



Towards an Artificial Carbohydrates Supply on Earth

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How to feed a growing global population in a secure and sustainable way? The conventional, biogenic agriculture has yet failed to provide a reliable concept which circumvents its severe environmental externalities—such as the massive use of land area, water for irrigation, fertilizer, pesticides, herbicides, and fossil fuel. In contrast, the artificial synthesis of carbohydrates from atmospheric carbon dioxide, water, and renewable energy would allow not only for a highly reliable production without those externalities, but would also allow to increase the agricultural capacities of our planet by several orders of magnitude. All required technology is either commercially available or at least developed on a lab-scale (at least for sugar). No directed research has, however, yet been conducted towards an industry-scale carbohydrate synthesis because the biogenic carbohydrate production was economically more competitive. Taking the environmental and socio-economic externalities of the conventional sugar production into account, this economical narrative has to be questioned. We estimate the production costs of artificial sugar at ~ 1 €/kg. While the today's spot market price for conventional sugar is about 0.3 €/kg, we estimate its total costs (including external costs) at ≥ 0.9 €/kg in humid regions and ≥ 2 €/kg in semi-arid regions. Accordingly, artificial sugar appears already today to be the less expensive way of production. The artificial sugar production allows in principle also for a subsequent synthesis of other carbohydrates such as starch. These synthetic products could directly supply a large fraction of the human calorie requirements and could be in addition used as a feedstock to microorganisms, fungi, insects, or livestock in order to enhance the sustainability of the remaining biogenic production of, e.g., fats and proteins. This manuscript aims at rising research interest and awareness for a transition to a non-agricultural and more resource-conserving way to supply carbohydrates for food and feed.

Keywords: artificial synthesis, formose reaction, monosaccharides, sustainable food supply, water-smart food supply

1. INTRODUCTION

Since the inception of agriculture by mankind about ten millenia ago, the basis of the food supply for the human population has been the farming of field crops. Today, the conventional agriculture occupies more than a third of all land area but nevertheless requires the massive use of water for irrigation, fertilizers, pesticides, herbicides, and fossil fuel in order to meet our demand in food (Plourde et al., 2013; FAO, 2018). Just some of the negative environmental externalities of our agricultural system are groundwater depletion, soil erosion, environmental pollution, an

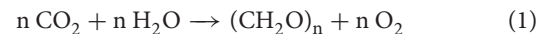
alarming decrease in biodiversity, and a contribution of 10–12% to the anthropogenic greenhouse gas emission fluxes (Famiglietti, 2014; IPCC, 2014a; Lu et al., 2015; Borrelli et al., 2017; Dudley and Alexander, 2017; FAO, 2017, 2019). On the one hand, these externalities are severe threats to the ecologically basis of our society and the reduction of agricultural activities to a sustainable level thus appears to be mandatory (O'Neill et al., 2018). On the other hand, the expected growths in global population and per-capita meat consumption will demand an even higher agricultural output (OECD and FAO, 2018). This dilemma becomes even worse if the ongoing climate change indeed causes a steady decline in agricultural productivity as the increasing number of droughts throughout the globe may indicate (IPCC, 2014b). With the conventional agriculture failing to provide a convincing answer to the question: how to provide a secure and sustainable food supply to a growing global population?

The predominant bottlenecks in the biogenic food supply are the extremely poor energy conversion efficiency of the plant-driven photosynthesis with typical efficiencies of 1–3% for solar-to-biomass and below 0.5% for solar-to-food (in this paper, food refers to the energy intake supplied to humans by digesting the end-product) and the enormous demand for water, amounting to 400–2,000 kg of fresh water for 1 kg of food (Rockström et al., 2007; Zhu et al., 2008; Gerbens-Leenes and Hoekstra, 2009). In contrast, the abiotic synthesis of complex organic compounds from carbon dioxide (CO₂), water (H₂O), and (solar/renewable) energy—also called artificial photosynthesis or power-to-X—could not only provide solar-to-food conversion efficiencies beyond 10% but is in addition virtually free of environmental externalities. In particular, it would require less than 1 kg of water to synthesize 1 kg of food. This contrast in conversion efficiencies gave rise to research interest in replacing biofuels by entirely synthetic fuels as ecologically sustainable fuels for the transportation sector or as a storage technology for renewable energy. For instance, power-to-gas synthesis of hydrogen (H₂) or methane (CH₄) has been installed on an industrial scale with energy conversion efficiencies of 77% and 41%, respectively (Thema et al., 2019). For the synthesis of more complex carbon compounds such as liquid hydrocarbons from atmospheric CO₂, energy conversion efficiencies of up to 70% have been predicted (Graves et al., 2011; Sunfire, 2019b).

