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D6.1 Scenario analysis to explore the future role of synthetic methane and syngas

WP6 Techno-economic and environmental assessment

WP LEADER	Andrea Pestarino (RINA-C)
DELIVERABLE RESPONSIBLE	TNO
DELIVERABLE AUTHOR(S)	Remko Detz, Nicole Meulendijks, Pascal Buskens, Bob van der Zwaan, Sara Abd Alla
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EXECUTIVE SUMMARY

In this deliverable we report about the analysis of scenarios that has been performed as part of task 6.2. We show how natural gas demand might change in Europe according to different projections up to 2050. Next to that, we analyse how syngas produced in a renewable way can replace fossil-fuel based syngas production and thereby play an essential role in the decarbonisation of industry. We show that in essentially all industrial applications renewable H_2 and/or CO can replace syngas from fossil fuel feedstocks, and quantify the flows of these chemical building blocks required for the transformation of industry towards a net-zero emitting sector.

CONTENTS

SCENARIO ANALYSIS TO EXPLORE THE FUTURE ROLE OF SYNTHETIC METHANE AND SYNGAS

1.1 Introduction

As part of Task 6.2, a scenario analysis is performed to explore the future role of synthetic methane and syngas. The role of synthetic products such as methane and syngas in Europe and the World towards 2050 is investigated.

First, the methodology is described in section 1.2. In the next part (1.3), the emphasis lies on natural gas demand, and demand for gaseous fuels in general. The projected trends are illustrated and indicate the potential role of synthetic methane in the future energy system. In section 1.4, a syngas scenario analysis is presented, both current use and an outlook towards 2050.

1.2 Methodology

For the synthetic natural gas scenario analysis, a comprehensive literature review is performed to explore the future role of synthetic methane. Key insights are obtained by analysis of natural gas projections from several scenario studies.

For the syngas scenario analysis, several sources have been consulted to derive the different flows of syngas used for several applications. In the tables below, a summary of the data and sources are given (see also [1]).

Table 1 Data for the flows from syngas to the applications of syngas.

Syngas to…	Efficiency	Size (Mt)	Size based on	Sources
Ammonia	98%	170	Ammonia	[2]
Refining	98%	38	Hydrogen	[3]
Other pure H_2	98%	4	Hydrogen	[3]
Other mixed H_2	98%	30	Hydrogen	[3]
Methanol	99%	100	Methanol	[4] [2] [5] [6]
Fischer Tropsch	99%	27	FT liquids	[7]
Hydroformylation	99%	10	Oxo chemicals	[8]
Iron and steel	99%	13 1000	Hydrogen + Coal	[3] [9] [10]
Electricity	58%	6	Coal	[11] [12] [13]
SNG	95%	6	Coal	[14] [15] [16]
Acetic acida	73%	8	Acetic acid	[17] [18]

Table 2 Data for the flows from fossil fuels to syngas.

… to syngas	Efficiency [2]
Coal	76%
Natural gas	86%
Oil	81%

Assumptions for the construction of the Sankey diagram:

- The processes that do not specify the fraction of natural gas, oil or coal used in the production of the syngas use a distribution of 80% natural gas, 3% oil and 17% coal [5]. For ammonia this distribution is slightly different with 71% natural gas, 9% oil and 21% coal. For refining and the *other* categories a distribution based on the production of hydrogen is used: 50% natural gas, 30% oil and 20% coal [19], because for those processes only the hydrogen in the syngas is necessary. The distribution for FT is based on the ratio CTL and GTL [7]. The iron and steel industry is based on the quantity of CO produced in relation to the wt% of carbon in coal, according to the quantity of coal used in the iron and steel industry [11]. It is assumed that the hydrogen that is produced in the coal gasification is used in a separate process, as it is not used in the normal process. The H_2 necessary in the iron and steel industry is produced from natural gas [11]. Electricity, SNG and acetic acid are only produced with coal because either only CO is necessary, or because production plants only in combination with coal gasification exist.
- For the electricity production an overall efficiency of 44% is assumed [11] [13].
- For FT the data from Haarlemmer *et al.* [7] is adjusted for 85% capacity.

Table 3 Lower heating values (LHV) used in calculations for the Sankey diagram.

