018). Conversely, by removing the assumption of continuous energy supply, the cost of production would be significantly higher. Indeed, assuming, for example, an energy surplus period equal to 1000 h per year and still a CAPEX value of 1 M€ for 1 MW_{el} electrolysis, with the above-mentioned assumption on depreciation but a lower maintenance of 1% - indeed the equipment would be less stressed - a production cost of hydrogen of about 0.5 €/Nm³ may be calculated. Moreover, in this configuration, discontinuous hydrogen amount would be produced. In the case of a continuous production provided with the implementation of a battery system, the cost of production would be even higher. Of course, both these last figures are not economically competitive. Indeed, the conventional Methane Steam Reforming (MSR) has a cost of production of hydrogen ranging between 0.07 and 0.25 €/Nm³ of H₂, according to natural gas price fluctuation (Iea and hydrogen production, 2018).

Since hydroelectric energy has a limited capacity and the emerging Virtual Power Purchase Agreements, which try to achieve synthetic continuous renewable energy supply, are still far to settle down, the electrolysis configuration with continuous supply of fully renewable energy can not be taken today as a reference comparable to methane steam reforming. Indeed, only in case of considering grid-based electrolysis, the technologies would both lie on industrially-feasible assumptions which allow to assess a complete evaluation, covering together economic and environmental aspects. Thus, with the aim of comparing the benefits of different pathways for hydrogen production, a configuration of electrolysis supplied by energy coming from the grid, hereinafter named grid-based electrolysis, has been taken into account in our work. Therefore, as comparing this technology with the other technologies included in our analysis - MSR and electric Methane Steam Reforming (eMSR) - we have considered indirect CO₂ emissions derived from the grid. In our evaluation, also the costs of production relevant to the different technological lines are addressed. The final objective is to analyze both the feasibility and sustainability of grid-based electrolysis, MSR, and eMSR technologies for hydrogen production in the case of variable future boundary conditions.

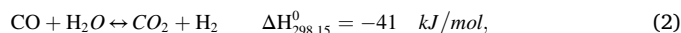
The starting point of our analysis is that today the share of renewable energy, in electric power production, in Europe, is of about 32.3% (Jones et al., 2018), and the forecasted values goes up to 41%–50% within 2030 (IRENA, 2018), and 64%–97% within 2050, see Fig. 1.

Methane steam reforming has been selected as the reference technology since this technology accounts for the 50% of global H₂ production (IEA, 2008; Barreto et al., 2003). Two reactions are involved in

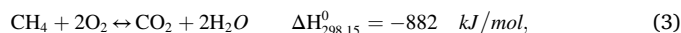
converting methane into hydrogen: the strongly endothermic reforming reaction (1)



and moderately exothermic water-gas-shift reaction (2)



It is quite evident that the process is endothermic on the whole, and the heat required for reaction 1 is provided by methane combustion (3)



Thus, it is quite evident that if the heat of reactions is provided by electricity, the amount of CO₂ is drastically reduced. Depending on the overall process architecture, CO₂ reduction may achieve up to 40%, i.e. about 0.51 kg of CO₂ per Nm³ of H₂ produced (Spath and Mann, 2000).

By providing the heat of reaction through electricity, the overall scheme of the conventional SR process needs to be modified. Purge gas from PSA will not be burned anymore into the radiant section, but it will be recycled back into the feed stream. This will imply to remove CO₂ from the syngas with a dedicated unit. Not to mention that without a convection section all the streams' pre-heatings need to be performed in a different way. A preliminary comparison of the block diagram for conventional MSR and eMSR is given in Fig. 2a and b. Although it is still a matter of how the eMSR will be practically implemented (Wismann et al., 2019a, 2019b; Oshima et al., 2013; Lu et al., 2019), its impact, as previously mentioned, in terms of reduction of natural gas and the CO₂ emission reductions, is so important to justify major research's effort towards this direction.

Moreover, eMSR is able to absorb a reasonable amount of electricity, thus, becoming also an alternative technology for energy storage, comparable with electrolysis, by proper adapting the plant capacity to the fluctuation of the grid.

