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Renewable natural gas as climate-neutral energy carrier?

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ABSTRACT

Natural gas is a potent greenhouse gas but remains an attractive energy resource for a good number of reasons. Because complementing the use of natural gas with carbon dioxide capture and storage yields several drawbacks, producing synthetic natural gas instead could be an interesting alternative. Methanation is an established and well-known process, and with atmospheric carbon dioxide as input it could deliver a climate-neutral energy carrier, which we refer to as renewable natural gas. At present, however, methanation is exceedingly costly. In this paper we try to answer two main questions: (I) can innovative methanation such as based on sunlight-powered plasmon catalysis compete with more conventional methanation options using the Sabatier reaction in e.g. adiabatic fixed-bed processes; (II) can these two alternatives ever compete with abundantly available natural gas? Under realistic assumptions for technology learning, we find that innovative methanation technology could compete with conventional methanation systems sometime between 2032 and 2039 in our base case scenario. The required learning investments for the innovative option would amount to about 80 M€, spent on an installed capacity of around 750 MW. We also conclude that the levelized cost of methane remains dominated by the cost of hydrogen until at least the middle of the century. Methanation could in principle compete with natural gas by 2050, but only if a carbon tax is levied of at least 270 €/tCO_2.

1. Introduction

While methane – commonly referred to as natural gas – is a greenhouse gas (GHG) whose global warming potential (GWP) is much higher than that of carbon dioxide, it remains an attractive energy resource for at least three reasons. First, it is only half as carbon-intensive as coal and, when used for power production, it can adequately be employed to compensate for the intermittency of currently the largest new renewable electricity options, solar and wind energy. Second, it is a versatile energy carrier, since it can not only be utilized for electricity generation but also for transport, industry, and the residential and commercial sectors. Third, a large global infrastructure exists for the transportation and distribution of natural gas, through pipelines and by shipping, both in gaseous and liquid form.

Even if fugitive emissions of methane during the stages of production, transmission, and usage, can in principle be avoided – while in reality hardly achievable entirely – its current use invariably contributes to undue climate change as its combustion leads to emissions of carbon dioxide, a GHG that is at the origin of most of the expected (and already observed) increase in the average global atmospheric temperature [1]. The common solution, proposed by industry, academia, and the public policy scene, is to complement the use of natural gas with carbon dioxide capture and storage (CCS). Adding CCS to the use of natural gas, however, yields several substantial drawbacks, of which we here mention four. First, even without considering the possibly imperfect storage of carbon dioxide in deep geological formations, CCS technology never avoids all emissions of carbon dioxide, but is characterized by a capture rate of typically 90% [2]; this is at odds with the target of the Paris Agreement to limit the temperature increase to 1.5 °C and hence to reach net-zero carbon dioxide emissions by the middle of the century [1,3]. Second, for already a couple of decades CCS has been characterized in many publications as ‘a promising way to deal with the challenge of global climate change’, but adverse public opinion has in many cases been the cause of it thus far still hardly having been implemented in practice [42–43]. Third, the large-scale deployment of CCS would require a worldwide infrastructure for the transportation of carbon

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dioxide from where it has been captured to where it is injected for long-term underground storage; apart from the associated costs, this would necessitate the establishment of dedicated industry and regulatory institutions [4,5]. Fourth, CCS is practically only suitable for large point-sources of carbon dioxide, and hardly realizable for small decentralized usage, for instance for capturing carbon dioxide emitted from the combustion of natural gas for heating purposes in buildings. Transporting carbon dioxide from such dilute sources to a storage site poses additional challenges.

An alternative that circumvents these obstacles for the broad diffusion of CCS, by obviating the need for CCS altogether, could be to synthetically produce natural gas with carbon dioxide and hydrogen as inputs. Producing synthetic natural gas – which we here refer to as renewable natural gas if e.g. solar- or wind-based electricity is used to operate the production process – could, on the one hand, avoid the difficulties experienced with CCS. On the other hand, it would constitute an energy carrier that involves net-zero GHG emissions, if the carbon dioxide used in the production process emanates from the ambient air [6]. Hence, renewable natural gas as climate-neutral energy resource could perhaps allow us to continue to profit from the multiple benefits of natural gas, while precluding the intricacies associated with natural gas complemented with CCS. Renewable natural gas could thus potentially constitute an interesting alternative to natural gas usage equipped with CCS.

