CO2 methanation activated by magnetic heating: life cycle assessment and perspectives for successful renewable energy storage

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Abstract

Purpose Technologies with low environmental impacts and promoting renewable energy sources are required to meet the energetic demand while facing the increase of gas emissions associated to the greenhouse effect and the depletion of fossil fuels. CO_2 methanation activated by magnetic heating has recently been reported as a highly efficient and innovative power-to-gas technology in a perspective of successful renewable energy storage and carbon dioxide valorisation. In this work, the life cycle assessment (LCA) of this process is performed, in order to highlight the environmental potential of the technology, and its competitivity with in respect to conventional heating technologies.

Methods The IMPACT 2002+ was used for this LCA. The process studied integrates methanation, water electrolysis and CO_2 capture and separation. This "cradle-to-gate" LCA study does not consider the use of methane, which is the reaction product. The functional unit used is the energy content of the produced CH_4. The LCA was carried out using the energy mix data for the years 2020 and 2050 as given by the French Agency for Environment and Energy management (ADEME). Consumption data were either collected from literature or obtained from the LPCNO measurements as discussed by Marbaix (2019). The environmental impact of the CO_2 methanation activated by magnetic heating was compared with the environmental impact of a power-to-gas plant using conventional heating (Helmeth) and considering the environmental impact of the natural gas extraction.

Results It is shown that the total flow rate of reactants, the source of CO_2 and the energy mix play a major role on the environmental impact of sustainable CH_4 production, whereas the lifetime of the considered catalyst has no significant influence. As a result of the possible improvements on the above-mentioned parameters, the whole process is expected to reduce by 75% in its environmental impact toward 2050. This illustrates the high environmental potential of the methanation activated by magnetic heating when coupled with industrial exhausts and renewable electricity production.

Conclusions The technology is expected to be environmentally competitive compared with existing similar processes using external heating sources with the additional interest of being extremely dynamic in response, in line with the intermittency of renewable energy production.

Keywords CO_2 methanation · Magnetic heating · Life cycle assessment · Intermittent energy production

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1 Introduction

The increase of greenhouse gas emissions along with the depletion of fossil fuels impose the development of technologies that make use of renewable energy sources. These sources being intermittent, finding an efficient way to store them appears as an absolute necessity. Magnetic hyperthermia is a field that has been investigated for decades, mostly for medical applications (Hergt et al. 2006; Hervault and Thanh 2014; Salunkhe et al. 2014). More recently, it has been shown that magnetically induced heating could be exploited in catalysis, using for example iron-based nanoparticles (NPs) as

magnetically stimulated heating agents to activate catalytic reactions in a perspective of energy storage. It has been suggested that heating the catalytic system by magnetic induction gives a major advantage in terms of activation rate; magnetic NPs reach their steady state temperature within 100 ms, and the system can be operational within a few minutes versus hours for traditional heating (Bordet et al. 2016). This should enable an efficient way for renewable energy to be integrated into local power-to-gas (P2G) or hydrogen generation units, as this on/off behaviour is perfectly adapted to the intermittency of this type of energy production (Pérez-Camacho et al. 2015). As a result, catalysis assisted by magnetic heating could be favourably implemented in the conversion of electric energy surplus into energetic gas vectors in case of overproduction. In this context, products of added value such as methane could be efficiently obtained using CO_2 as a source through the Sabatier exothermic reaction in the frame of P2G process. As a whole, the perspective of using magnetic hyperthermia as a delocalised and decarbonised way to perform P2G has to be considered.

First shown on the Fischer-Tropsch reaction (Meffre et al. 2015), this approach has been applied to other reactions such as methane reforming (Mortensen et al. 2017; Vinum et al. 2018; Varsano et al. 2019) or CO_2 hydrogenation (known as Sabatier reaction, in Eq. 1) (Bordet et al. 2016; Wang et al. 2019).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \Delta_r H^0\,(298K) = -165\ \text{kJ.mol}^{-1}. \tag{1}$$

Focusing on Sabatier reaction with Ru NP catalysts activated by iron carbide NPs, Bordet et al. reported excellent conversions of CO_2 (up to 93.7%) with exclusive selectivity for CH_4 using a total flow rate of incoming gases of 125 mL/min. In that work, 16.1 W (calculated from the H_2 incoming flow) were converted into 12.6 W (CH_4 outgoing flow) by using 1.82 kW power input for field generation (300 kHz), which corresponds to a global energy efficiency of roughly 0.7%. To be considered as a sustainable alternative, this value has to be comparable with the one obtained by traditional heterogeneous catalysis activated by conventional heating claimed to be up to 80% (National Technical University of Athens et al. 2017). Thus, it is clear that optimisation of the magnetically activated process is necessary in order to be competitive. One way to achieve this goal is by increasing the flow rates while simultaneously decreasing the energy required to generate the magnetic field necessary to trigger catalysis. However, these considerations concern the catalytic system exclusively, which does not consider the energy required for reactant production (H_2, CO_2) and its potential environmental impact. Such analysis has been performed in the case of catalysis using traditional external heating sources as opposed to fossil fuels in the case of hydrogen and methane production (Collet et al. 2017).