Chemical	LHV (PJ/Mt) [20]
Natural gas	47.1
Oil	42[1]
Coal	29[1]
CO	10.1
H_2	119.8
Methanol	19.9
Fischer-Tropsch fuel	43[1]
SNG	50
Ammonia	18.6
Acetic acid	13.2
Syngas	23.8[1]
Oxo chemicals (butanol, isobutanol 2-ethylhexanol)	34.3[1]

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[1] Calculated, assumed or an average of the different kinds.

Table 4 Data on syngas with a H_2/CO ratio of 2.

Chemical	Molar ratio (mol)	Weight ratio (kg)	LHV ratio (PJ/Mt)	Molecular weight (kg/kmol)
CO	1	0.875	8.8	28
H_2	2	0.125	15.0	2
Syngas		1	23.8	10.7

1.3 Synthetic Natural Gas

The EU's 2050 goal for reducing GHG emissions is already 80–95%. As a result, for the purposes of this report, the focus is led on scenarios that respect the prerequisites for at least an 80% decrease in GHG emissions. Stronger decarbonization scenarios call for more than just energy sources. Efficiency improvements, electrification, and technical advancements are necessary, but they also call for society behavioral adjustments. Both categories project a significant reduction in natural gas consumption, but only scenarios that reduce GHG emissions by 95–100% estimate a nearly full phase-out of natural gas.

The situation is even more complex when it comes to the overall demand for gaseous fuels. The scenario analysis performed for the long-term plan of the European Commission (shown in FIGURE 1. Projected gas demand up to **2050** (IN BCM) (SOURCE: BASED ON COMMISSION (2018); IEA (2018); TYNDP (2018); TRINOMICS (2018); BP (2019); SHELL (2018); EQUINOR (2018); EUROGAS (2018))

) provides a clear illustration: the scenarios *1.5TECH* and *1.5LIFE*, which aim to achieve a 100% reduction in greenhouse gas emissions, predict higher demand than some of the -80% GHG scenarios that do not emphasize a substantial evolution of a particular form of gas. Therefore, the creation of low and zero-carbon alternatives including biogas, biomethane, synthetic methane, renewable syngas, and hydrogen is necessary to reach net-zero GHG emissions by 2050.