As pointed out in the next section, methanation is an established and well-known process, and – with atmospheric carbon dioxide as input – it could in principle deliver a climate-neutral energy carrier. At present, however, methanation is exceedingly costly. In this paper we therefore try to answer two main questions: (I) can innovative methanation such as based on sunlight-powered plasmon catalysis [7,8] compete with, and eventually become cheaper than, more conventional methanation options using the Sabatier reaction in e.g. adiabatic fixed-bed processes [9,10]; (II) can these two alternatives eventually compete with abundantly available natural gas? Answers to these questions are important for determining whether natural gas – renewable or produced from geological formations – will have a future in a world economy that sometime this century will need to involve net-zero GHG emissions if mankind is to limit the average global temperature increase to a maximum of 1.5 °C. In Europe, renewable natural gas could possibly be an energy carrier that can help delivering on the Green Deal [11]. Recently, a few studies about the costs of renewable methanation have appeared in the scientific literature [12–16]. Still, our understanding of the techno-economics of methanation can be substantially enhanced by closing in on some of the remaining knowledge gaps – this is what in this paper we intend to do. Section 2 of this article first briefly recapitulates the history of the Sabatier reaction and synthetic natural gas production. In Section 3 we describe the methodology that we use for the calculation of the costs of methanation processes for renewable natural gas production. In Section 4 we report our results, in Section 5 we discuss our findings, and in Section 6 we formulate our main conclusions and proffer a few recommendations.

2. History

The Sabatier reaction, in which carbon dioxide and hydrogen are converted into methane and water (Eq. (1)), was discovered in 1897 by French chemists Paul Sabatier and Jean-Baptiste Senderens [17,18]:

$$CO_2 + 4H_2 \rightleftarrows CH_4 + 2H_2O \quad (1)$$

Similarly, this exothermal Sabatier reaction can be used to hydrogenate carbon monoxide (CO) to produce methane. For more than a century the Sabatier process has been used in industry, mostly to clean gases from traces of CO and CO_2. Obtaining pure hydrogen by ridding CO and CO_2 traces has been one of its main applications, serving the Haber-Bosch process that converts hydrogen and nitrogen into ammonia. Later, during periods when natural gas was expensive, the reaction has been used to convert coal into synthetic natural gas (SNG). The first such commercial plant, the Great Plains synfuel plant in the USA, was realized in 1984. During the 2010s, several coal-to-gas plants have been constructed in China, as a means to help meeting the country's domestic demand for methane. NASA has been using the Sabatier process for decades in space, for their life support system to recover water from exhaled CO_2. Electrolysis of water produces the required hydrogen, as well as oxygen needed for respiration.

For over a century, methanation has been an active field of research. Research and demonstration activities have recently intensified in the context of the energy transition required to render energy supply sustainable – and climate-neutral in particular. The renewed interest in the process of methanation during the last decade can be explained by the need to search for renewable fuels and feedstocks [19,20]. Conversion of CO_2 with hydrogen produced via electrolysis with renewable electricity can provide renewable natural gas, which may substitute fossil natural gas or traditional coal-based SNG. It is thus imaginable that methane continues to play a role in an energy system with net-zero GHG emissions [21,22]. Scientists therefore continue to explore the use of conventional methanation processes, such as based on in-series connected fixed-bed reactors [9,10]. Also more novel and modular approaches are being investigated, like based on plasmon technology that converts CO_2 and H_2 into CH_4 fueled by sunlight in a photo-reactor [7,8]. An advantage of plasmon technology over conventional methanation may be its flexibility in scale: the former can in principle easily be adjusted to the size of the CO_2 sources, also if these are relatively small. One could thus design small-scale plasmon based methanation devices and add any number so as to meet the supplied volume of CO_2. For a comprehensive overview of methanation research conducted during the past century, as well as a list of current investigations and projects, see [10].

3. Methodology

Recent studies point out that it is possible to transition towards net-zero, and after 2050 even to net-negative, CO_2 emissions, with a likely role for renewable hydrogen or other renewable fuels [1,23,24]. Renewable natural gas is a candidate renewable fuel, but fundamental research alone will not be sufficient to give it a role in the forthcoming energy transition. It is of critical importance that the costs of producing renewable natural gas become sufficiently low, so as to be able to compete in regional and global markets for a diverse suite of potential energy carriers. This has been recognized by a number of recent studies on the techno-economics of renewable natural gas [40,41]. For answering the two principal questions of this paper – whether innovative methanation can become cheaper than conventional processes, and whether methanation can ever compete with fossil natural gas – we need to perform a techno-economic analysis that allows for determining the levelized cost of methane (LCOM).