In this paper, we intend to perform a "cradle-to-gate" life cycle assessment (LCA) of CO_2 methanation activated by magnetic heating. Assuming that Sabatier reaction can be self-maintained through its exothermicity, this work considers realistic developments that can be performed to minimise the electric power required to generate the magnetic field and therefore maximise the energy efficiency of the system (Marbaix 2019). This enables to set up a first overview of the environmental impact of this technology, integrated in a water electrolyser and carbon capture architecture to (1) define a guideline for future development by identifying the main technological challenges that have to be met for a successful future implementation, (2) confirm the promising perspective of integration in a future delocalized P2G process and (3) ensure that the technology is environmentally competitive with traditional P2G processes. Through this work, it is shown that increasing the flow rates from 0.1 to 10 m^3/h can drastically reduce the environmental impact of the methanation unit. The energy mix and the CO_2 source exhibit high impact as well, and confirm the interest of coupling this system to a sustainable production (e.g. wind turbines) and highly CO_2-concentrated smokes. It is also shown that the catalyst lifetime (100–1000 h) is not significant in the life cycle assessment. As a result, an ideal scenario taking place in 2050 uses 10m^3/h of incoming gases, 1000-h lifetime catalyst and CO_2 emitted by polluting industries such as cement plants. These considerations enable to reduce within 30 years roughly by 75% of the environmental impact of P2G using magnetic hyperthermia and make this technology fully comparable with the state of the art of CO_2 methanation using traditional external heating sources. As additional advantages of this technology, the excellent dynamics and cyclability of magnetic heating offer promising and adaptable implementation perspectives for the storage of renewable energy.

2 Methods and data

2.1 Definition of the system

2.1.1 LCA method

The method chosen for this LCA is the IMPACT 2002+ (Jolliet et al. 2003). It combines the intermediate (midpoint) and the final (endpoint) impact approaches. The term 'midpoint' expresses the fact that this point is located somewhere on an intermediate position between the life cycle inventory (LCI) results and the damage on the impact pathway. In consequence, a further step may allocate these midpoint categories to one or more damage categories, the latter representing

quality changes of the environment. A damage indicator result is the quantified representation of this quality change and calculated by multiplying the damage factor with the inventory data. The damage indicator result is often also named 'damage impact score' or simply 'damage category'.

The midpoint or damage category approach is more detailed (four categories), but it can be less relevant depending on the goals and scope of the study (Chevalier et al. 2011), while the endpoint approach has higher relevance but less certainty (Bare et al. 2000). By choosing the IMPACT 2002+ method, the LCA comprises a mix of several midpoint indicators and several damage category indicators that permit to reduce the uncertainty of the study and still be relevant for decision-making. The methodology IMPACT 2002+ proposes a feasible implementation of the aforementioned combined midpoint-/damage-oriented approach. Added concepts and methods for the comparative assessment of human toxicity and ecotoxicity were developed for the IMPACT 2002+ methodology. The intermediate impacts are not shown in this study for readability purposes. The damage categories are human health, ecosystem, climate change and resources, and the respective units are DALY, potentially disappeared fraction of species/m^2/year, kilogramme/CO_2/eq and MJ primary.

2.1.2 Functional unit

To be consistent with the ISO 14040:2006 norm, the functional unit is defined as the quantified performance of the system. Therefore, the functional unit chosen for this LCA study is the energy content of the produced CH_4. All the results are based on 1 MJ of CH_4, its higher heating value (HHV) being 55.5 MJ/kg_{CH4}. Lower heating values (LHV) have not been used in the present study in order to stay consistent with other studies (Gruber et al. 2018). This LCA excludes the use of CH_4 once produced. Thus, the approach is a "cradle-to-gate" analysis as opposed to a "cradle-to-grave" LCA when the product use is considered.

2.1.3 System boundaries

The system boundaries of this LCA study have been defined as follows:

- The CO_2 methanation process is considered as an integrated technology that cannot operate independently from hydrogen supply (water electrolysis) and CO_2 feedstock (CO_2 separation and compression).
- We assess the environmental impact of the methanation by hyperthermia integrating the environmental impacts of the water electrolysis and CO_2 separation and compression.
- We compare with other methanation processes such as recently reported Helmeth project (National Technical University of Athens et al. 2017).

For these reasons, we decided to include CO_2 capture and separation, water electrolysis together with the methanation unit using magnetic heating in the system boundaries (shown in Fig. 1).

2.2 Life cycle inventory

The life cycle inventory identifies and quantifies the raw material usage, energy consumption and wastes released for water electrolysis, CO_2 separation and methanation using magnetic hyperthermia. As magnetic hyperthermia is a recent technology, its performances will be improved in the next decades. Thus, we report perspectives of technology improvements and variation of energy mix to highlight the potential of the whole methanation process toward 2050. A summarised table of data is shown in Table 1. The ecoinvent database is used in the default allocation.

