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CO_2-based methane: an overlooked solution for the energy transition

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Abstract

Background Fossil fuels can be replaced with electricity and hydrogen. However, the implementation and use of these low-carbon energy carriers require a sociotechnical transition. This transition might not be completed in time.

Main text CO_2-based methane is a substitute for natural gas that is less carbon-intensive. This methane is synthesized by capturing CO_2 from air and by performing water electrolysis to produce hydrogen. CO_2-based methane is compatible with our current fossil-based society. An analysis of the substitution of natural gas with different energy carriers will be performed, and the results will be compared. The effects of CO_2-based methane, hydrogen, and electricity will be evaluated for energy storage, high-temperature level heat production, and residential heating. The multi-level perspective will be applied to assess these energy carriers in the context of our society.

Conclusions CO_2-based methane is the least energy efficient energy carrier among those analyzed. Nevertheless, this type of methane supports the acceleration of the energy transition.

Highlights

- CO_2-based methane is a valuable, renewable, and carbon-neutral energy carrier that supports a timely energy transition.
- The implementation of hydrogen and electricity requires more modifications to our current sociotechnical society than the implementation of CO_2-based methane.
- The urgency of reducing CO_2 emissions is not being considered adequately in the current societal discussion, and a multi-level perspective analysis should provide valuable results that account for the temporal aspect.

Keywords Energy transition, Renewable energies, Sociotechnical transition, CO_2-based methane, Hydrogen, Multi-level perspective

Background

Fossil fuels are widely used in our society in the production of energy or in the form of raw materials. In 2019, the combustion of fossil fuels contributed 89% of global CO_2 emissions [1]. CO_2 emissions are the main force driving global warming. An increase in the global temperature has many negative consequences. The goal is to limit this increase to 1.5 °C. In the Sixth Assessment Report [2], the IPCC predicted that a 1.5 °C increase will be reached in the near future (2021–2040).

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The energy transition is envisioned to reduce CO_2 emissions by replacing fossil fuels with renewable and carbon-neutral energy sources and energy carriers. However, efforts to make the above-mentioned vision come true are limited, and their progress is slow. CO_2 concentration in the atmosphere increased from 287 ppm in 1850 to 412 ppm in 2022 [3]. Reports on the topic have been published for more than 30 years [4]. The Paris Agreement, an international legally binding treaty for the mitigation of emissions, was agreed upon in 2015 [5]. This slow energy transition can be compared to previous transitions, first from biomass to coal and then from coal to oil and gas; these transitions took decades or even centuries to complete [6, 7]. For example, the transition from pre-industrial biomass to coal took 96–160 years, and the next energy transition from coal to oil/gas/electricity took 47–69 years [6].

The energy transition is a sociotechnical transition that aims for the creation of a sustainable energy system [8]. Sustainable transitions are goal-oriented. This transition involves the alignment and coordination of many dimensions of our societal landscape to achieve the same goal [9]. This goal necessitates the modification of existing systems [10], which have complex mechanisms that hinder the transition [11]. These specific features and the heavy modifications required for our societal landscape will delay the transition to a carbon-neutral society by 2050. The slowness of the energy transition is inhibiting our chances of limiting global warming. This restriction is emphasized in the IPCC working group III report [12], which urges an immediate and major energy transition away from fossil fuels; otherwise, the global temperature increase will not be adequately limited.

Natural gas is a versatile fuel that can be used in many of the functions of fossil fuels. In 2018, natural gas provided 22.8% of the total energy supply [13]. Natural gas is considered a transition fuel that can smooth the energy transition [14]. CO_2 emissions are halved when natural gas is used for electricity generation instead of oil or coal [15]. Yet, it is a finite and CO_2-emitting fossil fuel. For many applications, natural gas can be replaced by renewable and carbon-neutral energy carriers such as hydrogen and electricity.

Replacing natural gas with hydrogen or electricity in specific applications is a challenging task. The development of new infrastructure is needed [16, 17]. New technology must also be developed, or existing technology should be further developed, based on hydrogen or electricity [18, 19]. In addition, the replacement of natural gas needs to be socially accepted [20]. However, the substitution might not be made as fast as needed. In line with previous energy transitions, our "urgent" energy transition is likely to take at least 50 years, suggesting that the global temperature increase will extend beyond the 1.5 °C target.

CO_2-based methane is an energy carrier that is less disruptive than electricity or hydrogen as a substitute for natural gas. This energy carrier has the same composition as the main component of natural gas: methane (CH_4). CO_2-based methane can be synthesized from CO_2 captured from air and H_2 from water electrolysis, resulting in a renewable and carbon-neutral energy carrier. Due to the high energy demand for the capture of CO_2 and for the synthesis of H_2, the synthesis of CO_2-based methane has a higher energy demand than that of either H_2 or electricity alone. However, it might be possible to provide a relatively straightforward substitution of natural gas. For instance, seasonal energy storage via CO_2-based methane involves natural gas infrastructure, while hydrogen and electricity require the development of new infrastructure and/or the performance of several modifications to the current infrastructure. There is thus a trade-off between the energy demand for the production of the energy carrier and for the acceleration of the transition using existing infrastructure.

These trade-offs can be understood by applying the multi-level perspective (MLP) theory proposed by Geels [8]. The MLP explains the transition from a carbon-producing societal landscape to a carbon-neutral landscape by analyzing the interactions within sociotechnical configurations at three levels: macro, meso, and micro. The micro-level represents niches. These niches are safe spaces where technological innovation emerges. These innovations struggle to be further developed and implemented in the functions of the sociotechnical regime. Regimes are "relatively stable configurations of institutions, techniques and artifacts, as well as rules, practices and networks" [21]. Within one regime, seven dimensions can be identified: technology, user practices and application domains (markets), the symbolic meaning of technology, infrastructure, industry structure, policy, and techno-scientific knowledge. These regimes and their dimensions constitute the meso-level [22]. The regimes and their dimensions are influenced by the sociotechnical landscape (our society), where events such as globalization, global warming, economic crisis, war, and cultural changes destabilize the system facilitating the breakthrough of innovations.