We adopt the same methodology for calculating the LCOM as applied for the determination of the levelized cost of renewable fuel production in [25]. The LCOM is determined by dividing the total annually incurred costs by the amount of methane generated per year. The total annual costs consist of the discounted annualized initial investment costs, the annual operating and maintenance (O&M) costs, and the annual feedstock (CO_2 and H_2) costs (for the corresponding equations see [25]). In our calculations we adopt standard assumptions for common plant features: a lifetime of 25 years, a capacity factor of 50%, and a discount rate of 10%. The reported capital expenditures (CAPEX) for methanation across distinct plants differ significantly and can range from 130 up to more than 1000 €/kW. [9] Within this range we adopt a central CAPEX value, which represents the initial investment cost that is discounted and annualized in our equation to calculate the LCOM. We assume that the CAPEX for conventional reactors is approximately 400 €/kW in 2020 (costs are reported in €(2015), unless otherwise noted). Since innovative reactors possess a much lower technology readiness level (TRL) that conventional systems, it is not trivial to assess the CAPEX values for the

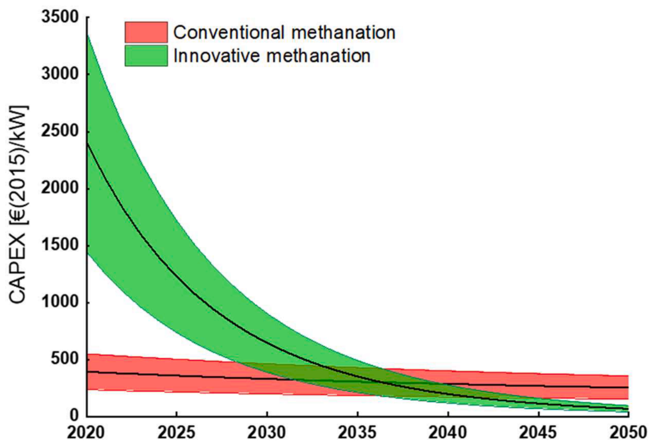

Fig. 1. Our projections for methanation investment cost developments.

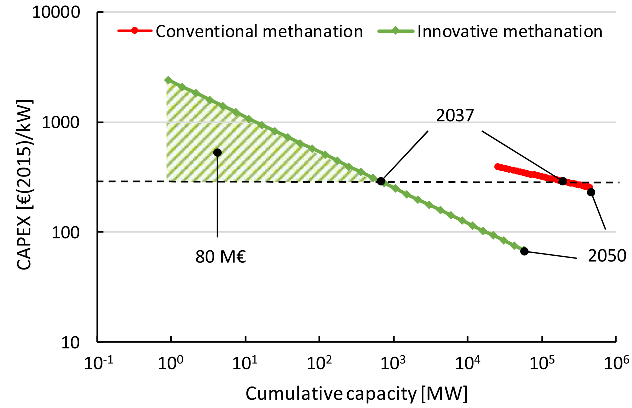

Fig. 2. Learning investments for methanation.

former, but a Figure six times that of conventional ones is readily defendable. We assume that O&M costs amount to 4% of CAPEX, and remain constant during the plant's existence. Investment costs for gas treatment and/or storage facilities are not included in our analysis.

We suppose that both methanation options are subject to learning-by-doing, by which costs reduce as a result of the acquisition of experience as expressed by learning curves. The learning rate (LR) of a learning curve quantifies the relative cost reduction with every doubling of installed capacity of the technology under consideration. We make assumptions regarding the LR for the CAPEX of both methanation processes, and attempt to render these as realistic as possible. We adopt LR = 10% for conventional methanation, hence a relatively low value, given that it is quite a mature technology [26], and because rather large plants are usually constructed that tend to be characterized by typically low LR values [27]. We allow the cumulative installed capacity (CIC) realized to date to grow from about 25 GW in 2020 to 450 GW in 2050 (methanation capacity is expressed in GW (MW/kW) of CH_4 output (lower heating value); electrolyser capacity is expressed in GWe (TWe/MWe/kWe) of electricity input). For innovative methanation, we adopt a higher LR value of 20%, which is around the median value found in the literature for a large range of distinct energy technologies [28], and which has been observed for e.g. PV and microwave ovens [29,30]. This relatively high LR value is justified by the fact that innovative methanation – for instance based on plasmon catalysis – is an immature technology and is thus still in the early phase of development. Its innovativeness – like decades ago for PV and microwave technology – also justifies a high LR for sun-light driven plasmon catalysis based methanation. Furthermore, it is a technique that is modular and is likely to remain relatively small, since it readily allows for upscaling by simply adding large numbers of small individual units. It has been shown that small technologies have the potential to learn faster than large-scale ones [27,31]. We allow the CIC realized to date for this innovative methanation option to grow from 1 MW in 2020 to 58 GW in 2050. With 450 + 58 GW of methanation capacity in 2050 one could generate, assuming a capacity factor of 50%, around 8 EJ worth of methane, which represents about 6% of current natural gas usage.