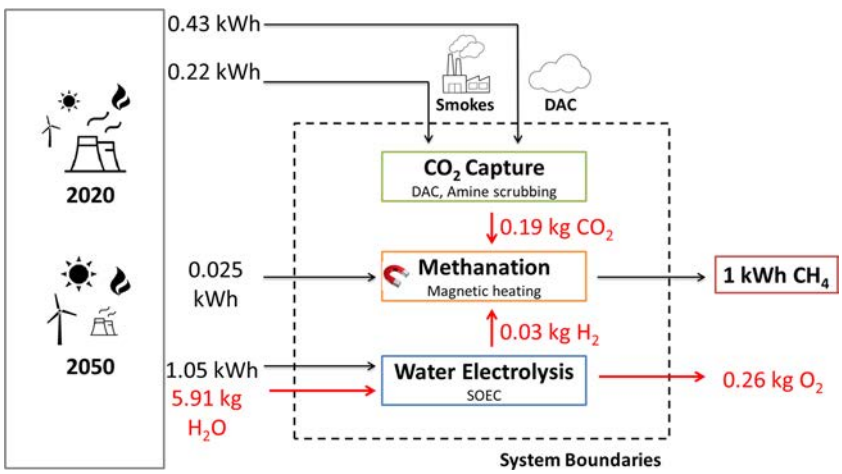

Fig. 1 System boundaries and reference processes for the conducted LCA

Table 1 Life cycle inventory of CO_2 capture, water electrolysis and methanation using magnetic hyperthermia in 2020 and projected values toward 2050

CO_2 Capture					
DAC		Unit	Data	Reference	Data used in this article
Heat	2020	kWh/kg_{CO2}	1.5–2	Meylan et al. (2016)	2 (Heat air-water heat pump 10 kW, system in ecoinvent database)
French electricity mix			0.25		0.25
Heat	2050		0.2	Fasihi et al. (2019)	Not considered in this article
Electricity			1.3		
Amine scrubbing					
Heat	2020	kWh/kg_{CO2}	1.1	(Reiter and Lindorfer (2015)	1. 1(Heat air-water heat pump 10 kW, system in ecoinvent database)
French electricity mix			0.06		0.06
Heat	2050		0.9–1.1	Bui et al. (2018)	Not considered in this article
Electricity					
Water electrolysis					
Deionised water		kg/kg_{H2}	9	x	9 (from tap water at user market for in ecoinvent database)
O_2 production		kWh/kg_{H2}	0.56	National Technical University of Athens et al. (2017)	0.56 of French electricity mix
Alkaline	2020	kWh/kg_{H2}	89	Götz et al. (2016)	Not considered in this article
	2050		63.5		
PEM	2020		83.4		
	2050		53.4		
SOEC	2020		36.8	Peterson and (Miller 2016)	35 of French electricity mix
	2050		35.1		
Methanation using magnetic hyperthermia					
Yield CH_4 300 °C, 25 mL/min	2020	Percent	100	Assumed in this article	100
	2050				
Power input	2020	Watt	30		30 of French electricity mix
	2050				

2.2.1 Electricity input

The electricity is an input in the system boundaries for all the three units (CO_2 capture, methanation and water electrolysis). The French electricity production has been taken as a reference with its particularity that it is mostly based on nuclear power plants. Indeed, the 2020 energy mix reported in Fig. 2 includes 72.6% of nuclear power against 9.9% in 2050 in agreement with the reference guideline given by the French Agency for Environment and Energy management (ADEME) (ADEME 2018). Coal, present in the 2020 energy mix is eliminated in the 2050 reference. This major decrease is expected to be compensated by renewable energies including hydropower, photovoltaic (PV) panels and onshore wind turbine power sources. Moreover, as the perspective of the P2G activated by magnetic heating is to be delocalised and paired with a renewable and intermittent source of energy such as wind turbines for example, wind as a single source of energy will also be studied.

2.2.2 CO_2 compression/separation

Due to its role in global warming, the introduction of carbon taxes and quotas urge industrials to reduce their CO_2 emission. One out of several solutions for industrials is to pair it up with a process using CO_2 as a reactant. In the case of methanation, CO_2 constitutes the carbon feedstock to valorise through hydrogenation. Several possibilities to capture and store to use this greenhouse gas (Markewitz et al. 2012; Cuéllar-Franca and Azapagic 2015; Vilches Arenas et al. 2018) are being studied.

Hence, the methanation process is an elegant way to valorise the CO_2 of industrial plants. In this LCA, we implemented both direct air capture (DAC) and CO_2 separated out of industrial exhausts (e.g. cement plant). DAC energy consumption of 2020 is estimated between 1.5 and 2.25 kWh/kg CO_2 based on two industrial processes (Meylan et al. 2016; Fasihi et al. 2019). New technologies such as ion-exchange resin used for DAC enables to reduce its energy consumption down to 0.6 kWh/kgCO_2, but data for total energy consumption (including fans) are still under debate (Fasihi et al. 2019). Thus, we exclude them from the scope of this study. Different processes of CO_2 separation from the cement plant smokes exist, but amine scrubbing is among the most efficient one (Leung et al. 2014). This technology is based on the adsorption/desorption process on amines such as monoethanolamine (MEA) (Rochelle 2009, 2016). The data used in the present study take the heat and electricity consumption for CO_2 separation and compression by amine scrubbing into consideration (Reiter and Lindorfer 2015). According to the American Physician Society, this technology is less energy-consuming than DAC (1.16 kWh/kgCO_2) due to a higher concentration of CO_2 in the industrial smokes (Socolow et al. 2011). Moreover, it has been recently reported that the energy consumption of amine scrubbing based on the use of MEA for carbon capture is not expected to be significantly reduced (Bui et al. 2018). Finally, as no information is given regarding their lifetime, the chemicals such as MEA and solvents are excluded, and it is assumed that their role in the LCA is minor regarding the global electricity consumption of the process.