It is surprising that the numerous publications on power-to-X never mention the artificial synthesis of food, although the transition towards an artificial synthesis of food appears to be a possible solution for the dilemma highlighted above. This can be illustrated impressively by the theoretical area required to feed an adult human: The global annual average solar irradiation reaching Earth's surface is about $185 \text{ W m}^{-2} = 16.0 \text{ MJ m}^{-2} \text{ d}^{-1}$ (Wild et al., 2013). The recommended calorie intake for an adult human varies between $7\text{--}19 \text{ MJ d}^{-1}$ subject to parameters such as age, weight, gender, and physical activity (FAO, 2001). Assuming a mean calorie demand of 12 MJ d^{-1} (and ignoring the minor differences between the physical and physiological energy contents of food), thus in theory a ground area of just 0.75 m^2 could harvest enough solar energy to feed an adult human.

The World Health Organization recommends a human diet whose calorie intake is contributed by 55–75% via carbohydrates,

15–30% via fats, and 10–15% via proteins—indicating that carbohydrates are the most important component in our food supply (WHO and FAO, 2003). Carbohydrates are—when strictly defined—compounds with a chemical formula $C_m(H_2O)_n$. The most relevant carbohydrates are monosaccharides $(CH_2O)_n$, (e.g., glucose and fructose both with $n = 6$) and monosaccharide polymers $C_n(H_2O)_{n-1}$ which are called with respect to their degree of polymerization disaccharides (e.g., sucrose and lactose both with $n = 12$), oligosaccharides, or polysaccharides (e.g., starch and cellulose). The abiotic monosaccharide synthesis scheme



is understood in principle and practical experience for all intermediate steps is available (see next section). The artificial synthesis of monosaccharides allows in principle also for a subsequent artificial synthesis of any monosaccharide polymer, that is of any carbohydrate (Clancy and Whelan, 1967; Seeberger and Haase, 2000; Plante et al., 2001; Seeberger and Werz, 2005; Kadokawa and Kobayashi, 2010).

To date, however, a practical use of artificial carbohydrates has been investigated only for niche applications. For instance, the National Aeronautics and Space Administration (NASA) investigated in the 1960s the artificial production of carbohydrates as possible food supply for manned space missions (see the NASA history and related references at <https://history.nasa.gov/SP-202/sess5.2.htm>). While those early studies apparently ceased in the 1970s, NASA has recently reanimated the investigations aiming for an efficient artificial sugar supply on Mars (NASA, 2018). Unnatural monosaccharides such as L-glucose were investigated as a possible zero-calorie sweetener in the food industry or diabetes therapy but the synthesis costs have been estimated to be not competitive to other commercially available sweetener (Vogel and Robina, 2008).

In contrast, no effort has yet been made to investigate an industry-scale production of artificial carbohydrates as direct or intermediate parts of a food supply on Earth. This ignorance was comprehensible because an economical competitiveness of artificial carbohydrates with biogenic food appeared to be absurd in the past. As of today, the commercializations of power-to-food have therefore focussed on partially artificial approaches which aim on the production of higher-priced protein, e.g., by feeding bioreactors with CH₄ (potentially generated by power-to-gas processes) (Cumberlege et al., 2016; Matassa et al., 2016).

This economic narrative has to be reassessed for a future food supply. First of all, because the future imperative of a sustainable food supply will presumably cause a strong increase in the production costs for conventional carbohydrates. In addition, the expected production costs for artificial sugar have been reduced by orders of magnitude in the last decades due to decreasing costs for renewable energy, enhanced electroliser efficiencies, and enhanced CO₂ direct-air-capture (DAC) technology (e.g., Lackner, 2009; Keith et al., 2018).

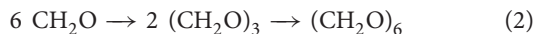
This paper reports a first feasibility study on the transition towards an at least partially artificial production of carbohydrates. The study is oriented along already demonstrated

technologies and its techno-economic characteristics, e.g., efficiencies and costs, are taken from today or the near-future estimates. For the sake of clearness, our analysis focuses on the synthesis of monosaccharides and in particular hexoses. More specific, all quantitative estimates are conducted for glucose, which is the most important hexose in the human metabolism. The last parts of this paper discuss our findings for a broader spectrum of possible synthesis products.