Feedstock costs include those associated with hydrogen, carbon dioxide, and electricity as inputs. For hydrogen we have calculated the production costs (4.2 €/kgH_2), which we suppose are the same as the costs including delivery to the methanation plant, based on optimistic assumptions. This enables us to determine the minimum conditions under which renewable methanation could become competitive. We suppose that the electrolyser CAPEX reduces from 1000 €/kW_e in 2020 down to 195 €/kW_e in 2050 (which corresponds to an LR of 12% for a CIC of 1.5 TW_e in 2050). For carbon dioxide we assume initially a relatively low value of 20 €/tCO_2 in 2020, since it is likely to be derived from biomass in the early stages of development, while we assume it increases to 100 €/tCO_2 in 2050, when it is produced through direct air capture (DAC) technology. Electricity is, of course, assumed to be of renewable (e.g. solar- or wind-based) origin and costs 0.050 €/kWh in 2020, reducing to 0.025 €/kWh in 2050 (under an LR of 18% for a CIC of 15 TW of wind and solar power capacity combined in 2050).

4. Results

In Fig. 1 we demonstrate what the implications are, until 2050, of our assumptions for the present-day values of the CAPEX of conventional and innovative methanation systems as well as their respective LRs into the future. The plot shows that innovative methanation could compete with conventional methanation sometime between 2032 and 2039 in our central scenario for the development of the CAPEX of conventional systems. For the base case of both methanation processes, a competitive break-even point is reached in 2037. In Fig. 1 we indicate uncertainty ranges for both options, under the assumption that the CAPEX may vary by ±40%. Combining the most conservative case for conventional technology with the most optimistic scenario for innovative technology, we see that competitive break-even is already achieved by 2028. Inversely, combining the most optimistic case for conventional technology with the most conservative scenario for innovative technology, we see that competitive break-even is only achieved in 2045.

We calculate the overall investments in innovative technology necessary to reach competitivity with the conventional option. We also determine the *additional* accumulated investments required to realize the cost reductions that reach the break-even point depicted in Fig. 1, which we refer to as the learning investments [26]. Fig. 2 depicts, on a double logarithmic scale, the CAPEX of methanation against the CIC. The learning investments are indicated for the innovative technology by the hatched green area. The cumulative investments in the innovative technology needed to reach the break-even year of 2037 amount to 290 M€, of which almost 80 M€ are learning investments. At this point nearly 750 MW of innovative methanation capacity has been installed, hence an increase in the CIC of almost three orders of magnitude in less than two decades. The total investments for the conventional technology accumulate until 2037 to 44,000 M€, at which point its CIC reaches a level of over 150 GW. In other words, only a small fraction (<1%) of the total financial investment requirements for methanation have to be dedicated to the innovative technology, if the learning process proceeds as projected.

Fig. 3 shows our projections for the LCOM in €(2015)/kgCH_4 (left plot for conventional methanation, right plot for innovative methanation). Our assumptions for the current CAPEX of electrolysers and the industry's ability to reduce their costs based on the accumulation of experience (i.e. by learning-by-doing) imply a hydrogen production cost of around 4.2 €/kgH_2 today and less than 1.4 €/kgH_2 in 2050, as can be seen in Fig. 3 (note though that the unit on the y-axis is €(2015)/kgCH_4

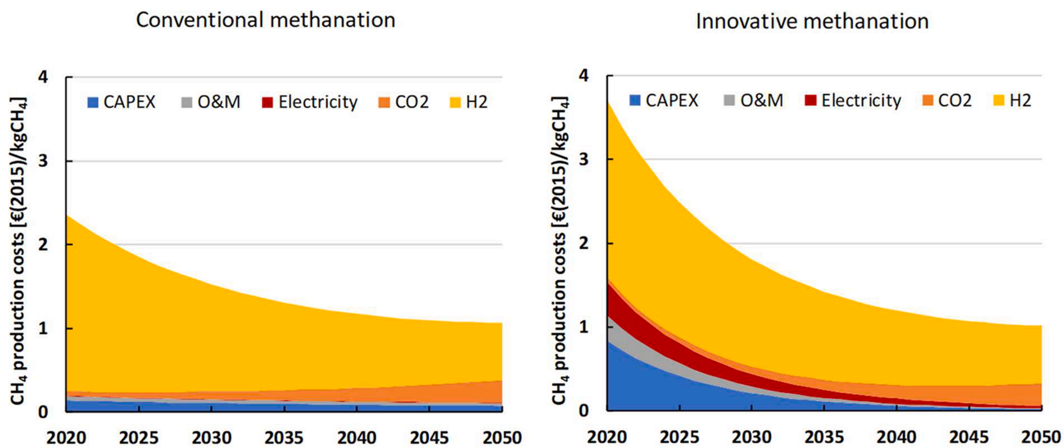

Fig. 3. Projections for the levelized cost of methane.