2.2.3 Electrolyser, water input and O_2 output

In this study, three technologies of water electrolysers are considered, i.e. proton exchange membrane (PEM), alkaline and solid oxide electrolysis cells (SOEC). It has been reported that alkaline and PEM technologies consume 89 and 83.4 kWh/kg_{H2}, respectively, with perspectives of nearly 20 kWh/kg_{H2} reduction toward 2050 (Götz et al. 2016). These technologies exhibit interesting features when considering grid balancing and P2G applications, such as high maturity, low maintenance and cost or highly efficient on/off behaviour (Buttler and Spliethoff 2018). However, it has been discussed that SOEC might be the most promising electrolysis technology in terms of efficiency. Indeed, the US Department of Energy (DOE) expects a system electrical usage (heat excluded) down to 35 kWh/kgH_2 toward 2050 (Hansen 2015;

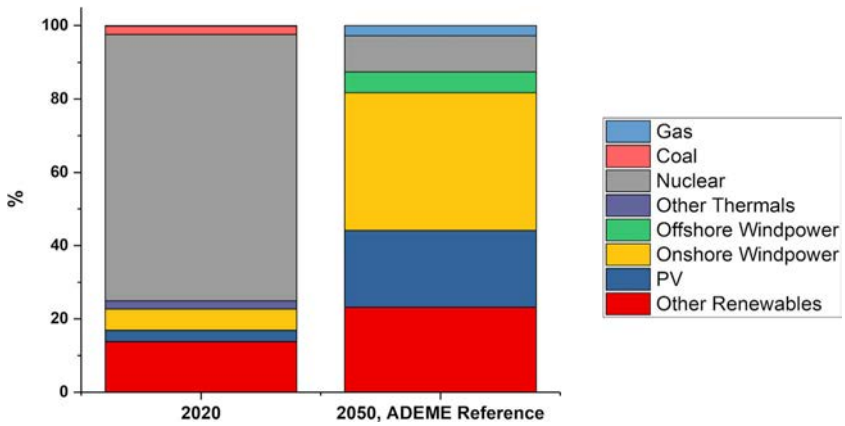

Fig. 2 French electricity mix in percent of total energy production prospected for 2020 and 2050 following a reference scenario given by ADEME agency. Other thermals include oil, other renewables include hydropower and biomass

Peterson and Miller 2016). For these reasons, SOEC technology has been implemented according to DOE perspectives. Moreover, a need of deionised water up to 9 kg/kg_{H2} has been considered as well. O_2 production is implemented as a usable by-product, which corresponds to an electricity consumption of 0.56 kWh/kg_{H2} (National Technical University of Athens et al. 2017).

2.2.4 Methanation using magnetic hyperthermia

Since the results reported by Bordet et al. for CO_2 methanation through Sabatier reaction, our group has been working on the improvement of the process in respect to (1) conversion of CO_2 and selectivity toward CH_4, (2) the composition of the catalytic bed and (3) the minimization of the energy required to perform the catalysis. We assume in this study a 100% yield of CH_4 under moderate incoming flow of $CO_2 + H_2$ (5 mL/min CO_2 + 20 mL/min H_2; total mass flow, 25 mL/min, i.e. 0.001 m^3/h) at 300 kHz. The composition of the catalyst is based on Fe as heating agent and Ni as a catalyst of CO_2 hydrogenation, these active species being supported on CeO_2. The catalyst considered in the present study consists of 30 g Ni (Nickel, 99.5% market for in the ecoinvent database), 650 g Fe (iron pellet market for in the ecoinvent database) and 500 g cerium oxide (cerium concentrate, 60% cerium oxide market for in the ecoinvent database), which makes it consistent with similar reported catalysts in the literature (Meylan et al. 2016).

The energy required to achieve the above-mentioned performances can be considerably reduced through intermittent application of the magnetic field. Thus, the system can be kept at the operational temperature through a regulating loop, serving magnetic pulses to maintain the temperature of the system at the consign level ± 10 °C. A representative temperature of 300 °C using 30 W of power supply in average, converting 100% of CO_2 into CH_4 will be implemented in the present LCA. Lower temperatures do not allow reaching such catalytic performances. With regard to the assumptions made for this study, the same demands on electricity are implemented for both 2020 and 2050. No scale effect between the laboratory process and an industrial pilot has been considered despite the potential decrease in performances that could be observed upon upscaling. This will be briefly discussed later. The water that is produced through the reaction is not considered, but it could be advantageously integrated in the electrolyser in a future work to optimise the system.