The emission impact of eMSR can be then further reduced by implementing a CO₂ capture through mineralization process, which is justified in the case of eMSR and not MSR since these two technologies produce different amount of CO₂ through different process architecture. Indeed, for conventional MSR, CO₂ should be removed from flue gas, but this would be quite expensive, due to the low CO₂ partial pressure, thus strongly impacting the Cost of Production (COP) of hydrogen. Therefore, minimization of CO₂ load should occur before its capture. Generally speaking, the carbon capture and storage of CO₂ from a conventional scheme for energy or hydrogen production requires high energy consumption both for capturing and compression (Wilberforce et al., 2019). Moreover, CCS (in situ) technology emergence has also suffered other barriers: competition with (direct low-emission) renewable technologies; - social skepticism due to the lack of shared knowledge on this quite new technology and the related well known "Not in my backyard" phenomenon; - lack of long-term policy of CCS implementation (Tcvetkov et al., 2019). Ex-situ CO₂, instead, would not imply social issue; and it would also ensure better control of mineralization reactions kinetic which are conventionally slow.

For all these reasons, eMSR technology coupled with mineralization seems to be an appealing solution which is worth being deeply analyzed.

In this paper, first, a process scheme for eMSR coupled with an innovative process scheme for CO₂ mineralization is provided. Then, the results coming from this architecture assumptions are analyzed. A comparison, on the basis of CO₂ emission and economic feasibility, between grid-based electrolysis, MSR, eMSR with CO₂ mineralization is later performed and discussed.

2. eMSR with mineralization process

2.1. eMSR process

To achieve values relative to eMSR a reference plant with a capacity

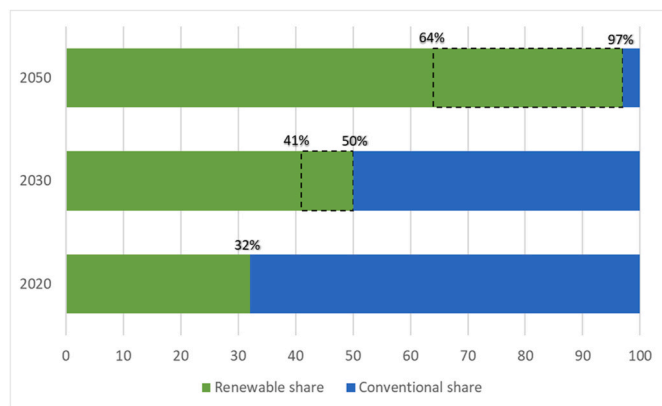


Fig. 1. Forecasting of renewable share in electrical power within the next years (IRENA, 2018).

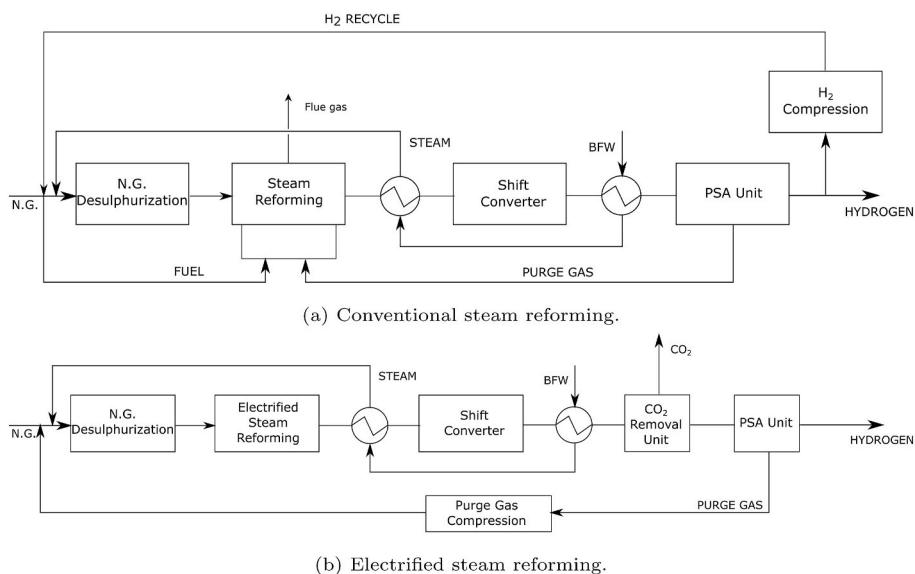


Fig. 2. Process block diagrams.