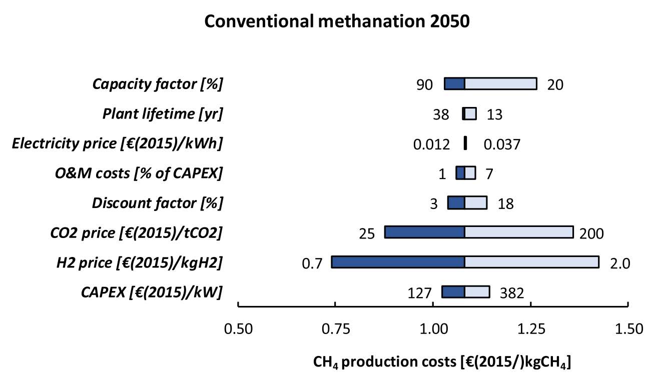

Fig. 4. Sensitivity test for the levelized cost of methane (conventional technology in 2050).

and not €(2015)/kgH$_2$). Hydrogen costs of as low as 4 €/kgH$_2$ can at present only be reached in the most optimal conditions, both in terms of electrolyser CAPEX requirements and the price of renewable electricity. It has been pointed out that renewable hydrogen production costs today may amount to more than 10 €/kgH$_2$ in several European countries, and can probably only reduce to <2 €/kgH$_2$ by 2050 in some of these countries [32]. In the present analysis we have purposefully adopted optimistic values for the production costs of hydrogen, as it enables us to formulate the minimal conditions under which renewable methanation could become competitive. The other cost components listed in Fig. 3 are the CAPEX and O&M costs of the methanation system, as well as the renewable electricity needed to run it and the CO_2 required as feedstock. The electricity costs are hardly visible in the left graph, because the contribution of electricity to the overall costs of conventional methane production is low. In the right graph of Fig. 3, however, the electricity component is non-negligible. We assume that, for innovative light-driven plasmon catalysis processes, light is generated by renewable electricity and that between 2020 and 2050, thanks to innovation and optimization, the electricity use can be reduced by more than a factor of 6 (a conservative estimate, according to [7]). As can be seen from Fig. 3, we expect that the LCOM remains dominated by the cost of hydrogen until at least the middle of the century (in agreement with conclusions by others [40,41]), followed by the cost of CO_2 (because of our increasing cost assumptions for this input gas).

In Fig. 4 we show the sensitivity test results for our LCOM calculations (conventional methanation in 2050; see Fig. A1 in the Appendix for a similar plot for 2020; similar figures apply to innovative methanation). For all our main input assumptions we performed single parameter variations for the LCOM in 2050 for the central scenario of the

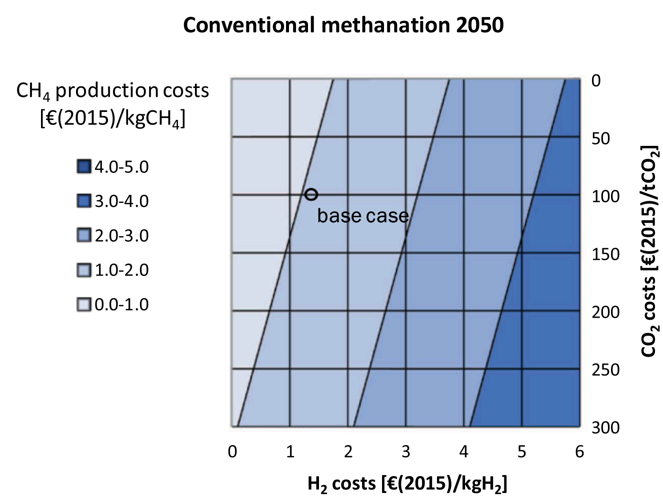

Fig. 5. Dependence of the levelized cost of methane on the costs of H_2 and CO_2 (conventional technology in 2050).

conventional technology. For each of the 8 entries (with units in square brackets) we adopted the changes listed as numbers in the graph, while the sizes of each resulting bar indicates the impact of these changes on the LCOM (in €(2015)/kgCH$_4$). As evidenced in this Figure, the 2050 input prices of H_2 (changed up to 2.1 €/kgH$_2$ and down to 0.7 €/kgH$_2$) and CO_2 (modified up to 200 €/tCO$_2$ and down to 25 €/tCO$_2$) are the most significant determinants for the value of the LCOM, directly