2.3 Sensitivity analysis

With regard to the life cycle inventory, some parameters were subjected to a sensitivity analysis taking both the uncertainties concerning the up-scaling process into consideration and the consistency of our comparison to other existing technologies of P2G. In addition, this sensitivity analysis has to be understood as a highlighter of technology improvements that have to be achieved for a successful technology implementation in the future. Starting with the catalyst composition, it has been assumed that the catalytic performances could be maintained while increasing the total flow rate from 0.001 to 0.1 m^3/h, 1 m^3/h and 10 m^3/h with a constant GHSV. Considering that the increase of flow rate is expected to lead to higher amount of heat released, thanks to the exothermicity of the reaction, the power input for magnetic field generation has been kept constant and does not depend on the flow rate in this study. This is a consistent assumption as the increase of flow rate from the laboratory scale up to an industrial pilot will have as a result less external heat supply to be required and thus, the power input for magnetic field to sustain the catalysis would be reduced. Process chemistry needed for the fixed bed reactor development (including temperature control and cooling) is not considered in the frame of this study though. The lifetime of the catalyst has not been addressed yet, but stability can be experimentally maintained for at least 10 h on stream. It has been reported in various projects that the lifetime of a Ni-based catalyst for this application could vary from 100 h to more than 8000 h (Meylan et al. 2016). Thus, it seems reasonable to project the lifetime of our catalyst from 100 h up 1000 h in this LCA. Maintenance of the system is not considered in the present study, but it is obvious that a longer lifetime of catalyst is preferable. Finally, as mentioned earlier, the influence of the CO_2 source (DAC or out of industrial smokes such as cement factory) and the energy mix were implemented as well.

3 Results and discussion

3.1 2020 scenario

As a starting point, CO_2 methanation using magnetic hyperthermia has been implemented following a 2020 reference scenario using SOEC water electrolysis, CO_2 capture from industrial exhausts, 1000-h lifetime catalyst and a total flow rate of $CO_2 + H_2$ of 0.1 m^3/h. As shown in Fig. 3, the hyperthermia unit represents roughly 60% of the environmental impact of the technology in the four damage categories, while electrolysis is responsible of nearly 30% and CO_2 capture between 3 and 17%.

More precisely, the non-renewable energy indicator that expresses the quantity of primary non-renewable energy required to produce in our case is 1 MJ of CH_4 that enables to define a "sustainability efficiency" η_{sus} defined as shown in Eq. 2. This ratio clearly shows the investment in terms of primary fossil fuels that is required to produce 1 MJ of sustainable energy (CH_4). The higher the ratio, the lower is the investment in terms of non-renewable fossil fuels (Arvidsson

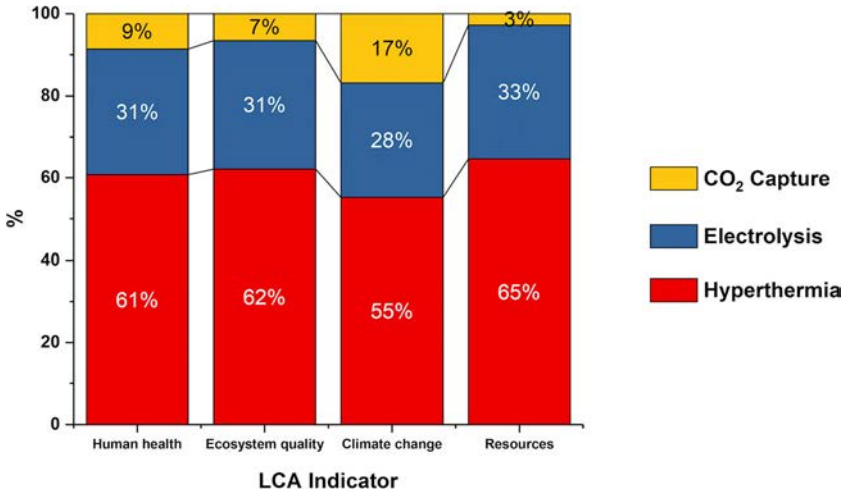

Fig. 3 Damage categories observed by the LCA of the 2020 scenario, using SOEC water electrolysis, CO2 capture from industrial exhausts, 1000 h life time catalyst and a total flow rate of CO2 + H2 of 0.1 m3/h. The human health was 3.1e 7 DALY, ecosystem quality 0.108 PDF.m2/year, the climate change 0.257 kg CO2 eq and resources 40.1 MJ primary

and Svanström 2016). The characterisation factors for non-renewable energy consumption, in terms of total primary energy extracted, are calculated using upper heating values. As a result, 11.1 MJ of primary non-renewable energy are required to produce 1 MJ of CH_4, $\eta_{sus} = 9\%$. Thus, the 2020 scenario clearly shows a large margin of technology improvement concerning the hyperthermia unit in order to increase this value.

$$\eta_{sus} = \frac{1\ \text{MJ sustainable } CH_4}{\text{Quantity of primary non renewable energy required}} \quad (2)$$

3.2 Perspectives of improvement

3.2.1 Flow rate

One of the possibilities to improve the hyperthermia system is the flow rate. As mentioned in the sensitivity analysis, three total $CO_2 + H_2$ flow rates were studied, i.e. 0.1/1/10 $m^3\ h^{-1}$. The results are shown in Fig. 4a. Increasing the flow rates from 0.1 to 1 m^3/h shows an impressive decrease of 50% in the environmental impact. This is mostly explained by the increased amount of energy produced in CH_4 form, when using higher flow rates, while using the same electrical input for field generation. The difference of the impact between 1 and 10 m^3/h is not as significant though, due to the energy required for the magnetic field. As a whole, environmentally speaking, the hyperthermia system is more interesting for flow rates above 1 m^3/h. This value is in agreement with common pilots or small industrial plants dedicated to P2G and encourages us to upscale our technology toward these values (Bailera et al. 2017).