2. THE FORMOSE REACTION

Although there may be several possible routes to synthesize monosaccharides from CO₂ and H₂O, the original and present literature concentrates on the path via formaldehyde (CH₂O) which is known as the formose reaction (Butlerow, 1861; Fischer, 1913; Breslow, 1959; Vogel and Robina, 2008). The formose reaction has raised scientific interest as a possible key step in the origin of life on Earth and several naturally abundant catalysts for the abiotic synthesis of formose products have been investigated (e.g., Lambert et al., 2010; Iqbal and Novalin, 2012; Delidovich et al., 2014; Kitadai and Maruyama, 2018; Pallmann et al., 2018). Formaldehyde can be synthesized from syngas (a mixture of carbon monoxide (CO) and H₂) and syngas can be obtained, for instance, from the co-electrolysis of CO₂ and H₂O.

The optimum synthesis path from CO₂ and H₂O to, e.g., glucose is subject to future research. For this first feasibility study, we exemplify the concept by highlighting that Deng et al. (2013) demonstrated for the formose reaction scheme



an almost perfect carbon yield—that is the fraction of initial carbon atoms which are part of the desired output species—in hexoses (96%) which could be in principle further enhanced to >99%. While their set-up and reaction scheme was designed to yield branch-chained ketohexoses (which they further processed to precursors for hydrocarbons), they unintendedly also synthesized straight-chained ketohexoses such as fructose with carbon yields of about 5% at 273 K and 11% at 303 K. Though not yet demonstrated, we assume in the following that an adjusted thermodynamic and catalytic set-up allows for an almost perfect carbon yield (96%) in straight-chained hexoses. For the rest of this paper, hexose refers to straight-chain hexoses only.

From thermodynamics, the conversion of CO₂(g) and H₂O(l) to hexose



requires at least the differences in the free enthalpies of formation of $\Delta H_{\text{hexose}}^{f,0} \approx \Delta H_{\text{glucose}}^{f,0} = 2.802 \text{ MJ mol}^{-1}$ (under standard conditions and varying between the different hexoses by several parts per thousand, e.g., $\Delta H_{\text{fructose}}^{f,0} = 2.810 \text{ MJ mol}^{-1}$).

The total theoretical energy demand $E_{\text{hexose}}^{\text{theo}}$ is the sum of ΔH_{hexose} plus the energy required to extract the input resources from the environment. The theoretical minimum energy demand to extract CO₂ and H₂O from the local

atmosphere is $E_{\text{CO}_2}^{\text{theo}} = 19.5 \text{ kJ mol}^{-1}$ and $E_{\text{H}_2\text{O}}^{\text{theo}} = 11.5 \text{ kJ mol}^{-1}$ (see **Appendix A** and e.g. Atkins et al., 2018). The energy demand to extract H₂O from the environment is nevertheless typically much lower, e.g., industry-scale sea water desalination requires just $E_{\text{H}_2\text{O}}^{\text{desal}} = 0.2\text{--}0.4 \text{ kJ mol}^{-1}$ (Meindertsma et al., 2010). Thus the energy demand for the water extraction is, at least in humid or coastal regions, negligible compared to the energy demand for the CO₂ extraction. The total energy demand to synthesize a hexose then reads

$$\begin{aligned} E_{\text{hexose}}^{\text{theo}} &= \Delta H_{\text{hexose}}^{f,0} + 6 \cdot E_{\text{CO}_2}^{\text{theo}} + 6 \cdot E_{\text{H}_2\text{O}}^{\text{desal}} \\ &= 2.92 \text{ MJ mol}^{-1} \sim 16.2 \text{ MJ kg}^{-1} = 4.5 \text{ kWh kg}^{-1} \end{aligned} \quad (4)$$