Attention will be given to the mechanisms by which the dimensions are modified and to the characteristics surrounding the use rather than the production of these energy carriers. Therefore, our analysis is focused on the downstream application of CO_2-based methane, hydrogen, or electricity. This research will provide an overview of the benefits each energy carrier can offer beyond energy efficiency. These benefits influence the pace of the transition because we are a society that cares about more than just efficiency.

The aim of this study is to investigate the contributions of CO_2-based methane using a multi-level perspective for three functions of natural gas: seasonal energy storage, industrial high temperature level heat (HTLH), and residential heating. Regarding seasonal energy storage, the sub-function of the distribution will be considered. These functions are considered wicked functions. We used the term wicked to refer to a complex challenge resulting from the interactions between stakeholders and participants involved [23].

There is a need to evaluate CO_2-based methane as a renewable and carbon-neutral energy carrier from a multi-level perspective, which has not been done in previous research. We will compare the contribution of CO_2-based methane to the energy transition with the contributions of hydrogen and electricity. For each of the functions in which natural gas will be replaced, the dimensions from the sociotechnical regime will be modified to different degrees based on the application of CO_2-based methane, hydrogen, or electricity. We discuss the wicked functions of three energy carriers and the key contributions of CO_2-based methane regarding the economic, environmental, and societal impacts.

CO_2-based methane as a niche in the multi-level perspective

Synthesis of CO_2-based methane

The production of methane from CO_2 is a well-known reaction called the Sabatier process that relies upon three simultaneous reactions: CO_2 methanation, a reverse water-gas shift reaction, and CO hydrogenation. The Sabatier process has been mainly used to remove CO_2 and CO in H_2-rich flows in processes such as ammonia synthesis to prevent catalytic poisoning. The reaction (Eq. 1) represents the overall hydrogenation of CO_2 to methane under standard conditions. This reaction is exothermic, and for each mol of methane, four moles of H_2 are required.

$$\mathrm{CO_2} + 4\mathrm{H_2} \longrightarrow \mathrm{CH_4} + 2\mathrm{H_2O}\left(\Delta \mathrm{H}^{25\,^\circ\mathrm{C}} = -165\frac{\mathrm{kJ}}{\mathrm{mol}}\right). \tag{1}$$

Equation (2) represents the reverse water-gas shift reaction. This reaction is simultaneous to Eq. 1. This reaction is endothermic and is favored above 500 °C.

$$\mathrm{CO_2} + \mathrm{H_2} \longrightarrow \mathrm{CO} + \mathrm{H_2O}\left(\Delta H^{25\,^\circ\mathrm{C}} = 41\frac{\mathrm{kJ}}{\mathrm{mol}}\right). \tag{2}$$

If CO is produced via Eq. (2), then the hydrogenation of CO is another possible reaction. This reaction is the most exothermic.

$$\mathrm{CO} + 3\mathrm{H_2} \longrightarrow \mathrm{CH_4} + \mathrm{H_2O}\left(\Delta H^{25\,^\circ\mathrm{C}} = -206\frac{\mathrm{kJ}}{\mathrm{mol}}\right). \tag{3}$$

The reactions that produce CH_4 from H_2 and CO_2 are exothermic. The Sabatier process is a thermochemical process that normally occurs at temperatures in the range of 250–450 $^\circ C$ [24]. Based on thermodynamic laws, low temperatures promote these reactions, but they are kinetically limited at low temperatures. The heat from the reactions increases the temperature, thereby reducing the selectivity of CO_2 as the source of carbon in the reaction and favoring the reverse water–gas shift reaction, which produces CO and H_2O. Catalysts have been implemented as solution. A commercially used catalyst is nickel on an alumina support that is operated at temperatures below 500 °C [25] to prevent reverse water–gas shift reactions. In addition to low temperatures, high pressure favor the production of CH_4. The equilibrium compositions in the reactions are affected by the changes in the numbers of molecules. To promote the overall hydrogenation of CO_2 to CH_4, a pressure range of 10–30 atm is applied. High operation pressures and low temperatures are not economical because a catalyst with sufficient activity is needed [26].

CO_2-based methane as an energy carrier: intensity

The synthesis of CO_2-based methane via a thermochemical approach requires CO_2 and H_2. Considering that CO_2-based methane is produced in a renewable and carbon-neutral manner, the source of CO_2 is air, and the source of hydrogen is water. Flue gas is beyond the scope since we believe air to be independent of the source of CO_2. The energy required for the synthesis of hydrogen and for the capture of CO_2 from air is electricity from renewable sources. Amine-based CO_2 capture is used by two commercial companies for Direct Air Capture (DAC) [27]. Amines react selectively to atmospheric CO_2 binding it to later release it when the amine is heated to $100 - 150\,^\circ\mathrm{C}$ [28]. For hydrogen, alkaline water electrolyzers are the most mature technology [29]. Water is decomposed in a cell by applying a current through it by using conductive substances called electrolytes. In alkaline water electrolysis, the electrolyte is under aqueous alkaline conditions and is placed in two different compartments (one anode and one cathode) [30].

Table 1 Energy demands for the synthesis of CO_2-based methane and hydrogen

	CO_2-based methane		**Hydrogen**	
	MTW	**BAT**	**MTW**	**BAT**
Hydrogen energy demand $\frac{kJ}{mol_{H_2}}$	286 [a] (*4=1144)	379 [c] (*4=1516)	286 [a]	379 [c]
CO_2 capture energy demand $\frac{kJ}{mol_{CO_2}}$	20 [b]	364 [d]	N.A.	N.A.
Total energy demand $\frac{kJ}{mol_{CH_4}}$	1164	1880	286	379
Combustion energy $\frac{kJ}{mol_{CH_4}}$	890 (HHV)	801 (LHV)	286 (HHV)	240 (LHV)
Intensity $\frac{MW_{in}}{MW_{out}}$	1.3	2.4	1	1.6

N.A. not applicable

[a][32] [b][31] [c][35] [d][33]

The energy demand for the synthesis of CO_2-based methane is based on the type of technology used. We compare the energy demand for the minimum thermodynamic work (MTW) and the best available technology (BAT), which is the most mature technology available for capturing CO_2 from air and for performing water electrolysis. A comparison of the theoretical result to the practical results can provide a clear understanding of the process with the best opportunity to improve. MTW and BAT will be analyzed by the energy demand in kilo Joule per mol of either CO_2 or H_2 (in $\frac{kJ}{mol}$), and the efficiency of the conversion from the input energy to the output energy will be analyzed in Mega Watts. Energy is consumed to produce CO_2 and H_2 which can be emitted once CO_2-based methane is combusted ($\frac{MW_{out}}{MW_{in}}$).