3.2.2 Catalyst lifetime

The catalyst lifetime is another characteristic that has not been studied at the lab-scale yet and therefore, it can be seen as an additional factor for improvement. Different lifetimes are considered, namely 100/500/1000 h on stream and optimum catalytic performances. The results are shown in Fig. 4b. The results obtained show that between the three lifetimes studied, there are no significant differences on the environmental impact. This is due to the very low environmental impact of primary resources needed to compose the catalyst compared with the electrical energy needed to perform catalysis, electrolysis and CO_2 capture. Thus, the catalyst lifetime is not a concern based on the environmental point of view.

3.2.3 CO_2 source

As expected from the energy consumption for CO_2 capture using DAC or amine scrubbing out of industrial smokes, the impact on all four damage categories of DAC is nearly 20% higher than the CO_2 separation/compression from the cement plants (Fig. 4c). Therefore, coupling methanation by hyperthermia to a CO_2 emitter plant (here cement plant) is proven to be more interesting than feeding the methanation unit with CO_2 captured directly from the atmosphere. This observation reinforces the strategy of delocalised CO_2 methanation using hyperthermia coupled with an existing polluting industrial plant. Although cement plants are moderately large emission sources compared with large-scale fossil-fuelled power plants, they possess several characteristics favourable for CO_2 capture, such a relatively high CO_2 concentration in their flue gases, few emission points, stable operation and, in some specific cases, available waste heat. The cement industry has been showing increased interest in CO_2 capture technologies in recent years, especially in Europe where the European

Cement Research Academy is located. Production of cement is estimated to account for about 7% of anthropogenic CO_2 emissions, thus contributing significantly to climate change. The other potential sources are power plants, refineries, iron and steel industry and petrochemical industry (Gale et al. 2005).

3.2.4 Energy mix

Figure 4d shows the impact of the French energy mix of 2020 and 2050 following the ADEME reference scenario. In the case of direct intermittent energy coupling, we considered the full electrical power input supplied by onshore wind turbines. The 2020 French energy mix displays a negative impact at least 20 to 25% higher on all factors, namely "climate change", "ecosystem quality", "human health" and "resources", than the 2050 energy mix or the wind turbine scenarios, despite the low carbon emissions of electricity generated by nuclear power plants. However, the most important difference between the present situation and either the 2050 scenario or the full production by wind turbines is present on the "resources" plot (Fig. 4d). The category "resources" is based on the additional energy needed for further mining of the resource in the future (Jolliet et al. 2003). In this respect, the 2020 energy mix exhibits a very high impact, since it is mostly based on nuclear and coal power. Therefore, methanation using hyperthermia shows a very high potential of sustainability when based on a decarbonised energy mix or, more importantly, when coupled with a highly decarbonised and low resource-consuming electricity production, such as onshore wind turbine.

3.3 2050 scenario

The results of optimization allow studying the best-case scenario which combines (1) the 2050 energy mix given by the ADEME reference guideline for electricity production, (2) CO_2 captured from the plant exhausts, (3) catalyst lifetime of 1000 h and (4) a total flow rate of 10 m^3/h. With these expected optimised criteria, the outputs of the LCA are more likely to be representative of the system we are aiming toward 2050. The damage categories outputs are shown in Fig. 5. Very interestingly, the methanation by the hyperthermia bloc has almost no impact any more (2%) compared with the CO_2 separation/compression (23–48%) and to the water electrolysis (50–74%) blocs. This major difference is due to the very low power consumption of the methanation unit, while electrolysis and CO_2 capture needs are high as they have to provide high flow rate of reactants. These results are encouraging as they show that under these conditions and compared with 2020's scenario, the environmental impact of the 2050 scenario does not depend anymore on the methanation bloc, which is