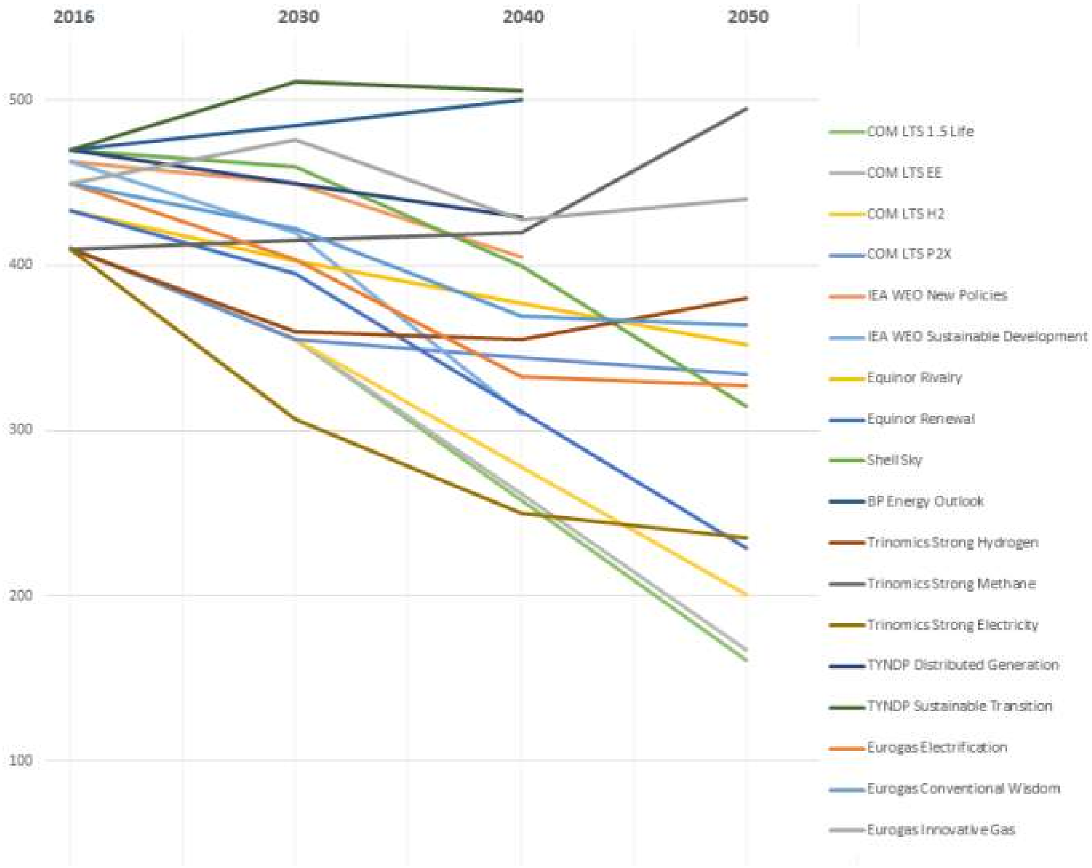

FIGURE 1. PROJECTED GAS DEMAND UP TO 2050 (IN BCM) (SOURCE: **[21]** BASED ON COMMISSION (2018); IEA (2018); TYNDP (2018); TRINOMICS (2018); BP (2019); SHELL (2018); EQUINOR (2018); EUROGAS (2018))

1.3.1 What will be the role of synthetic methane in the future energy system?

Natural gas is widely available, and most forecasts indicate that the LNG demand will increase. A decline in gas demand and a change in the composition of gaseous fuels are also projected in most scenarios that are considered to be in conformity with the Paris Agreement goals (often at least 80% reduction in GHG emissions by 2050). Despite the fact that natural gas would still be used because it is more affordable than alternative gaseous fuels, the scenarios envision renewable synthetic methane and hydrogen playing a significant role. In terms of demand, industry is probably a significant factor because, as of today and absent significant cost reductions in new technologies, gas is a necessary input for the manufacturing of cement and fertilizers. In this context, bio-based synthetic gas, hydrogen (blue or green), carbon capture, utilization and storage (CCUS) are potential other contributors to a decarbonized Europe [21]. However, significant cost reductions are necessary (for the use of hydrogen), the competition for biomass must consider additional Sustainable Development Goals (SDG) (the food-water-energy nexus and biodiversity issues), and funding must be secured for the development of CCTS infrastructure (carbon dioxide transport and storage) [22].

1.4 Syngas

1.4.1 Introduction

In order to mitigate global climate change, a net-zero CO_2 emitting industry is necessary to align with the targets of the Paris Agreement [23]. A challenge for the refinery and chemical industry is that fossil CO_2 is not only emitted as a result of the energy required for the industrial processes or as a byproduct of the chemical processes, but also a substantial share of the carbon is also contained in the products. These industrial carbon-based products are often combusted or incinerated, or they eventually decompose, after their use and hence lead to CO_2 emissions. Despite these emissions are commonly attributed to other sectors, such as agriculture, transport, or waste treatment, they really originate from industry.

A way to avoid these often mis-attributed or sometimes even un-accounted industrial CO_2 emissions from carbon-based products is to use carbon in a circular fashion [24] [25]. This can be realised by the use of biomass or, alternatively, atmospheric CO_2 as chemical feedstock, for instance to produce syngas (or synthesis gas), which is a mixture of carbon monoxide (CO) and hydrogen (H_2). At present, syngas is predominantly employed as intermediate chemical building block in a variety of industrial processes. It is produced from fossil fuels such as coal, oil, and natural gas, in well-established production processes that are relatively efficient and low in costs. To enable a future in which circular carbon is used as feedstock for renewable syngas production, the costs of the corresponding processes will need to go down. The SPOTLIGHT process to produce CO is an example of such a process and the costs are assessed in more detail in task 6.1.

In this chapter we present an overview of the current and future role of syngas in industry. This analysis should provide insight in the future demand for renewable syngas when considering these new value chains.

1.4.2 Role of syngas in industry: presence

Today, syngas is almost entirely produced from fossil resources. In Table 5 we list the main reaction mechanisms in the four processes currently in use to convert fossil fuels into syngas or pure CO. The fossil resources are converted to syngas by various processes, such as steam methane reforming (SMR), coal gasification (CG), partial oxidation (POX), and autothermal reforming (ATR) [26]. In these processes, multiple reactions take place, as specified in Table 5 [27] [28] [29] [11]. The product gasses are utilized for several applications. For hydrogen production, all carbon is generally converted into CO_2 and released to the air to maximize the formation of H_2. Hydrogen is used in refining, ammonia production, and various other applications. CO is also used directly as reagent to, for instance, reduce iron oxide for steel production and as building block for acetic acid production. A mixture of CO and H_2 is, for example, applied in the Fischer-Tropsch process, hydroformylation reactions, and the synthesis of methanol and methane.