The minimum amount of thermodynamic work required to separate CO_2 from air is $20\frac{kJ}{mol_{CO_2}}$ [31]. For hydrogen production, a minimum thermodynamic work of $285.8\frac{kJ}{mol_{H_2}}$ is demanded [32]. The actual processes require an energy input higher than the minimum thermodynamic work energy. For the already established DAC companies, two different materials are used: high-temperature aqueous solution and low-temperature solid sorbent [33]. The differences between these materials are the materials used for binding CO_2 and the range of temperatures applied to release CO_2 from the binding material. The company ClimeWorks is a pioneer in low-temperature DAC. Their CO_2 capture process is operated with a patented amine-based adsorbent that is regenerated at $95\,^{\circ}C$ [34]. The energy demand is $364\frac{kJ}{mol_{CO_2}}$, which is considered the benchmark for other DAC technologies [33]. For water electrolysis, the practical energy demand is $379\frac{kJ}{mol_{H_2}}$, which is based on alkaline electrolysis [35].

Table 1 shows the different energy demands for both the MTW and BAT. By comparing the energy demand in the synthesis of CO_2-based methane, it can be seen that the greater difference is in the capture of CO_2. For CO_2 capture, the BAT requires 18 times more energy than the MTW does. For hydrogen synthesis, BAT requires 1.3 times more energy than MTW. These differences in energy demand influence the total energy demand for the synthesis of CO_2-based methane, which increases the gap between the input energy and the output energy. The ratio between the input energy and the output energy is the intensity. For BAT, the low heating value for methane and hydrogen is considered the output energy, while for MTW, the output energy is the high heating value. The intensity for BAT is 2.4, which requires more than twice the amount of energy that can be emitted when it is combusted. For MTW, the intensity is 1.3 suggesting that almost all the input energy can be emitted. For hydrogen serving as a fuel, the BAT intensity is 1.6, and for the MTW, it is 1.

Analysis of three natural gas functions substituted by CO_2-based methane, hydrogen, or electricity

Seasonal energy storage function

Current state and expected changes in seasonal energy storage with emphasis on the Netherlands

The global energy demand may reach $640EJ$ in 2050 and it is expected that 50% of the end use of energy will be in the form of electricity [36]. Up to 90% of the electricity will be generated by renewable energy. Wind and solar power, as major sources of renewable electricity, will provide 70% of the electricity. These renewable sources are intermittent, suggesting that their supply is not constant.

This intermittency poses new challenges to our current energy storage systems as the demand for energy

Table 2 Characteristics of power storage for mechanical and chemical principles

Energy storage medium	Energy density $\frac{kWh}{m^3}$	Round trip eff. %	Cost distribution $\frac{\$}{Km*kW}$
Natural gas	10^a	$45 - 57^b$	$0.04–0.16^{c,g}$
CO_2-based methane	″	$16 - 24^d$	″
Hydrogen	3.5^e	$22 - 29^f$	0.1^g to 2^c
PHS	$0.5 - 1.3^h$	$80^{i,j}$	$0.5 - 3.6^{c,g}$

[a][46] [b][47] [c][45] [d][48] [e][49] [f][50] [g][51] [h][52] [53] [j][54]

increases. This increased demand is especially challenging in countries where there is low radiation and low temperatures throughout the year, making seasonal energy storage a high priority [37]. Estimates of how much energy storage a country may need when relying completely on electricity from renewable energy vary [38, 39], but certainly, the demand for seasonal storage should increase when the renewable electricity supply increases.

Energy storage can be based on a variety of distinct principles such as mechanical, electrical, chemical, electrochemical, and thermal energies [40]. The overall goal is to transform one type of energy to another, store it, and then, when needed deliver it back in an efficient, stable, and reliable manner. In the analysis of seasonal energy storage, we compare the conversion of renewable electricity to CO_2-based methane, hydrogen, pumped hydro power storage (PHS), and natural gas. We do not consider electricity directly as a medium for seasonal storage since the current capacities of technologies are on the order of hours [41].

Mechanical energy storage via pumped hydropower storage (PHS) comprised the majority (96%) of the total energy storage capacity 633 TJ in 2017. To a lesser extent, thermal storage contributed 1.9%, electrochemical storage via batteries contributed 1.1%, and a sub-category of mechanical energy storage contributed 0.9% to the total energy storage capacity. This sub-category consists of electromechanical storage via flywheels and compressed air energy storage [42]. Each of these technologies has many performance parameters but to compare them the energy density, round trip efficiency, and cost of distribution will be considered.

Table 2 compares these parameters for natural gas, CO_2-based methane, hydrogen, and PHS. Compared with other energy carriers, natural gas and CO_2-based methane have the highest energy densities under standard conditions. These high densities can be increased up to $1200\frac{kWh}{m^3}$ at 200 bar [43]. The round trip energy efficiency is the ratio between the amount of energy withdrawn and the amount of energy input into to the system [44]. Therefore, for natural gas the energy efficiency is determined by the transformation from chemical energy to electricity. The value in the table is sourced from the use of a natural gas combined cycle power plant. CO_2-based methane round trip efficiency is almost half of the natural gas round trip efficiency. In addition to having the highest energy density, natural gas has the lowest distribution costs [45], similar to CO_2-based methane. Hydrogen has a low energy density under standard conditions, but if compressed at 200 bar, it can reach $360\frac{kWh}{m^3}$ [43]. The round trip efficiency is based on the synthesis of hydrogen via water electrolysis and the production of electricity in a fuel cell. Hydrogen has a higher round trip efficiency than CO_2-based methane but the distribution costs are also higher. The PHS energy density is the lowest among the compared energy storage systems. Nevertheless, the round trip efficiency is 3 times greater than that of CO_2-based methane and 2 times greater than that of hydrogen. Electricity transportation is more expensive than methane or hydrogen transportation.