of $10000 \text{ Nm}^3/\text{h}$ of H_2 has been evaluated. Fresh methane at 45°C and 7 barg is mixed with the purge gas recycled from Pressure Swing Adsorption (PSA); then this gas mixture is compressed at 42 barg and heated up to 350°C (through heat recovery with the outlet of the Water Gas Shift (WGS) reactor) in order to achieve temperature requirement for a desulfurization reactor. After purification, the stream is mixed with steam at 300°C and 40 barg, under a proper S/C ratio. An electrical heater is used to heat this mixture stream which is the feed of reforming. Finally, the feed is sent to the electrical reformer from which it outflows at 34,9 barg and 890°C ; the reforming reaction occurs with a Steam to Carbon ratio equal to 2.5. The outlet of reforming is cooled down to 350°C , the relative thermal energy is recovered to produce steam at 42 barg. The outlet syngas is then sent to a high temperature WGS reactor and to low temperature WGS reactor, in which are reached a CO conversion, respectively, of 69% and 97%. The gas stream, rich of H_2 and CO_2 , is sent to an amine separation unit by which the CO_2 is separated; the CO_2 amount - 4908 kg/h - is collected and, in this case, sent or not to the mineralization section. Finally, the gas rich in H_2 is sent to the PSA system to be purified, achieving a recovery factor of 92%.

The overall energy consumption of the eMSR process at issue is 14 MW of which: 4% for compression; - 82% for the heating; - 14% for steam generation.

2.2. Mineralization process scheme

Carbon mineralization is an emerging process to remove carbon dioxide (CO_2) from industrial process by transforming it in the form of magnesium or calcium carbonate. Such carbonates may then be safely and permanently stored, as mineralization is a naturally occurring process involving silicate materials and rocks rich in Ca and Mg - both not-toxic material (Snæbjörnsdóttir et al., 2020; Xie et al., 2015).

Carbon mineralization is one of the most recent techniques of Carbon Capture and Storage (CCS), a field whose relevance has been acknowledged over the last 20 years (Bandilla, 2020). This technique, by entrapping CO_2 into carbonates, exploits the favorable thermodynamic conditions for which molecules of carbonates are more stable than the CO_2 , which is a very stable molecule in turns, see Fig. 3. Mineralization can occur in-situ or ex-situ. In the first case, CO_2 is entrapped directly in mineral site; on the contrary, in the second case, the mineral is taken off its site, properly treated and let come in contact with CO_2 stream in suitable reactors. In this second option, parameters influencing the rate of reaction are more easily manipulable, and this is an advantage

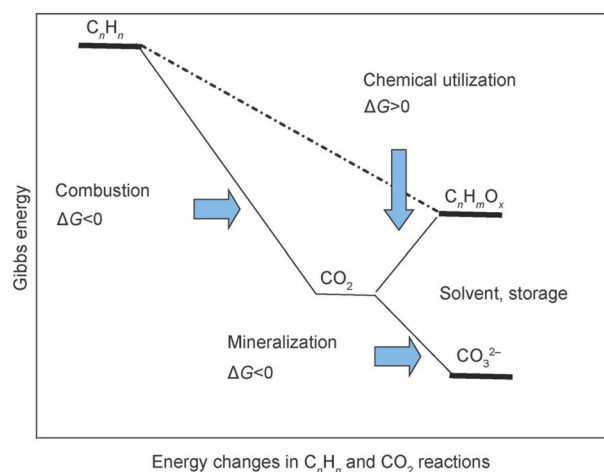


Fig. 3. Gibb energy value of molecules involved in the mineralization process (Xie et al., 2015).

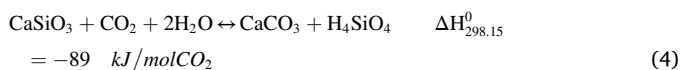
considering that mineralization reactions are favoured by thermodynamics but are characterized by low kinetic times (Mazzotti et al., 2005).

One of the major advantages of the proposed architecture is the fact that CO_2 stream, coming from eMSR, is available with a purity higher than 99%, thus, avoiding a cost for purification or supply, which is of about 30–90 €/ton of CO_2 (Abbas et al., 2013; Ho et al., 2008). Such pure CO_2 stream can be compressed at any pressure required to accelerate the mineralization process.