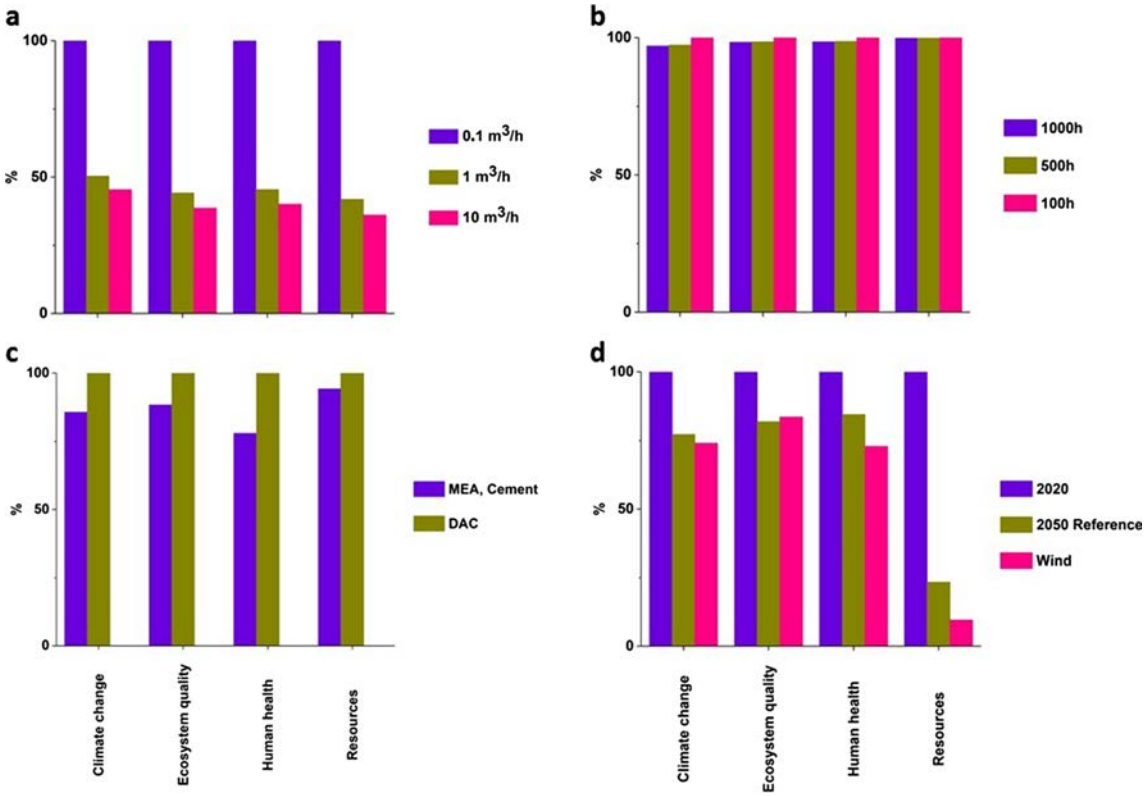

Fig. 4 Sensitivity analysis of CO2 methanation activated by magnetic heating based on the 2020 scenario and varying (**a**) total CO2 + H2 flow rate, (**b**) lifetime of the catalyst, (**c**) CO2 source and (**d**) energy mix for electricity required by the system

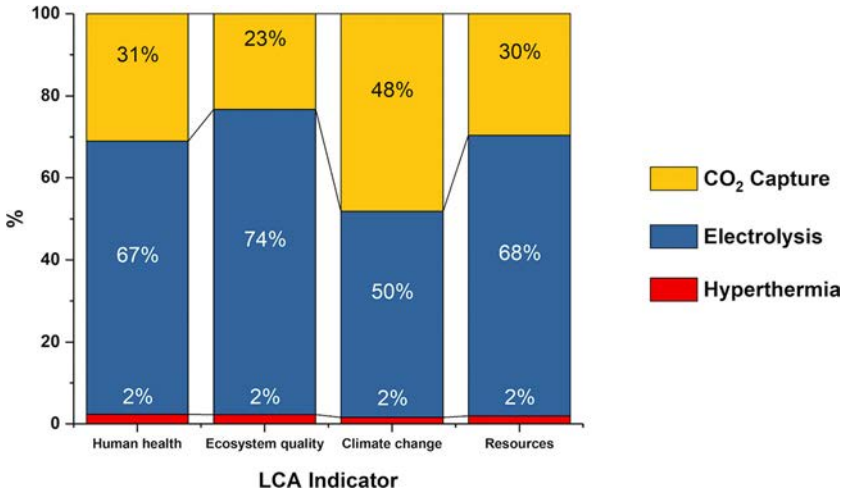

Fig. 5 Damage categories observed by the LCA of the 2050 scenario, using SOEC water electrolysis, CO2 capture from industrial exhausts, 1000 h life time catalyst and a total flow rate of CO2 + H2 of 10 m3/h. The human heath was 8.39e 8 DALY, ecosystem quality 0.0295 PDF.m2/year, the climate change 0.0886 kg CO2 eq and resources 2.94 MJ primary

the core of our team research. From the environmental point of view, the predominant use of renewable energy sources as energy input enables to produce 1 MJ of renewable energy while 0.81 MJ of primary non-renewable energy is needed. As a result, $\eta_{sus} = 123\%$. Therefore, the system is viable as more renewable energy is produced compared with the non-renewable energy consumed. Finally, as shown in Fig. 6, these perspectives of technology improvements enable to reduce by 75% the impacts on the climate change, the ecosystem degradation and the human health, while resources use is decreased by 95%. This result constitutes (1) a roadmap for future development at the laboratory and pilot scale for successful implementation and (2) the confirmation that coupling the technology with a highly decarbonised production of electricity enables to decrease drastically the environmental impact of P2G assisted by magnetic heating.