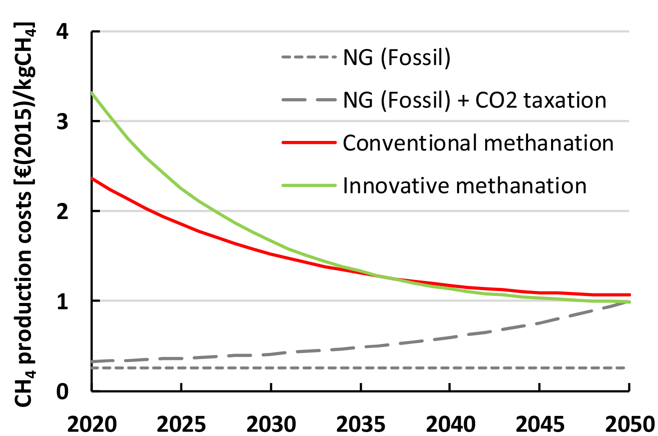

Fig. 6. Competitivity of methanation with natural gas plus CO_2 taxation.

followed by the capacity factor (that we varied up to 90% and down to 20%).

Fig. 5 depicts an additional sensitivity test for our LCOM analysis, in the form of a contour plot that shows how the LCOM is a function of the costs of H_2 and CO_2 (for conventional methanation in 2050; see Fig. A2 in the Appendix for a similar plot for 2020; similar figures apply to innovative methanation). We display the variation of the costs of methane with the costs of these two main feedstocks, since we demonstrated in Fig. 4 that they are the two most influential parameters determining the LCOM. Fig. 5 represents the LCOM in 2050 for the base case of the conventional technology; by showing its relationship with the costs of H_2 and CO_2 simultaneously the most relevant part of the LCOM solution space becomes apparent. The graph shows, for instance, that if the cost of H_2 does not fall below a threshold of 3 €/kgH_2 and the cost of retrieving CO_2 through DAC remains higher than 150 €/tCO_2, then the LCOM cannot become cheaper than 2 €/kgCH_4.

Among our most critical findings – but arguably also involving the largest intricacies and uncertainties – are reported in Fig. 6. This Figure shows the LCOM for both the conventional and the innovative methanation process until 2050, along with the price of natural gas, both in- and excluding a tax on CO_2 emissions. The natural gas price (0.26 €/kgCH_4) is assumed to be constant for our present purposes and based on the average price of five European and North American indices during the period 2010–2019 [33]. In reality, this price is of course subject to volatilities over time, and will in the very long run probably increase as a result of the depletion of easily accessible resources. We assume that the carbon tax levied on the use of natural gas starts off at 25 €/tCO_2 in 2020 (roughly half the current level in the EU's Emissions Trading System, ETS) and exponentially increases to 280 €/tCO_2 in 2050 (an annual increase of approximately 8%/yr). As can be seen, under these conditions methanation could in principle compete with natural gas by 2050. As expected, renewable methanation through either conventional or innovative concepts is unlikely to ever become competitive with natural gas without a carbon tax. Only with substantial CO_2 pricing, at a level of at least 280 €/tCO_2 by 2050 under our present assumptions regarding notably the cost of hydrogen, can the LCOM reach competitive break-even in 2050. In the case of less optimistic costs for the production of renewable hydrogen than the ones adopted in our present analysis, the carbon tax would still need to be higher. In Fig. A3 in the Appendix we present our findings from the calculations described above in a complementary manner, by showing what the minimum CO_2 tax ought to be as function of the cost of hydrogen in order to reach competitive breakeven between conventional methanation and natural gas. As can be seen, in essentially any imaginable circumstance one would require a carbon tax of hundreds of €/tCO_2 in 2050.

5. Discussion

There is no doubt that the process of renewable methanation today receives increased interest, not only from natural scientists, but also from the business community. Indeed, several pilot and demonstration plants have been constructed during the last decade, which is testimony of this revitalized attention. The largest renewable methanation plant built thus far is the Audi e-gas plant in Werlte [34]. In the process employed in this plant, electrolytic hydrogen is used to convert CO_2 from the adjacent biogas facility into renewable natural gas, which is subsequently inserted in the natural gas grid. Electricity from wind energy is used as input, which ascertains the hydrogen being produced in a renewable fashion and that allows the facility to run for approximately 4000 h/yr. The installed electrolyser capacity amounts to a little over 6 MW_e. Our present article is thus not merely dedicated to an esoteric subject fit for purely academic purposes only; it proffers a study of the long-term prospects for a renewable fuel technology with real-life significance and imaginable potential. The scientific literature, however, thus far misses a techno-economic analysis of mid-century perspectives for renewable methanation, notably because no study has yet adopted a learning curve methodology to compare different methanation options and assess the learning investments required for fundamental innovation in this domain. This is the gap that this paper fills.