The direct mineralization with water has been selected as CO_2 capture technology. Despite indirect mineralization technologies could have lower characteristics times of reaction, direct mineralization with water is a more reliable and consolidate technology; indeed, it has been one of the first technologies studied at pilot plant (Naraharisetti et al., 2019). Data for the reactions times at defined operating conditions have been taken from the study of Gerdemann et al. (2007). Three different minerals have been analyzed: olivine, wollastonite, and serpentine. Process schemes for all the materials have been evaluated. However, the process which employs wollastonite seems more convenient; indeed, it involves less energy consumption for compression, it is more reactive than olivine not requiring chemicals additions to the water, and due to

the enough high level of reactivity without requiring CO₂ liquefaction (Gerdemann et al., 2007). Each of these factors ensures a minimization of CAPEX value. Thus, here will be described only the process relative to wollastonite mineralization.

Generally speaking, carbonation is a process favoured from a thermodynamic point of view also at low/ambient operating conditions; as matter of fact, it occurs in natural eco-system. Hence, this kind of reaction needs to be kinetically improved, in order to achieve characteristic times suitable for the industrial framework. The carbonatation reaction of wollastonite is the following (4).



The material balance of the overall scheme is addressed in Fig. 4 together with block scheme of the process, the mineralization unit treats a CO₂ amount of 5 ton/h, coming from eMSR process, at 35 °C and 0.5 barg. This stream has to be compressed to 41 barg with 4 intercooled stages compression unit, indeed high pressure promotes the increasing of the reactions' rate. A compression ratio of 2.275 and an interstage cooling temperature of 35 °C have been set. Between third and fourth stages the recycled CO₂ stream from the reactor, previously cooled and laminated, is mixed to the initial CO₂ stream. The recycle stream comes from the reactor where only 82% of conversion is reached. Thus, reactor is fed with CO₂ flowrate equal to 6 ton/h, at 41 barg and 116 °C.

As far as the mineral is concerned, the wollastonite undergoes grinding in a stirred media detritors mill, to reach an average dimension of 10 μm. Distillate water is mixed with the mineral to achieve a slurry 30% w/v. The amount of wollastonite, 17.22 ton/h, is mixed with a water stream of 57,398 m³/h. The resulting slurry stream is pumped at 41.5 barg and heated up to 100 °C, by recovering the heat from the exhaust outlet slurry from the reactor.

The reactor is a stirred tank with a continuous mixing. The residence time is fixed at 1 h. The reaction (4) is exothermic and the released heat leads to a temperature increase inside the reactor up to 122 °C. As abovementioned, the unreacted CO₂ is recycled with the fresh CO₂. The slurry, after heat recovery with reactor inlet stream, is filtered to recover 70% of water. The utilities consumption related to the process are listed

in Table 1 per unit of CO₂ ton converted.

3. Emission analysis

3.1. MSR configuration versus grid-based electrolysis

Fig. 5 represents the CO₂ emitted associated to H₂ production relevant to MSR and grid-based electrolysis working on a continuous bases versus the share of renewable energy. The values are based on a set of parameters listed in Table 2; values for MSR have been evaluated through internal simulation and are mentioned and in line with other literature work (Barba et al., 2008; De Falco et al., 2008). In such configuration, H₂ is produced from electrolysis powered with electricity from a grid mix made up from renewable and non-renewable energy sources. In particular, the actual average energy mixing in Europe is composed of energy produced by 18.9% from natural gas, 10.0% from hard coal, 9.2% from lignite, 25.5% from nuclear plants, and 32.3% from renewable (Jones et al., 2018). The estimated CO₂ emitted is approximately 0.28 kg of CO₂ per kWh produced.

As it is also highlighted in Fig. 5, MSR is unable to act as storage for electrical surplus, as a matter of fact, the conventional architecture absorbs little amount of electricity, only related to natural gas compressor - the main contribution - pumps and fans, being the heat of steam reforming reaction provided by the combustion of mixture of natural gas and purge gas from the final purification of H₂ via Pressure Swing Absorption (PSA). This means that, considering the remote future scenario, in which the renewable share is expected to reach quite the totality, MSR would not be anymore the relevant technology in terms of H₂ production.

Table 1
Utilities consumption per unit of ton of CO₂ converted.