3. TARGETED HEXOSE STEREOISOMER SYNTHESIS

One point to watch in the abiotic synthesis of sugar is the necessity to manufacture a particular stereoisomer, as will be detailed below. (Straight-chained) hexoses can exist in 16 possible aldohexose stereoisomers and 8 possible ketohexose stereoisomers and these 24 isomers can be furthermore grouped in 12 possible pairs of enantiomers distinguished by the prefixes D- and L-. Aldohexoses and ketohexoses differ in their functional group (i.e., containing an aldehyde group or a ketone group). Stereoisomers have the same atomic constitution but different orientations of their atoms in space. Enantiomers have molecular structures which are mirror images of each other and have thus identical chemical and physical properties except for their ability to rotate plane-polarized light in opposite directions, however, their physiological properties can differ. Most life on Earth synthesizes only 6 hexoses (D-glucose, D-fructose, D-mannose, D-galactose, D-tagatose, L-sorbose), another 4 hexoses (D-allose, L-altrose, D-gulose, D-psicose) have been found in some microorganisms, but the remaining 14 hexoses have not been observed in nature. Accordingly, the metabolism of life on Earth has specialized exclusively on the biogenic stereoisomers. In particular, the metabolism can usually—and if at all—digest only one of the two possible enantiomers. Abiotic enantiomers taste identical for humans but can apparently not be digested by humans. Moreover, they may have adverse effects on the human digestion system (e.g., relaxing properties, Raymer et al., 2003) and the long-term effects of a life-long nutrition with significant amounts of unnatural hexose enantiomers on humans have not yet been studied sufficiently (Wang et al., 2017). In fact, presumably only a small fraction of microorganisms can use L-glucose as an energy source at all (Bautista et al., 2000; Shimizu et al., 2012; Fukano et al., 2018).

A mixture of hexoses synthesized via the formose reaction could contain all possible stereoisomers and could be furthermore expected to be a racemic mixture—that is it contains equal amounts in all D- and L-enantiomers. In practice, a high or even exclusive yield in a particularly targeted hexose stereoisomer (or a mixture of several particular stereoisomers) has to be aimed for because a mixture containing non-digestible hexoses may be rejected as a healthy human diet due to physiological concerns. In addition, it has to be assured that

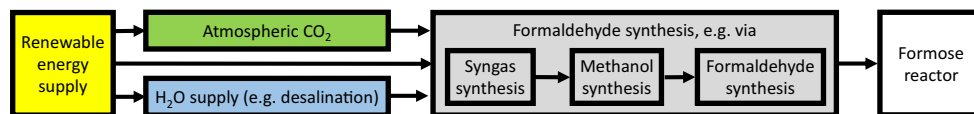


FIGURE 1 | Sketch of the integrated synthesis plant compartments. The only actual input is electric energy and the output are the targeted monosaccharides.

no potentially poisonous substances (e.g., catalysts) are in the final product. However, biogenic carbohydrates are also potentially contaminated with toxic substances (e.g., arsenic in rice). Physiological considerations on the human diet thus need to trade off between systematically avoided and potentially added contaminations.

There are three possible approaches to face this physiological constraint: (1) The most direct approach would be the application of catalysts which yield exclusively the targeted hexose stereoisomer(s). Such catalysts have been reported, e.g., for an enantioselective synthesis of D-glyceraldehyde in the presence of suitable L-amino acids (Breslow and Cheng, 2010), the enzymatic synthesis of three- to six-carbon monosaccharides via engineered D-fructose-6-phosphate aldolase from *Escherichia coli* (Szekrenyi et al., 2015, who prominently mentioned the synthesis of L-glucose), and a high yield of the formose reaction in six- and seven-carbon monosaccharides in the presence of a boronic acid (Michitaka et al., 2017). Although no catalysts have yet been proposed for a synthesis of, e.g., pure D-glucose—due to the lack in research interest?—it appears to be plausible that those can be developed as well.

(2) Alternatively (in absence of or in support for a non-exclusive catalyst), an adjustment of the thermodynamic conditions during the formose reaction as well as a subsequent separation and reprocessing of non-targeted stereoisomers may result in a high yield and high degree of purity in the targeted stereoisomer(s). Numerous methods are available for a subsequent separation of enantiomers, for instance, preferential crystallization (Levilain and Coquerel, 2010; Tassinari et al., 2019), diastereomer crystallization (Kozma et al., 1995), enantioselective liquid-liquid extraction (Schoor et al., 2011), or radiation with circular polarized light (Rukhlenko et al., 2016; Sugahara et al., 2018). The simplest approach of reprocessing non-targeted stereoisomers would be to burn them and thus to recover at the very least the energy demand to extract CO₂ and H₂O from the environment. But also more efficient approaches such as a “cracking” of the non-targeted stereoisomers back to formaldehyde appear to be possible.

(3) Less physiological concerns may be raised when the racemic diet is fed to livestock (for the production of meat, milk, and eggs) or insects and microorganisms (both for the production of biogenic proteins) as there is no plausible mechanism how the unnatural enantiomers could affect the quality of the final food product.

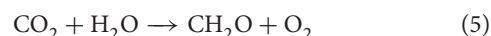
Which approach is ultimately applied is determined by techno-economic considerations.