The principle of power storage via PHS is based on the increase in the gravitational potential energy contained in the water. When there is a need for power, water is released downhill releasing the gravitational potential energy stored, and when there is excess power, water is pumped uphill [55]. Although PHS is by far the most developed electricity storage technology, its utilization is limited. These limitations are related to low energy density, water availability, geographical constraints, initial high investment, and long processes for the actual building. The Netherlands, without considerable height differences, is an example of how geographical restrictions make it impossible to use PHS for power storage.

Reverse pump hydropower (RPH) is a variant of PHS. The difference is that the lower reservoir allows water from the surrounding area to produce electricity. The reservoir becomes empty when there is excess energy.

RPH has been proposed in the Netherlands as an alternative, but is still under revision. The Netherlands bases its power storage on electrochemical technologies. The current storage capacity is 480 MWh [56], but as the share of renewable electricity will grow by 2050, the storage demand might reach a demand of 1037 GWh [57]. Thus, carbon-neutral energy storage infrastructure must be further developed.

Possibilities for seasonal energy storage distribution in the Netherlands

Currently, natural gas grids can provide twice the amount of energy available in electricity grids [58]. The length of all natural gas pipelines exceeds 136,000 km, and the natural gas grid has more than 7 million connections [59] The current hydrogen infrastructure has a length of only 1000 km [60], which is less than 1% of the length of natural gas pipelines [59]. Natural gas infrastructure can be used for hydrogen transportation. Natural gas pipelines can transport a mixture of 10% hydrogen and 90% natural gas [18]; however, with a hydrogen percentage higher than 10%, these pipelines need to be refurbished to prevent hydrogen leakage. This modification allows the pipes to handle high pressures during hydrogen transportation. Natural gas pipelines designated for distribution have different pressures ranging from 66 bar to 30 mbar. High pressures are used for the import and export of natural gas to large industries, while low pressures are used for the supply of natural gas to residential areas and small industries [61]. The transport of hydrogen requires pressures in the range of 150 to 200 bars [62]. The variance in the pressure range increase pipeline wear, leading to fragility and hydrogen leakage. In the European Union, by 2040, 75% of hydrogen pipelines are expected to be refurbished natural gas pipelines [63]. This expectation indicates that 17% of the already established natural gas pipelines need to be refurbished in the Netherlands.

Benefits of CO_2-based methane in depleted fields for seasonal energy storage

Methane storage at a capacity of hundreds of TWh is possible in depleted natural gas/oil fields, empty aquifers, and salt caverns. Juez-Larré et al. estimated that the Netherlands has the potential to store 1939 TWh of methane in depleted gas fields and 184 TWh of methane in salt caverns [64]. In addition, the potential capacity for methane storage, as underground storage offers many advantages. For example, advantages include information already obtained about the site, the presence of a stable geological structure that can operate for up to 50 years [65], the ability to safely store great volumes of gas at high pressures, and the capacity to supply daily or seasonal energy demand depending on the size of the storage site.

Barriers to hydrogen for seasonal energy storage

Hydrogen storage has many challenges, but in the Netherlands, it may be part of the future energy backbone. The storage of hydrogen as a gas or a liquid in salt caverns is the only storage technology available on an industrial scale [66]. Other alternatives in addition to salt caverns include vessels, geological sites such as depleted gas fields, and other underground storage options. In the Netherlands, the use of salt caverns for hydrogen storage has a potential of 43.3 TWh and in depleted gas fields, it is 277 TWh. The potential is lower than that of natural gas due to the integrity and durability of wellbore materials and interfaces between caverns and hydrogen [67].

Analysis of the use of CO_2-based methane and hydrogen for seasonal energy storage by using the multi-level perspective

The transition of an energy system based on renewable energy implies a transition in the storage and distribution of energy. The use of CO_2-based methane could bring many benefits compared to the use of other energy carriers such as hydrogen and electricity, including the use of already established infrastructure. From an energy point of view, CO_2-based methane has a lower round trip efficiency than both electricity and hydrogen. Nevertheless, the potential for its storage and distribution offers the highest capacities among various carbon-neutral energy carriers based on the cavern potential and the current natural gas distribution grid. These and other trade-offs can be translated to the MLP theory, specifically to the modification of the dimensions of the energy regime. The level of modification may vary based on the boundaries; they can consider the energy carrier or the system as a whole [22]. Nevertheless, drawing boundaries in these complex and interactive systems where several dimensions must be aligned to form a new sociotechnical regime is a difficult task [8] because technology and human complexity should be considered [11].

CO_2-based methane can exploit existing infrastructure such as gas-fired power plants, previously obtained knowledge, and educational programs concerning natural gas use. In addition, the industry supply chain is already developed. Techno-scientific knowledge and industrial structure refer to legacy infrastructure [68], where a fuel that is clearly compatible with the established fossil-based society is more competitive than other forms of energy carriers. Policy should be slightly modified to support the synthesis and use of CO_2-based methane over hydrogen.

The dimension of market and user practices are slightly modified in terms of market dynamics because of the opportunity for cost reduction for CO_2-based methane when renewable energy becomes more available and less expensive than it is now. The intermittency of renewable energy influences the capacity of the energy system to address the peaks and decreases in electricity availability, and as a result, the prices for power/electricity storage need to be adjusted [69]. For hydrogen and electricity, all the dimensions are heavily modified, except for the infrastructure for hydrogen. Natural gas infrastructure can be partially refurbished for the use of hydrogen, and in that case, the infrastructure dimension only requires slight modifications. Otherwise, the creation of the storage and distribution system is heavily modified. This intensive modification represents a challenge. The coordination of the different dimensions from the sociotechnical regime is not possible in a short period; thus such drastic development is not possible. Therefore, the use of CO_2-based methane in natural gas infrastructure is suitable for seasonal energy storage.

High-temperature level heat for industry

Current state and expected changes in high-temperature level heat (HTLH)

HTLH is required in heavy industry. This type of industry requires large amounts of constantly flowing energy in a centralized location. Heavy industry is a well established industry. The production processes were developed decades ago, and as a result, they are efficient and cost competitive. Examples of heavy industries include the steel, cement, petrochemicals, and glass. The production processes in this type of industry require high grade heat, i.e., HTLH: heat at temperatures higher than 1000 °C [70]. In 2018, 50% of the global final energy consumption was in the form of heat [71], and in 2016, natural gas provided 39% of the total energy supply for heat in the European Union [72]. The main sources of CO_2 emissions from process heat are the steel, cement, and petrochemical sectors, which generate 11% of the total global CO_2 emissions [73]. Therefore, it is of relevant importance to transition heat production to a renewable and carbon-neutral production process.