We have provided several levels of comparison between renewable natural gas, on the one hand, and fossil natural gas equipped with CCS, on the other hand. Also an important cost dimension exists, however, which constitutes another important driver for their mutual competitivity. The use of natural gas complemented with CCS is likely to become competitive with the use of natural gas without CCS under much lower carbon taxation than that needed to bring renewable natural gas to competitivity, typically at a level of around or below 100 €/tCO_2 [4]. Costs constitute clearly a comparative advantage of natural gas with CCS above renewable natural gas obtained through either conventional or innovative methanation.

The results reported in this paper are much in line with the conclusions by [19], who also find – but through a different methodology and analysis – that for research and realization of methanation, and the renewable production of other hydrocarbons for that matter, one of the first priorities should be a reduction in the costs of hydrogen production through electrolysis. This is one of our main recommendations, both for the scientific and policy making communities: the question whether methanation could ultimately deliver an attractive energy carrier is probably a premature one, as we should first ascertain that the costs of hydrogen production via electrolysis come down substantially, in some cases and/or countries by close to an order of magnitude. This should be done by both reducing the investments costs of electrolysers and by continuing to drive down the costs of renewable electricity generation.

One could wonder why in the future renewable hydrogen would need to be converted into renewable methane if hydrogen itself can already replace most of present methane-based applications that rely on conventional (fossil) natural gas. The fact that in order to produce renewable methane one needs, in addition to renewable hydrogen, an extra – possibly costly – feedstock, CO_2, could well make the renewable methane route less attractive than the renewable hydrogen route, in terms of both costs and energy needs, and perhaps also with regards to supplementary infrastructure requirements. These would be arguments against the development of renewable natural gas. If the renewable hydrogen economy will not be developed, for instance for currently unknown reasons, then perhaps the arguments against the development of renewable natural gas reduce in relevance. Renewable carbon-based products other than methane (such as derived from CO) could be more desirable for the production of several specific liquid fuels (think of kerosene), plastics, methanol, and some fine chemicals.

Pathways for producing renewable natural gas should be entirely free of fugitive emissions of CH_4, as otherwise these costly processes would replace a potent GHG (CO_2) with one (CH_4) whose GWP is some 30 times larger. Another case of comparison is that between methane and hydrogen, as the two may become competing energy carriers. Also their relative GHG strengths, if any, should therefore be considered. While methane is a GHG with a high GWP, hydrogen in itself is not a GHG. Yet if for the latter also indirect effects are taken into account, then it also ought to be considered a GHG [35,36]. Still then, methane has a much higher (100-year) GWP (close to 30) in comparison to hydrogen (around 5). If either of these two becomes an important energy carrier in the global energy system, then these GWP effects need to be taken into account, since it is unlikely that an energy system relying on either of these gases will be entirely free of leakage [37].

6. Conclusion

Methanation is an established and well-known process, and with atmospheric carbon dioxide and hydrogen produced through electrolysis of water with renewable electricity as feedstocks it could deliver a climate-neutral energy carrier. Natural gas is an attractive energy carrier, as a vast transportation and distribution infrastructure exists, it possesses a high energy density, and many demand-side technologies

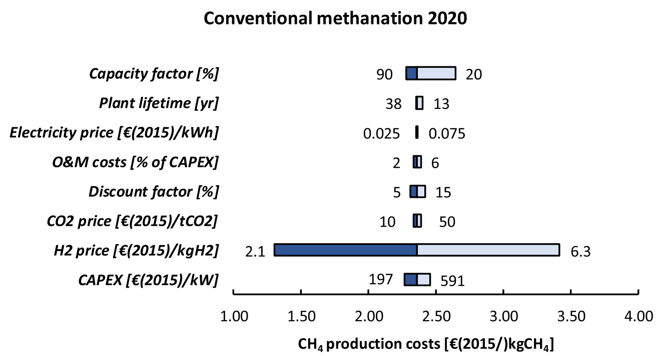

Fig. A1. Sensitivity test for the levelized cost of methane (conventional technology in 2020).