Table 5. Reaction equations reflecting the main processes to produce syngas from fossil fuels.

	REACTION	REACTION NAME	PROCESS
CONVENTIONAL ROUTES	$C_xH_y + x\,H_2O \rightleftarrows x\,CO + (x+½\,y)\,H_2$	Steam reforming	SMR, CG, ATR
	$C_xH_y + ½x\,O_2 \rightarrow x\,CO + ½y\,H_2$	Partial oxidation	CG, ATR, POX
	$CO + H_2O \rightleftarrows CO_2 + H_2$	Water gas shift (WGS)	SMR, POX, ATR, CG
	$C + CO_2 \rightleftarrows 2\,CO$	Boudouard reaction	CG

FIGURE 2 depicts a Sankey diagram for how the present use of syngas in industry relies entirely on H_2 and CO produced from fossil-fuel resources [1]. The total global demand of syngas is difficult to clarify because syngas is generally used as intermediate in several industrial processes. We estimate that more than 31 EJ of syngas in various mixtures is annually produced. This quantity of syngas is used as intermediate in the production processes of fuels, chemicals, and materials. Nearly 12 EJ is applied as pure hydrogen [3]. More than 15 EJ of syngas, mainly CO from coal, is used for iron production [9]. For the synthesis of products that contain carbon, such as methanol, methane, hydrocarbon fuels, oxo chemicals, and acetic acid, currently almost 4 EJ of syngas is used [4] [30] [7] [28] [8] [17]. Some syngas is generated from coal for electricity production in IGCC power plants and in total more than 6 EJ of energy is lost due to heat and waste flows [13].

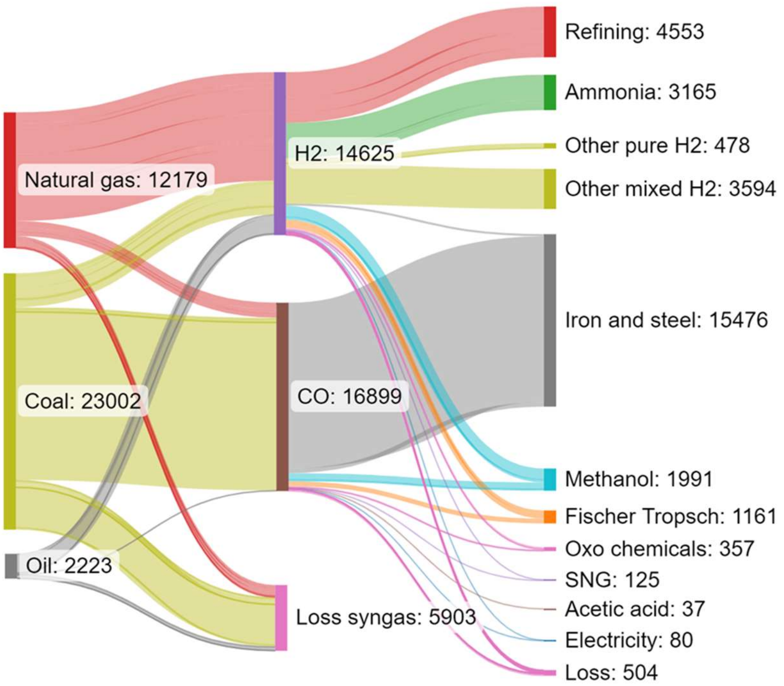

FIGURE 2. SANKEY DIAGRAM FOR THE CURRENT USE OF SYNGAS IN INDUSTRY. VALUES ARE GIVEN IN PJ PER YEAR OF ENERGY STORED IN THE PRODUCT RELATED TO SYNGAS (1 EJ = 1000 PJ).

1.4.3 Role of syngas in industry: prospects

FIGURE **3** summarizes the pathways for the use of syngas as intermediate for the generation of a series of final products in industry. The traditional production routes are indicated that rely today essentially only on the use of fossil fuels as input resources, as well as the future possible alternatives that employ renewable feedstocks through a number of different processes.