In industry, heat recovery is an option for low-temperature heat. The recovery of heat to 140–150 °C is feasible via heat exchangers and high-temperature heat pumps [74, 75]. In addition to heat management, geothermal energy is another source of low temperature heat. This source of thermal heat is renewable and carbon-neutral. In the Netherlands, it is planned that by 2050, geothermal energy will provide 6% of the low-temperature heat needed in industry [76]. Nevertheless, in the Netherlands, more than half of the heating demand cannot be supplied by heat pumps because the required heat temperature is greater than 150 °C. HTLH and heats higher than 150 °C represent 20% and 41% of the total heat demand [75]. The challenge with these high temperatures is that this heat cannot be recovered from other processes, and it needs to be produced from fossil fuels. This finding highlights the need for a renewable and carbon-neutral source of energy that can be used to generate heat at temperatures higher than 1000 °C.

Benefits of CO_2-based methane use for HTLH production

Methane can be used to produce HTLH via different technologies and transmission mechanisms. Among these technologies, the most common are furnaces and boilers. Furnaces provide heat directly through the combustion of natural gas, while boilers provide heat via water or air. The lifetime of these natural gas-based furnaces and boilers is 20–25 years [77, 78]; however, as these processes maintain high enough efficiencies they are generally used for up to 40 years [79]. The substitution of natural gas for CO_2-based methane in furnaces or boilers does not require any change to the process or to the production system.

Barriers to the implementation of hydrogen for HTLH production

HTLH can be produced by combusting hydrogen. This combustion can reach temperatures of 2400 °C [80]. The produced heat can be used directly from the produced flame or via the production of steam. The most common technology used for hydrogen combustion is catalytic combustion, which, relative to a natural gas boiler, requires a catalyst to promote combustion. However, at this time, hydrogen is used as a chemical feedstock and not in the production of HTLH. Of the 90 Mt of produced hydrogen in 2020, approximately 94% was consumed by the refinery and chemical sectors, and only 5% was used for the reduction of iron in an electrochemical process [81]. None of these hydrogen applications include the production of HTLH. There are many complexities involved in the replacement of a natural gas-based furnace or boiler with a hydrogen-based furnace or boiler in an industrial process. In addition to the disruption in the production process and the presence of several additional costs, companies need to train employees to use new equipment, develop new safety procedures, calibrate the equipment for the process, and, if needed, adapt the process infrastructure to fit the new equipment. It is therefore more attractive to continue using old natural gas equipment rather than adjusting it to suit a heat producing technology based on hydrogen.

Barriers to the implementation of electricity for HTLH production

Electricity is already being used to produce HTLH in heavy industry. Some of these technologies include electric arcs, induction heating, dielectric heating, direct resistance heating, and electron beam heating. The selected technology is based on the process. For example, in the iron and steel industry, an electric arc furnace is used at 1630 °C [82], while in the glass industry, electric coil furnaces are used that reach temperatures of 1800 °C [83]. Even though electric furnaces are similar to fossil-based furnaces and are already being used, transitioning all fossil-based furnaces to electric furnaces places a high demand on the electricity grid: transmission and distribution, the installation of the new furnace, the development of new safety and quality processes, the training of employees, and, in the mid-term, the production of a relatively high-cost good, which affects the markets. Additionally, electricity faces some of the barriers as hydrogen, such as perceived risk or bias toward the use of technologies that are not widely used [84], lack of time and capital for the purchase of new equipment, and lack of prioritization from industries [85].

Analysis of the use of CO_2-based methane, hydrogen, and electricity in the function of HTLH by using the multi-level perspective

HTLH can be produced via CO_2-based methane, hydrogen, and electricity. Combustion flames from CO_2 -based methane and hydrogen can reach temperatures of 2400 °C, while those from electricity can reach temperatures of 1800 °C. Hydrogen is not used for this purpose; this gives electricity an advantage over hydrogen. The non-use of hydrogen for the production of HTLH in heavy industry is related to the stable and efficient production processes based on natural gas, further complicating the transition of fossil fuels to hydrogen for the production of HTLH.

CO_2-based methane is a fast solution for decarbonizing the production of HTLH in all heavy industries, and it does not require modification of the sociotechnical regime. Hydrogen produces no carbon emissions when combusted, and it reaches the high temperatures needed in heavy industry. However, the sociotechnical regime needs to be heavily modified, as described in the section on barriers to the implementation of hydrogen for HTLH production. The current use of hydrogen in industry is almost exclusive to its use as a feedstock in the production of fertilizers and petrochemicals. Therefore, the development of a new sociotechnical regime for the employment of hydrogen is needed. Compared to hydrogen, electricity has the advantage that there is already a sociotechnical regime for its use in the generation of HTLH. The choice of hydrogen or electricity as an energy carrier is based on the requirements of the industry. CO_2-based methane has the advantage of allowing the use of low cost, high performance, and modern carbon-based heat generation technology. These technologies represent more than a century of science and engineering advancements, making the development of decarbonized technologies that are economically competitive challenging.

Residential heating function

Residential heating current state

Residential heating is a necessity, and its requirements are based on the geographical location of a country. In the Netherlands, natural gas is used for residential heating. Houses and buildings that use natural gas for heating constitute 93% of the total built environment. This number represents 7 million homes and 1 million buildings [86]. The demand for residential heating is influenced by the insulation of houses and buildings. Older houses have simpler insulation systems than newer houses. Old buildings with weak insulation can demand 4.5 times more energy than can newly insulated buildings. The lifespans of houses range from 80 to 200 years [87], and in the Netherlands, 50% of the built environment is more than 40 years old [88], indicating that half of all Dutch households are not well insulated.

In 2019, heating in the built environment emitted $23Mt$ of CO_2 equivalent. This value represents 12.5% of the total emissions in the Netherlands [89]. The Dutch government has the goal of reducing emissions by 49% by 2030 and 95% by 2050 relative to the 29.9 Mton emitted in 1990 [86]. To achieve these goals, heating in the built environment should reduce emissions by $7.7Mt_{\mathrm{CO_2eq}}$ by 2030 [90]. One method for reducing emissions is to use carbon-neutral energy carriers instead of natural gas. CO_2-based methane, electricity, and hydrogen are fuels that can provide energy for the heating sector in a carbon-neutral manner.