Mineral [ton/ton _{CO2}]	3.5
Water [ton/ton _{CO2}]	3.6
Energy consumption [MWh/ton _{CO2}]	0.7
Compression and pumping [MWh/ton _{CO2}]	0.1
Grinding [MWh/ton _{CO2}]	0.6

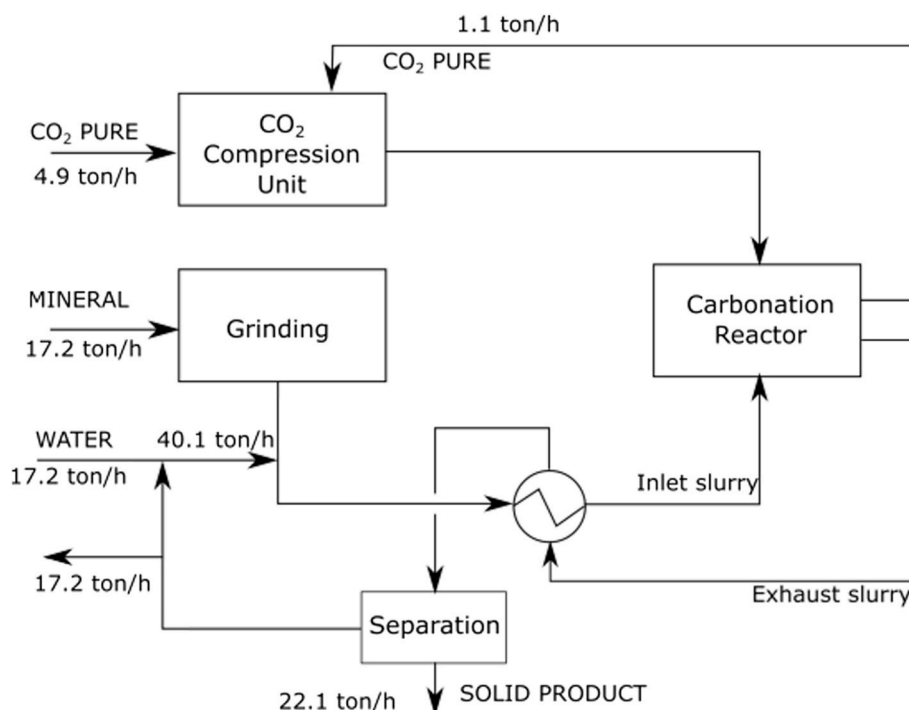


Fig. 4. Process block diagram of wollastonite mineralization.

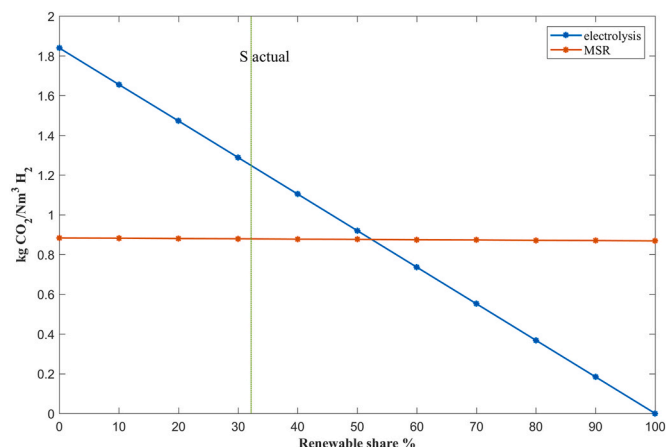


Fig. 5. Emission of grid-based electrolysis vs conventional MSR with variable renewable share.

Table 2

Energy consumptions and direct CO₂ emissions per kg of H₂ for grid-based electrolysis and MSR processes, as per today renewable share of power.

	Grid-based Electrolysis	MSR
Energy consumption [kWh/Nm ³ _{H₂}]	4.5 (Bertuccioli et al., 2014)	0.038 (Barba et al., 2008; De Falco et al., 2008)
Indirect CO ₂ emissions [kgCO ₂ /Nm ³ _{H₂}]	1.26	0.01
Direct CO ₂ emissions [kgCO ₂ /Nm ³ _{H₂}]	–	0.87 (Barba et al., 2008)

On the other hand, the break-even point, where both technologies emit the same amount of CO₂ per unit of H₂ produced, is reached for a share value of 52%. If such share level will be reached in Europe later than 2030, as forecasting results shown in Fig. 1 suggest, this implies that, until that moment, grid-based electrolysis would emit more CO₂ than conventional MSR, getting even the economic evaluation for grid-based electrolysis implementation meaningless.