have been developed that accommodate its use. Yet its combustion emits carbon dioxide, which is today the most important greenhouse gas. Complementing the use of natural gas with CCS yields significant drawbacks other than costs alone, as we briefly summarized in this paper [38]. Producing renewable natural gas would allow continuing to profit from its benefits, while precluding the drawbacks that the large-scale deployment of CCS in association with fossil natural gas would involve. In this paper we have researched the techno-economics of renewable natural gas, to complement and expand existing literature on the production costs of clean fuels such as can be used in the transport sector [39]. Arguing for learning rates of 20% and 10%, for innovative and conventional methanation respectively, we find that the former could compete with the latter by around 2037, with an uncertainty range between 2032 and 2039, or 2028 and 2045, depending on the level of optimism regarding the investment cost reductions achievable over time. The required learning investments for the innovative option would amount to about 80 M€, spent on an installed capacity of around 750 MW. This amounts to less than 1% of the overall accumulated investment requirements for methanation production facilities. We demonstrate that the cost of hydrogen production is the dominant contribution to the overall LCOM value, at least for the foreseeable future, that is, during the next three decades. Although challenging, it is imaginable that methanation becomes competitive with natural gas in 2050, but only if a carbon tax is levied of at least 270 €/tCO_2 under optimistic assumptions for the cost of renewable hydrogen production by then. This is compatible with the findings reported in several publications [40,41]. We provide a detailed discussion of our findings and formulate recommendations for both further research in this domain and for appropriate policy design that could stimulate the development of renewable natural gas. Based on our insights thus far, we conclude that innovative methanation such as based on plasmon technology could by 2050 in principle compete with more conventional methanation like using an adiabatic fixed-bed process, and that it is even imaginable that these two alternatives ultimately will be able to compete with abundantly available fossil natural gas, albeit at carbon taxation levels of at least hundreds of €/tCO_2.

CRediT authorship contribution statement

Bob van der Zwaan: Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Remko Detz:** Conceptualization, Data curation, Visualization, Formal analysis, Writing - review & editing. **Nicole Meulendijks:** Validation, Writing - review & editing. **Pascal Buskens:** Validation, Writing - review & editing.

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.

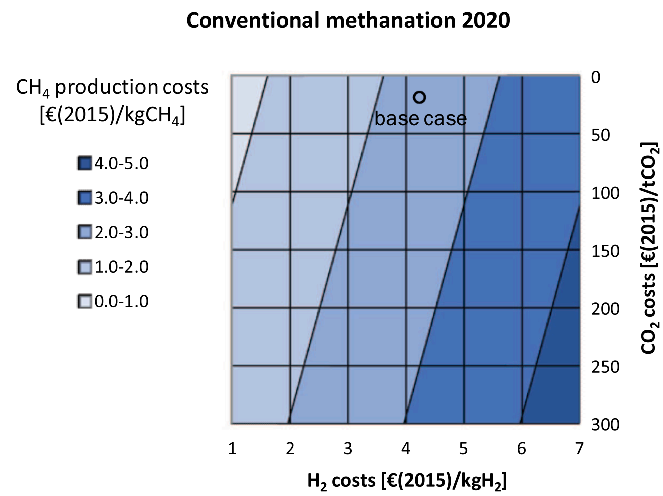

Fig. A2. Dependence of the levelized cost of methane on the costs of H_2 and CO_2 (conventional technology in 2020).

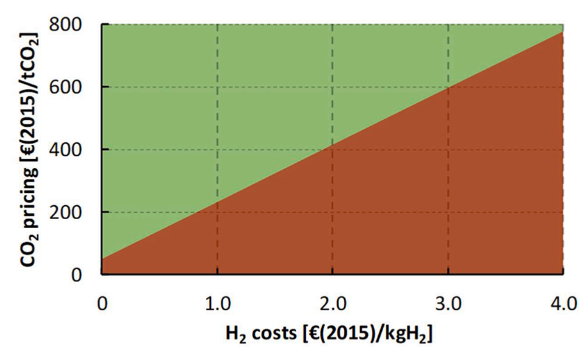

Fig. A3. Competitivity between natural gas and conventional methanation in 2050.

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Appendix

In Fig. A1 we show the sensitivity test results for our LCOM calculations (conventional methanation in 2020).

Fig. A2 depicts an additional sensitivity test for our LCOM analysis, in the form of a contour plot that shows how the LCOM is a function of the costs of H_2 and CO_2 (for conventional methanation in 2020).

Fig. A3 shows what the minimum CO_2 taxation level should be at any particular cost of hydrogen production to reach a breakeven point between natural gas and conventional methanation in 2050. As can be seen, if hydrogen costs still more than 2 €(2015)/kgH_2 by then, CO_2 pricing on natural gas should be more than 400 €(2015)/tCO_2 in order to obtain a competitive methanation process. Fig. A3 also points out that even if hydrogen is freely available, the CO_2 tax should still amount to around 50 €(2015)/tCO_2. Another way of formulating what can be derived from Fig. A3 is that the R&D community should endeavor to develop technologies able of delivering renewable hydrogen at the lowest possible price, perhaps also by exploring techniques other than electrolysis. Yet, we show that even in the most optimistic scenario CO_2 taxation of at least 100 €/tCO_2 will nearly always still be necessary.

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