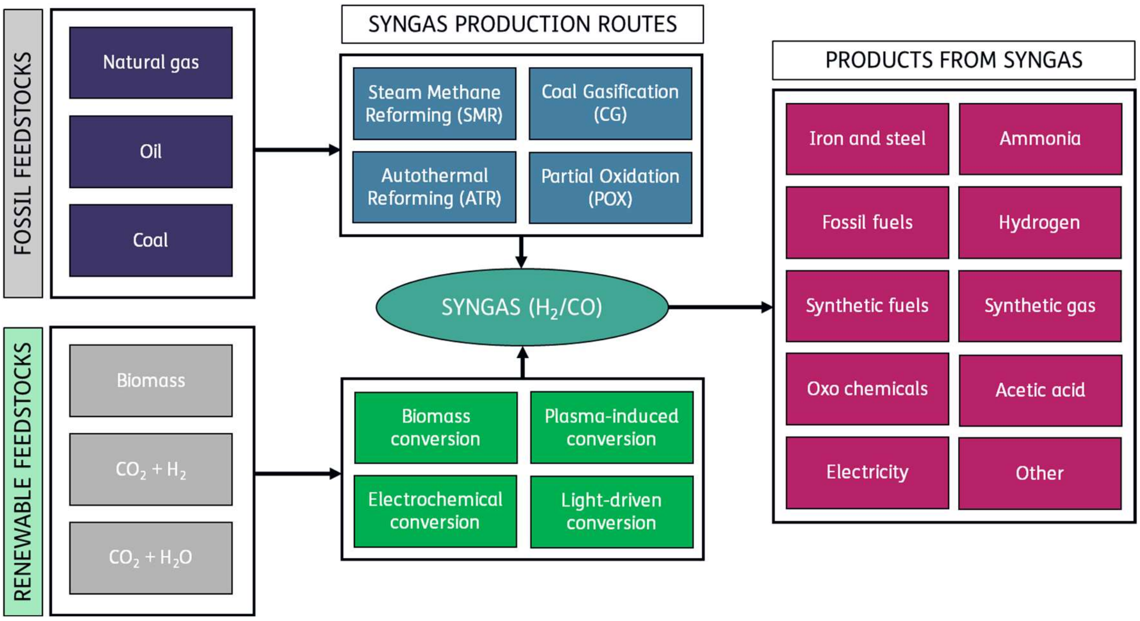

FIGURE 3. PATHWAYS FOR SYNGAS AS INTERMEDIATE FOR FINAL PRODUCTS IN INDUSTRY: PRESENCE AND PROSPECTS.

The nearly 12 EJ of syngas that is applied as pure hydrogen can potentially be replaced by renewable hydrogen directly. The more than 15 EJ of syngas for iron production is, despite that steel contains minor amounts of carbon, mainly used as reducing agent to convert iron oxide to iron metal. This process can potentially almost entirely be driven by electricity or hydrogen [3]. Syngas usage to manufacture products that contain carbon, such as methanol, hydrocarbon fuels, oxo chemicals, SNG, and acetic acid are more likely to remain dependent on syngas as feedstock. As a first approximation of the future market, we assume that demand for these carbon-based products will increase. Projections vary substantially, but here we assume that especially the market for methanol and Fischer-Tropsch (FT) fuels will increase to, respectively, 500 and 300 Mt (10 and 13 EJ) towards 2050 [4] [31] [32]. The production scale of oxo chemicals, SNG, and acetic acid is doubled in 2050 compared to 2020 data, together adding around 1 EJ to the total. FIGURE **4** depicts a Sankey diagram for how the future use of syngas in industry can rely entirely on H_2 and CO that are produced from non-fossil-fuel resources.