3.2. eMSR configuration versus grid-based electrolysis

In Fig. 6 the eMSR is added and compared with grid-based electrolysis and MSR again in terms of CO₂ emissions as a function of share of renewable energy. From Fig. 6, it is quite evident that, if the heat of reactions is provided by electricity, the amount of CO₂ can be reduced

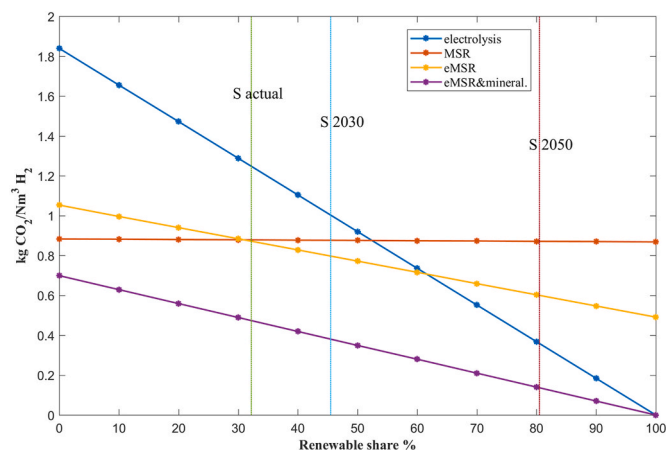


Fig. 6. Emission of grid-based electrolysis, conventional MSR, eMSR, and eMSR with mineralization variable renewable share.

more and more with the increase of renewable share. Indeed, at the actual renewable share, CO₂ emissions of eMSR and MSR are quite similar - eMSR technology implementation can be crucial, in terms of environmental benefits, for the foreseeable future.

The Break-even point (BEP) between grid-based electrolysis and eMSR is moving on the right and reaches more than 60% of share. This implies that, considering the introduction of eMSR in the panorama of H₂ production, methane conversion can still be competitive with grid-based electrolysis in the foreseeable future and even slightly further.

3.3. eMSR configuration with CO₂ capture through mineralization

Coupling the eMSR with CO₂ mineralization, the BEP between this scheme and grid-based electrolysis is obviously shifted to 100% of renewable share. Despite what we are get used thinking, this shows how methane reforming, with electric and mineralization implementations, can compete with grid-based electrolysis, from environmental point of view, regardless of any renewable sharing gride value. To get a more accurate view our comparison, it is essential to evaluate economic parameters, indeed the costs of production of technologies at issue have to be evaluated and compared - see next section.

A summary of the specific consumptions and co-products of all the technologies here analyzed is reported in Table 3.

4. Economic analysis

In order to evaluate the cost of production (COP), an eMSR process, coupled with a CO₂ mineralization unit, of a capacity of 10,000 Nm³/h of hydrogen is selected. Key economics parameters used for evaluation of each of the taken technologies are listed in Table 4.

The investment cost was estimated using a standard estimating tool, Aspen Capital Cost Estimator, and company long experience in construction hydrogen unit. This evaluation are mentioned in other previous works (Barba et al., 2008; De Falco et al., 2008). Table 5 provides investment cost for a conventional H₂ plant, an eMRS of the same size and CO₂ mineralization able to fix 5 ton/h of CO₂, and a grid-based electrolysis plant producing 10,000 Nm³/h - which means of 45 MWeI of capacity, by taking an average consumption of 4.5 kWh per Nm³.

On the basis of the key parameters listed in Table 4, the main operative cost are evaluated and reported in Table 6.

As can be seen, the COP in the case of eMSR with mineralization is still not competitive with the conventional MSR figure. Nevertheless, it is less expensive than grid-based electrolysis. Thus, in the current scenario, in order to have a H₂ production which ensures lower CO₂ emissions than conventional scheme (MSR), the implementation of eMSR coupled with mineralization appears to be the most attractive solution. Note that, eMSR as it is, would produce similar amount of CO₂ emission - in comparison to MSR - with a quite low penalty in economics.

Further, we evaluate the COP of technologies at issue for foreseeable -2030 - and more remote - 2050 - future scenarios. The parameters and resulting main variables listed in Tables 7 and 8 have been taken into

Table 3

Consumptions and co-products of references technologies per unit of Nm³ of H₂ produced.