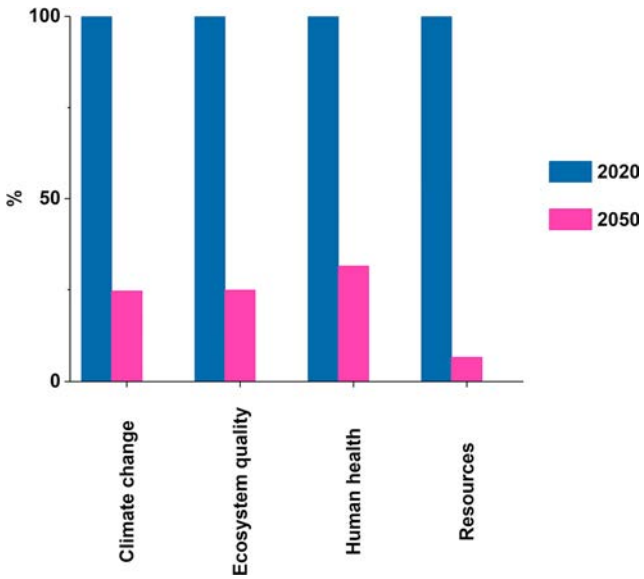

Fig. 6 Comparison of the damage categories observed by the LCA of the 2020 and 2050 scenarios

3.4 Comparison with other technologies

In order to understand the potential of CO_2 methanation using magnetic hyperthermia in sustainable energy conversion, we intended to compare our technology with a similar technology using a traditional heating system and pure CH_4 from fossil natural gas. Pure CH_4 has been implemented with a purity of 96% comparable with the purity of the methane composing the natural gas. Not implementing in our software, natural gas for electricity generation, we exclude its utilisation, while staying coherent with the intended "cradle-to-gate" LCA. Therefore, the methane chosen as an input is only extracted and not treated. The considered thermal process for methanation is the one employed in the project Helmeth (Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion). This technology considers similar high temperature electrolysis coupled with CO_2 capture and methanation unit, using a catalyst which contains > 50 wt% Ni supported on Al_2O_3 and diluted with inert silicon carbide

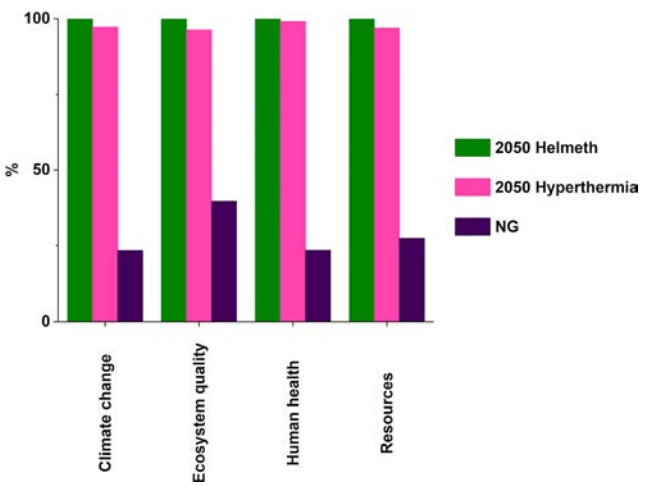

Fig. 7 Damage categories observed by the LCA of the CO2 methanation activated by magnetic heating in the 2050 scenario compared with Helmeth project projected in 2050 and natural gas (NG) extraction

(SiC), reaching 99.3% of H_2 conversion with 100% selectivity for methane (Gruber et al. 2018).

As a result, we can clearly see that both Helmeth and methanation using magnetic hyperthermia will exhibit equivalent features toward 2050 (Fig. 7). This result is due to the equivalent inputs considered for water electrolysis and CO_2 capture, to the system optimisation and to the very low-consuming methanation unit. This constitutes a very encouraging indicator for the scientific community to keep developing alternative technologies for renewable energy storage and sustainable fuel generation.

Nevertheless, methane from natural gas has a lower impact by 45% compared with the two other processes. However, the present LCA does not consider (1) the use of CH_4 through a traditional combustion process for power plant, which will increase its environmental impact, (2) the depletion of the fossil resources that leads the scientific community to look for alternative ways of energy generation.

4 Conclusion and future work

In this work, the "cradle-to-gate" life cycle assessment of CO_2 hydrogenation using magnetic heating has been assessed for the first time. The methanation unit has been integrated together with water electrolysis and CO_2 capture and separation, in order to consider the technology as a whole functional process. Considering the state of the art of the three main units, as well as their perspectives of improvement, the LCA could be implemented at both horizons 2020 and 2050. The influence of the total flow rates of reactants has been evaluated, showing a decrease of environmental impact up to 50% upon increasing this value from 0.1 to 1 m^3/h. The lifetime of the catalyst does not lead to a significant impact on the LCA. The influence of the CO_2 source and the incoming electricity provided by different ways of production has been shown, with respectively − 20% environmental impact when coupled with industrial smoke exhausts and up to − 25% when fed by decarbonised electricity production. As a result, this LCA enables to (1) define a guideline for future process chemistry developments, (2) prove that the technology is environmentally competitive compared with other similar technologies using traditional external heating sources, (3) confirm the strategy of a successful implementation with delocalised and intermittent energy production sources, for which magnetic activation is advantageous, thanks to a dynamic response to intermittent energy availability. In a future work, the full potential of the CO_2 methanation using magnetic heating will be implemented considering the synergic flows of CO_2 production by a polluting industrial plant and its energy demands. Thus, the grid balance through a biopark approach integrating rapid and efficient energy production and CO_2 valorisation using magnetic hyperthermia will be assessed.

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