Benefits of CO_2-based methane use for residential heating

The Dutch heating infrastructure is based on the use of natural gas (methane), and it can be decentralized or centralized. A methane-based boiler is an example of decentralized heat production. Boilers are placed in households and generally have efficiencies ranging from 70% to 80% based on the higher heating value (HHV) of natural gas [91]. On a large scale, a centralized system, which is also called district heating, provides heat for a network of households. The technology used can be a combined cycle gas turbine that produces electricity as the main output and heat as a by product. The electrical efficiency is 22%, and the heat efficiency is 43% [92]. This percentage is considered to result from losses in the distribution system, for example, the distance between the heat source and the sink (households/buildings) [93]. CO_2-based methane is a renewable carbon-neutral fuel that can replace natural gas in the Dutch heating system. It does not require the modification of the already established infrastructure and can therefore be widely employed in existing heating systems.

Barriers to the implementation of hydrogen for residential heating

The use of hydrogen to produce heat is similar to the use of natural gas or CO_2-based methane. Natural gas infrastructure can be used for the employment of hydrogen to a certain extent. The blending of hydrogen with natural gas has been proposed as a bridge for the transition from natural gas to hydrogen. A total of 10% hydrogen can be blended with natural gas [94], but this has not yet been achieved. Using a high percentage (15 – 20%) requires refurbishment of the whole natural gas infrastructure and the implementation of the technology where the blended gases will be used. If natural gas-based boilers are transformed into hydrogen-based boilers, the burner should be replaced with a catalytic burner, and it should limit hydrogen flames. A commercial hydrogen boiler is not currently available, and based on research, an efficiency of 90% can be assumed [95]. Another barrier is the acceptance of hydrogen in houses. Flynn et al. studied people's attitudes toward hydrogen technologies [96]. It was concluded that they should not be too disruptive to their current behaviors. The new technology should allow for maintaining the same habits in its operation and should match the levels of convenience and cost.

Barriers to the implementation of electricity for residential heating

The use of electricity for the heating of the built environment is considered via electric heat pumps. A heat pump draws heat from a low-temperature body; then, the heat is upgraded, and then the heat is subsequently released to a sink that requires heat (the house/building). A heat pump can use air, ground, and groundwater as low-temperature heat sources. A refrigerant is used to first take heat from the transferring medium and to then transfer the heat to a heat sink.

The efficiency of these systems is measured by the coefficient of performance (COP). The COP indicates the heat generated (e.g., in kW) per electricity demand (e.g., in kW). The COP is dependent on the difference in temperature between the transferring fluid and the sink. The COP can reach high as 4.2 for groundwater heat pumps and 3 for air-based heat pumps [97]. The use of a heat pump with a COP of 3 suggests that one unit (e.g., kW) of electricity can be used to produce 3 units (kW) of heat, making such a system 3 times as efficient as electric heating (where 1 unit of electricity generates 1 unit of heat). Therefore, in a Dutch household, the energy demand in the form of electricity is 3.8 MWh to fulfill the 11.4 MWh required for heating. However, the COP can decrease by up to 2.3 in winter when frosting is present and the need for heating is the highest [98].

Heat pumps are highly efficient, but they add an extra burden to the electricity grid. This extra electricity demand can overload the electricity grid. Nykamp et al. estimated the capacity changes in the electricity grid when heat pumps are added as the only source of heat to a residential area [99]. The capacity of the system should be almost doubled when all heat pumps are used simultaneously. Nevertheless, management options such as the installation of PV panels and batteries can provide flexibility in the grid. Litjens et al. modeled the coupling of ground heat pumps with PV panels and batteries [100]. This self-production and storage of electricity can alleviate a small amount of the overload in the grid. Nonetheless, these scholars considered buildings with certain characteristics: built around the year 2012, highly insulated, and detached or semi-detached. Only 2 million households in the Netherlands have these characteristics; thus other challenges may arise when all households and buildings will be heated using heat pumps. Another relevant aspect is the available space for the placement of PV panels and the ground space for the heat pump. The type of building, the space availability, and the additional demand on the electricity grid limit the deployment of heat pumps.

Analysis of the use of CO_2-based methane, hydrogen, and electricity for residential heating by using the multi-level perspective

The production of heat for the built environment is more efficient with the use of electricity. According to a comparison of this energy carrier to either CO_2-based methane or hydrogen, it can provide approximately 3 times more heat per unit of electricity, depending on the COP of the heat pump. However, the use of this carrier is dependent on the individual decisions of building owners, as short-term building remodeling is not always feasible. Furthermore, the challenges of increasing the electric grid capacity, developing new knowledge/education for the installation of heat pumps, producing heat pump components, and developing of new policies that support the implementation of heat pumps greatly modify the dimensions of the sociotechnical regime.

CO_2-based methane provides the least modification to these dimensions. In the case of hydrogen, the dimension of infrastructure can be slightly modified if natural gas boilers are refurbished, as was, for example, studied in [101]. However, when using a different technology or new hydrogen boilers, this dimension is heavily modified. In this function, the social acceptance of the employment of a different technology is quite dependent on social factors and on spatial constraints. Therefore, home and building owners will be motivated if new policies and subsidies are offered to substitute natural gas with a different energy carrier. These individuals must be willing to make this change.

Discussion

Time constant in the energy transition

Previous energy transitions lasted for decades, while the time to develop a new sociotechnological landscape for the usage of a specific fuel was not clear. Coal supplied 5% of the global energy supply in 1840; then, it took 35 years for coal to supply 25% of the energy supply and 60 years to supply 50%. In the case of oil, it took 40 years to increase its contribution to the energy supply from 5% to 25%. For natural gas to reach an energy supply of 25%, it took more than 60 years [102]. This relatively long transition is related to the development of a new sociotechnical regime, where the infrastructure and technologies needed to use these “new” fuels are developed. Examples of transitions to renewable energy are wind energy in Denmark and solar photovoltaics in Germany. In the case of Denmark, it took 40 years for wind electricity to provide 20% of the total electricity. In Germany, it took 55 years for solar photovoltaics to provide 20% of the total electricity [7].