	G-b Electrolysis	MSR	eMSR	eMSR + min.
CH ₄ [Nm ³ /Nm ³ _{H₂}]	–	0.44	0.25	0.25
Power [kWh/Nm ³ _{H₂}]	4.5	0.04	1.4	1.75
Direct CO ₂ emitted [kg/Nm ³ _{H₂}]	–	0.86	0.49	–
Indirect CO ₂ with 2020 grid share [kg/Nm ³ _{H₂}]	1.26	0.01	0.39	0.49
Ore [kg/Nm ³ _{H₂}]	–	–	–	1.75
Converted ore disposal [kg/Nm ³ _{H₂}]	–	–	–	4
Water [kg/Nm ³ _{H₂}]	0.8	–	–	1.8

Table 4

Key parameters for COPs definition.

Natural gas price	0.25 €/Nm ³
Electricity price	70 €/MWh
CO ₂ penalization	30 €/ton _{CO2}
Ore price	20 €/ton _{Ore}
Ore disposal	20 €/ton _{Converted ore}
Water price	3 €/m ³
Depreciation	10% of CAPEX per year
Maintenance cost	3% of CAPEX per year
Specific grid-based electrolysis power consumption	4.5 kWh/Nm ³
On stream time	8.400 h per year

Table 5

Investment cost of technologies.

Conventional H ₂ plant (10,000 Nm ³ /h)	20M€
eMSR H ₂ plant (10,000 Nm ³ /h)	30M€
CO ₂ mineralization plant (5 ton/h)	10M€
G-b Electrolysis (50 MWe) + auxiliary items	50M€

Table 6

Operative costs and final Hydrogen cost of production.

[€/M/y]	G-b Electrolysis	MSR	eMSR	eMSR + min.
CH ₄	–	9.2	5.3	5.3
CO ₂ emitted	3.2	2.2	2.2	1.2
Power	26.5	0.2	8.2	10.3
Ore	–	–	–	2.9
Converted ore disposal	–	–	–	6.7
Water	0.2	–	–	0.5
Dep. + Main.	6.5	2.6	3.9	5.2
COP [€/Nm ³ H ₂]	0.433	0.170	0.233	0.382

account.

Moving forward, within 2030, it is expected to meet a share of renewable equal to 45.5% - as average value. The forecasted value of CO₂ penalization will be slightly higher than the current one, 35 €/ton (Capros et al., 2013). Bearing in mind Fig. 6, in regard to CO₂ emissions, the scenario will be quite similar to the current one, except for the lowering of emissions related to eMSR; in this case, emissions are noticeably lower than MSR one. Grid-based electrolysis and eMSR coupled with mineralization are still, respectively, the worst and best solution - in terms of CO₂ emissions impact.

As for the economic aspect, see Fig. 7, grid-based electrolysis will be more advantageous of eMSR with mineralization only in the case of low energy price - about below 60 €/MWh - but it will be less competitive than pure eMSR, regardless of the cost of energy. Thus, grid-based electrolysis seems to be neither economically nor environmentally a good alternative to MSR. In this scenario, eMSR with mineralization is significantly more expensive than MSR. Nevertheless, H₂ production through this scheme would ensure, accordingly, a significant decrease in CO₂ emissions. On the other hand, eMSR, reasonably, would provide lower environmental benefits - still benefits though - without significant increase in COP.

As regards the 2050 scenario, it is deemed that by then renewable share of about 80.5% - as average value - will be reached and 100 €/ton could be paid as penalty for CO₂ emission (Capros et al., 2013). In this figure, grid-based electrolysis turns out to be favorable from a CO₂ emission point of view. Actually, this occurs at 52% of share - if

Table 7

Parameters of considered scenarios.

	CO ₂ grid [kg/Kwh]	CO ₂ pen. [€/ton]	Power cost [€/Mwh]	Ore disposal [€/ton]
S actual	0.28	30	70	20
S 2030	0.22	35	40–70	20
S 2050	0.08	100	40–70	20/0/-20

compared it with MSR - and at 60% - if compared it with eMSR. Nonetheless, eMSR with CO₂ mineralization will still imply lower CO₂ emission between the technologies at issue.