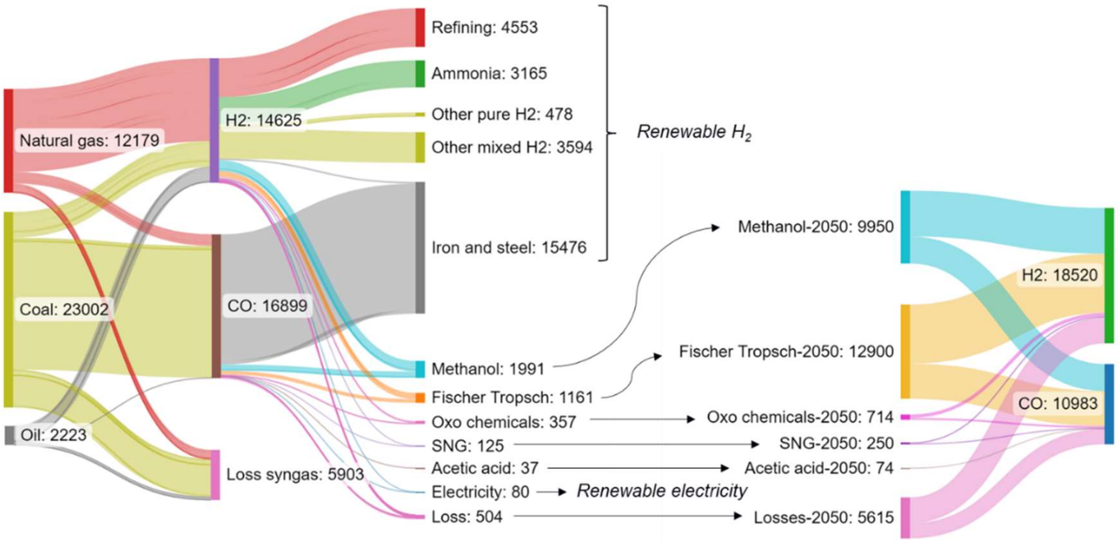

FIGURE 4. SANKEY DIAGRAM FOR THE FUTURE USE OF SYNGAS IN INDUSTRY. VALUES ARE GIVEN IN PJ PER YEAR OF ENERGY STORED IN THE PRODUCT RELATED TO SYNGAS.

Methanol can be used to produce chemicals through the methanol to olefines (MTO) process, fuels through methanol to gasoline (MTG) and MTO/Mobil olefins to gasoline and distillate (MOGD) and FT synthesis can generate both fuels and naphtha, the latter being a starting material for chemicals production [33] [34]. Currently around 11 EJ (~255 Mt) of fuels for shipping and 10 EJ (~230 Mt) of aviation fuel is consumed in 2021 [35]. Additionally, around 23 EJ (~535 Mt) of hydrocarbons are used as petrochemical feedstock, mainly to produce chemicals and plastics. Together, these products amount to 44 EJ (1020 Mt) and a large share is expected to remain carbon-based and demand for these products is likely to increase in the future. Our projections indicate that in 2050 approximately 24 EJ of carbon-based products will be generated through syngas-based routes, i.e. these routes do likely not cover the total future demand.

In our scenario, 29 EJ of renewable syngas is required to supply 24 EJ of carbon-based products. We should note that such a demand in 2050 would require a cumulative annual growth rate of 46%, which is significantly higher as historically observed for the adoption of most technologies [36]. It might help that several routes can produce renewable syngas, using different feedstocks and technologies. These routes exist of, for instance, biomass conversion processes, plasma-induced procedures, electrochemical methods, and light-driven approaches, amongst others. An example of the latter process is explored in the SPOTLIGHT project and may play a role to realize a more sustainable industry that uses renewable carbon. We also compared several alternative renewable routes to produce syngas as part of the techno-economic assessment (task 6.1). Part of this work has been submitted for peer-reviewed publication. More information on the techno-economics of the SPOTLIGHT process will be reported in D6.4.

CONCLUSIONS

Based on reported projections, the demand for natural gas up to 2050 is presented. The average trend shows a decline in gas demand. Still, gas is likely to be required in the future and alternative, renewable forms of gas should steadily replace natural gas. The exact form of the gas is uncertain and, therefore, the creation of low and zero-carbon alternatives including biogas, biomethane, renewable synthetic methane, renewable syngas, and hydrogen is necessary to reach net-zero GHG emissions by 2050.

We also analysed how renewable syngas can replace fossil-fuel based syngas and thereby play a crucial role in the decarbonisation of industry. We show that essentially all industrial applications can be subjected to decarbonization by making renewable H_2 and/or CO replace syngas produced from fossil fuel feedstocks like coal, oil and natural gas. We also quantify the present flows of these chemical building blocks, as well those required for the transformation of industry towards a net-zero emitting sector. In our scenario, 29 EJ of renewable syngas is required to supply 24 EJ of carbon-based products on a global scale.

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