The time that the energy transition takes is based on how quickly a new sociotechnical regime can be formed and on the degree of modification needed for each of the dimensions to incorporate new renewable and carbon-neutral energy carriers in our fossil-based sociotechnical regime. Kobos et al. developed a framework in which technology, regulatory, and market aspects are incorporated [103]. The technological aspect is based on the technological readiness level of the technology, the regulatory aspect is for the policies that should be developed to apply the mature technology, and the market aspect dictates whether the mature and policy ready technology will be accepted and used in the industry. For a general technology, it takes 9.5 years for it to progress from the niche to mature. It takes 6.75 years for a regulatory framework to be ready. Moreover, for the market to adopt the technology, it takes 5 years. In total, for a general technology, the total transition takes 20.5 years. The actual duration can vary depending on the level of support of the technology by means of funding, the regulatory framework by means of political support, and the market by means of the forecasted industry demand and whether the new technology is compatible with the already established market [104].

An example of temporal variation from the regulatory framework aspect is the legislation to encourage air quality improvement in California, USA. It took 40 years for the regulatory framework to have an impact by subsidizing technologies in line with the new policy [105]. Regarding hydrogen use in the European Union, the first time that it was mentioned in a policy document was in 2012 [106]. However, it is expected that the benefits of using hydrogen will not be apparent until 2050 [107]. The time gap between the first time mentioned and the expected benefits of hydrogen is thus predicted to be 38 years.

CO_2-based methane use does not face the challenges that hydrogen and electricity need to overcome to be used as substitutes for natural gas. Figure 1 shows the sociotechnical landscape and how the studied energy carriers behave in the energy transition.

The level of modification of each dimension from the sociotechnical regime is shown in Table 3. We considered three levels of modification of a dimension: no modification, minor modification, and major modification. The level of modification to the dimension is based on the barriers that need to be overcome the energy carrier in order to be used. CO_2-based methane is the energy carrier that requires the fewest modifications. Only policy needs to be modified to encourage the use of CO_2 and the development of regulatory frameworks. In the case of hydrogen, almost all the dimensions are substantially modified, with the exception of infrastructure, for which natural gas infrastructure is refurbished for hydrogen; thus, the infrastructure is only slightly modified. However, if new infrastructure is developed, this dimension is greatly modified. For electricity, the dimensions are less modified than those for hydrogen. The symbolic meaning of technology is not modified since electricity is already used in the analyzed functions. Techno-scientific knowledge and the market undergo minor modifications because education systems should be developed and implemented for the use of electricity in the industry and for the installation of residential heat pumps. Finally, the market needs to develop new electricity management systems to address the intermittency of renewable energies and the high demand expected from the industry.

The use of CO_2-based methane

CO_2-based methane implementation impacts our society in different manners. These impacts are reflected in our economy, environment, and society.

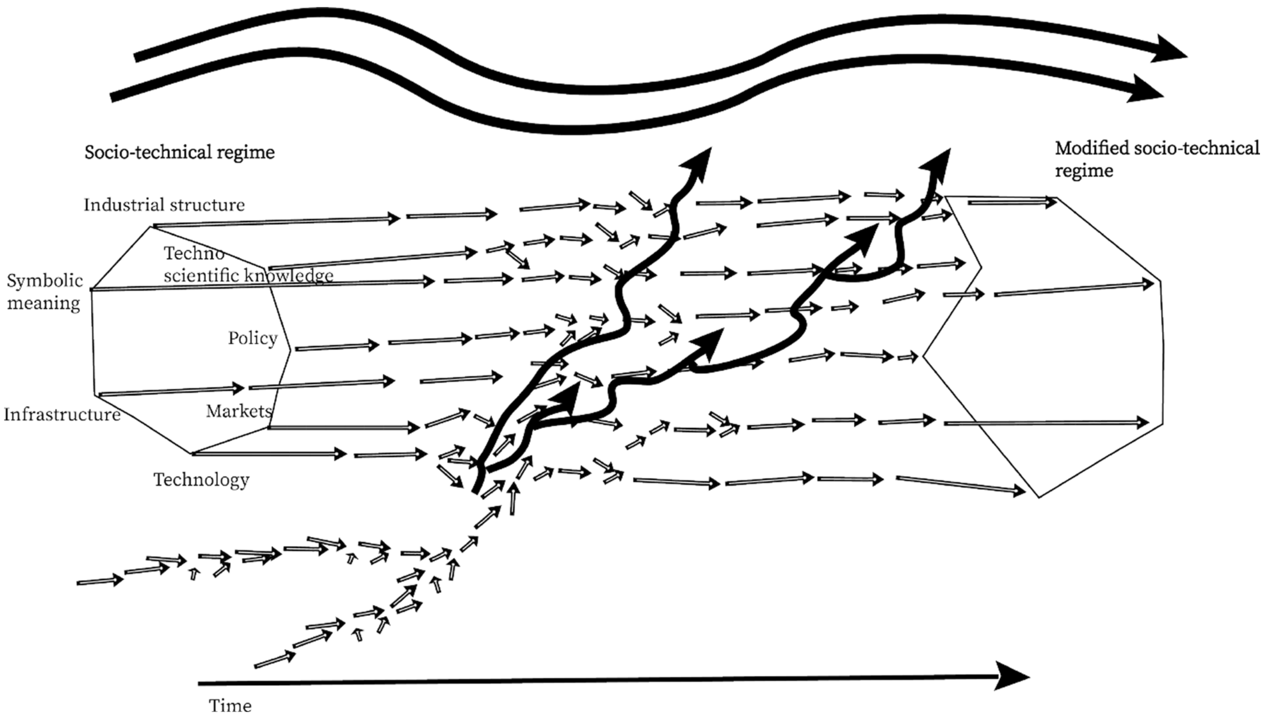

Fig. 1 Dynamics of a sustainable transition. The left arrow represents the implementation of CO_2-based methane. This arrow goes from the niche level to the societal landscape. The arrow has curvatures, especially in the policy dimension. The curvature represents the level of modification required for the dimension so that the energy carrier can be used. Even though a curvature is present, the fuel is implemented, and it can be used the societal landscape. The right arrows are also initiated in the niche, but the arrow splits instead of going further upward. This splitting represents the heavy modification of the dimension, and as a result, it takes more time to implement either hydrogen or electricity on the societal landscape. Modified from [8]