Fig. 8 shows as grid-based electrolysis will be the most expensive solution, even more than eMSR with CO₂ mineralization, only for energy price higher than 65 €/MWh. Thus, the choice of the most attractive alternative to MSR conventional H₂ production will definitely depend on energy cost, but also on which aspect will be preferred, either the

Table 8

Resulting variables of considered scenarios.

	S actual	S 2030	S 2050
CO ₂ emission from power [kg/kWh]	0.28	0.22	0.08
CO ₂ penalization [€/ton]	30	35	100
Power cost [€/Mwh]	70	40–70	40–70
Ore disposal cost [€/ton]	20/0/-20	20	20/0/-20
Capital cost for electrolysis [M€/MWe]	1	0.5	0.3

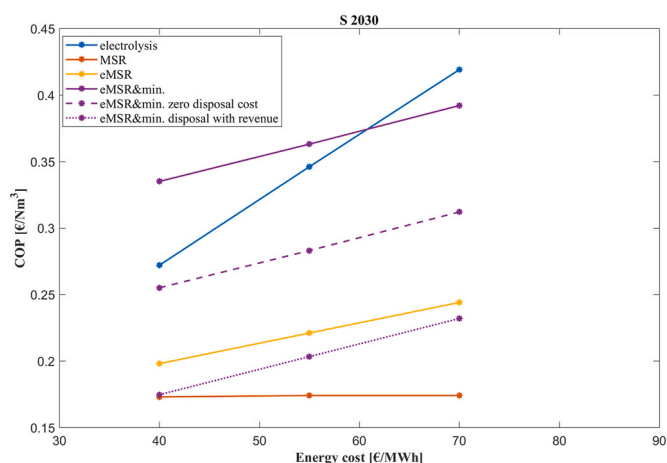


Fig. 7. COP evaluation for 2030 as functions of power cost.

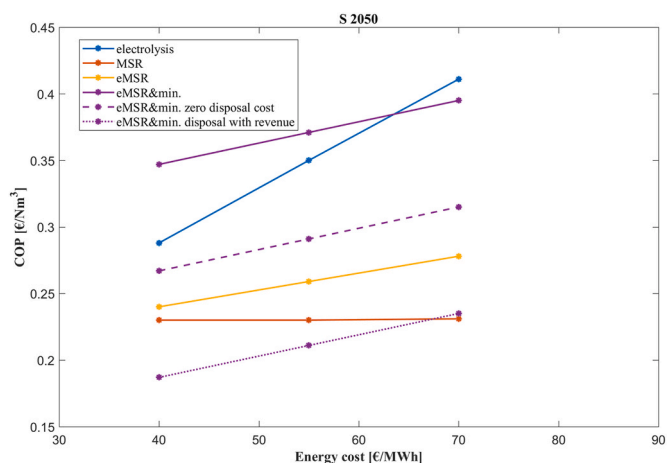


Fig. 8. COP evaluation for 2050 as functions of power cost.

economic or the environmental. Indeed, being inclined to spend more for H₂ production, the eMSR with mineralization - which ensures the higher CO₂ emissions reduction - would be the most attractive configuration.

Moreover, it must be taken into consideration that, in case of eMSR coupled with mineralization technology, further research efforts may lead to the realization of a process able to produce an exhaust ore without the related cost of disposal, or even with a potential revenue—for example, the converted ore could be used as building material. In the case of zero disposal cost eMSR with mineralization would be, without the shadow of a doubt, significantly preferable to grid-based electrolysis. Whereas, in the case revenues could be obtained, eMSR with mineralization would be even economically competitive with conventional H₂ way of production, MSR.

5. Conclusion

The analysis of CO₂ emissions and COP in relation to the four technologies - MSR, eMSR, grid-based electrolysis, and eMSR with CO₂ mineralization - allowed to preliminarily evaluate the benefits relating to each of them and to assess which could be the most attractive solution for H₂ production. Grid-based electrolysis, unlike many would think, is not necessarily the most compelling alternative to the conventional H₂ production pathway, as of now and looking forward.

Conversely, eMSR seems to be a valuable alternative in the current and future framework, especially considering that eMSR could be, in the future, coupled with CO₂ mineralization. On the basis of the results achieved in this work, a progressive investment approach could provide the best solution from both an economic and an environmental perspective.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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