Our economy is dependent on fossil fuels. Transitioning to CO_2-based methane in the analyzed functions can influence the price of the production of goods and the heating and powering of our houses. The current estimated prices for CO_2-based methane are in the range of $27\frac{\text{euro}}{\text{GJ}}$[125] to $63\frac{\text{euro}}{\text{GJ}}$ [126] (considering an exchange rate of 0.94 euros to USD). The price of natural gas in 2018 was $10\frac{euro}{GJ}$. However, in the first half of 2022, the price reached $34\frac{\text{euro}}{\text{GJ}}$ [127]. The increase in natural gas prices was influenced by the COVID-19 pandemic and the invasion of Ukraine by the Russian army. Geopolitical conflicts have a great impact on our economy, especially if the conflicts involve fossil fuel rich countries. Therefore, even though the current price for the production of CO_2-based methane is high, in the long run, transitioning toward a fossil-free and independent energy market, can stabilize the economy.

The environmental impact of using CO_2-based methane is double-sided. The carbon source for CO_2 -based methane is CO_2 from air. This carbon source is carbon-negative; thus, the concentration of CO_2 in the atmosphere decreases. Conversely, when CO_2-based methane is combusted, CO_2 emissions return to the atmosphere. The use of CO_2-based methane can help to increase the circularity of the emitted CO_2 and reduce the consumption of fossil fuels [128], since the same carbon that is emitted will be used to produce CO_2-based methane.

Socially, awareness of CO_2 use is low [129, 130]. The use of CO_2-based methane might not be perceived by the general public. Residential heating is the function where people will perceive a difference due to the increased cost. Cost increases can be prevented if subsidies are issued. Nevertheless, awareness about the use of CO_2 can provide additional room for the use of CO_2-based methane for further natural gas functions.

Conclusion

CO_2-based methane is a serious option under consideration in our complex societal landscape where the pace of innovation has a great influence on the sustainable energy transition. The use of CO_2-based methane allows the harnessing of the existing fossil fuel societal regime. Nevertheless, this carbon-neutral energy carrier has been disregarded due to its high energy demand for synthesis compared to the direct use of hydrogen

Table 3 Dimensions from the sociotechnical regime modified per function and energy carrier

Dimension	**CO_2-based methane**		**Hydrogen**		**Electricity**	
	Modification	**Barriers**	**Modification**	**Barriers**	**Modification**	**Barriers**
Infrastructure	No		Major	Infrastructure development [e] Not feasible in the short term [d] Higher cost [e]	Major	Lack of transmission cap Limited ability to integrate fluctuating generations [k]
Technology	No		Major	Technological immaturity [e,f,g]	Major	Not enough production to compete in the storage market [n]
Techno-scientific knowledge	No		Major	Experience deficit [e]	Minor	Co-management of elec requires knowledge[o]
Market	Minor	Development of acc mechanisms[a]	Major	No code/standards [e,h] Ramp-up risks [d]	Minor	Market rules too strict [n] Change in ownership[n]
Symbolic meaning technology	No		Major	Lack of social acceptance [e,f,g,i,j]	No	
Industry structure	No		Major	Alignment among manufacturers [e] Adjust billing method [m]	Major	Until high elec penetration, possible seasonal storage [p] Reconfiguration business model due to decentralization of electricity producers [q]
Policy	Minor	Subsidies required[b]	Major	New national and int policies [e,g,h]	Major	Lack of regulatory and policy frameworks [n] No long-term commitment from the government [m] Poor regulations to ensure renewable electricity supply [r]

[a][108] [b][109] [c][110] [d][111] [e][112] [f][113] [g][110] [h][114] [115] [j][116] [k][117] [118] [m][119] [n][120] [o][121] [p][122] [q][123] [r][124]

or electricity. In this research, we show that the energy demand for CO_2-based methane synthesis is not the sole deciding factor. Other influencing factors are the complexities of the societal landscape during the fast sustainable transition.

The efficiency of CO_2-based methane synthesis is 1.5 times lower than that of hydrogen synthesis and 2.3 times lower than that of electricity synthesis. These efficiencies are not the only factors to consider when replacing natural gas with renewable energy carriers such as hydrogen and electricity.

For these functions, CO_2-based methane is the preferred energy carrier for the fast substitution of natural gas in the energy transition toward CO_2 neutrality. In this substitution, the different levels of the societal landscape are considered, especially the at meso-level. This level represents the sociotechnical regime that is constituted by seven dimensions: technology, user practices and application domains (markets), the symbolic meaning of technology, infrastructure, industry structure, policy, and techno-scientific knowledge. The dimension analysis in the previous sections show that in the application of CO_2-based methane for the three selected functions, five dimensions do not require any level of modification. The low level of modification is apparent due to the already established regime for the employment of natural gas. Therefore, CO_2 -based methane can be immediately used in our current fossil-based society with only slight changes. In the case of hydrogen and electricity, all dimensions need to be modified. Considering infrastructure for hydrogen and electricity, the level of modification is based on the refurbishment of existing infrastructure or the development of new infrastructure. This analysis shows the importance of the temporal limitations we are facing regarding the need for an urgent reduction in CO_2 emissions, helping policy and technology makers understand that efficiency is not the only factor to consider in the energy transition. Accounting for all the factors involved in a sustainable technological transition for the energy system, it can be concluded that even though CO_2-based methane is the least energy efficient energy carrier, its employment can encourage the energy transition. This promotion is specially true in a world where there is no time to waste to reduce CO_2 emissions and prevent the devastating impacts of climate change.

Abbreviations

CO_2	Carbon dioxide
MLP	Multi-level perspective
MTW	Minimum thermodynamic work
BAT	Best available technology
HTLH	High-temperature level heat

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Author contributions

ISB: conception, design of the work, analysis, interpretation, writing original draft, and review. KW: conception, design of the work, analysis, interpretation, and review. AtH and CB: supported study organization and data analysis and revised the manuscript. BH: closely supervised the activities and provided feedback reviewed.

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Declarations

Ethics approval and consent to participate

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Competing interests

The authors declare that they have no competing interests.

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