4. ENERGY DEMAND OF THE ARTIFICIAL SUGAR SYNTHESIS

In this section, we exemplify a possible sugar synthesis plant outline (Figure 1) and estimate the energy conversion efficiency of the artificial sugar synthesis. The estimated key figures of the different process steps are summarized in Table 1. With the CO₂ direct-air-capture (DAC) technology and, e.g., sea water desalination at hand, the only actual input resource of the synthesis plant is electric energy. We exclude for the sake of universality the actual realization of the energy supply from our techno-economic investigation and consider that the energy is provided externally from a base-load source. Of course, an ecologically sustainable sugar synthesis would rely on renewable energy (e.g., a mixture of solar power, wind power, and hydroelectric power combined with an energy storage in order to provide a base-load supply). The actual technology enters our comparison via the electricity costs exclusively. For a subsequent comparison of the biogenic and artificial sugar production, we assume an energy supply by solar panels with a solar-to-power efficiency of $\eta_{STP} = 20\%$.

Today, the required CO₂ can be extracted directly with $E_{CO_2}^{coal} < 50 \text{ kJ mol}^{-1}$ from the exhaust flux of coal-fired power plants or other industrial CO₂ sources (Lackner, 2009; He and Hägg, 2014). In order to reach the goal of a carbon neutral industry by the mid of this century, the required CO₂ has then to be extracted instead from the ambient air by DAC. While the minimum thermodynamic energy demand is $E_{CO_2}^{theo} = 19.5 \text{ kJ mol}^{-1}$ (see Appendix A), the minimum practically required energy demand for DAC has been estimated to be $E_{CO_2}^{Lackner} = 50 \text{ kJ mol}^{-1}$ (Lackner, 2009). At present, the practically required energy demand for DAC, although it has been drastically reduced within the last decade, is still around 300 kJ mol^{-1} , e.g., Keith et al. (2018) reported for a pilot plant $E_{CO_2}^{Keith} = 243 \text{ kJ mol}^{-1}$, of which 231 kJ mol^{-1} are thermal energy input. Nevertheless, further drastic efficiency enhancements can be expected in the future of this just emerging technology.

The synthesis of formaldehyde ($\Delta H^{f,0} = 570.1 \text{ kJ mol}^{-1}$)

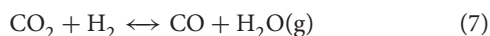
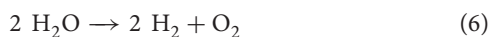


has a theoretical thermal efficiency of 84%. The mature industry-scale formaldehyde synthesis starts with the preparation of syngas ($m \text{ CO} + n \text{ H}_2$), e.g., via first water electrolysis (Equation 6, $\Delta H^{f,0} = 571.6 \text{ kJ mol}^{-1}$) and a subsequent reduction of CO₂ via the water-gas shift reaction (Equation 7, $\Delta H^{f,0} = 41.2 \text{ kJ mol}^{-1}$)

TABLE 1 | Process steps of the total synthesis of hexose from solar power.

Process step <i>i</i>	Reaction	ΔE^{theo}	ΔE^{prac}	η	γ	References
		$\text{kJ mol}^{-1}_{\text{hexose}}$				
<i>Gather input resources from the environment</i>						
1) Commercial solar panel	solar irradiation → electric energy			20%		Example value for η_{SIP}
2) Direct-Air-Capture	$\text{CO}_2(\text{air}) \rightarrow \text{CO}_2(\text{g})$	117	1458	8%		Keith et al., 2018
3) Water Desalination	sea water → $\text{H}_2\text{O}(\text{l})$	0.05	2.4	13%		Meindertsma et al., 2010
<i>Conversion of input resources</i>						
4) To Syngas	$\text{CO}_2 + 2 \text{H}_2\text{O}(\text{l}) \rightarrow \text{CO} + 2 \text{H}_2 + \frac{3}{2} \text{O}_2$	5127.6	5761.3	89%	100%	Omojola, 2015
5) To Methanol	$\text{CO} + 2 \text{H}_2 \rightarrow \text{CH}_3\text{OH}(\text{l})$	-768.6	0	85%	>99%	Spath and Dayton, 2003
6) To Formaldehyde	$\text{CH}_3\text{OH}(\text{l}) + \frac{1}{2} \text{O}_2 \rightarrow \text{CH}_2\text{O} + \text{H}_2\text{O}(\text{l})$	-938.4	1755.2	66%	91%	Bahmanpour et al., 2014
<i>formaldehyde subtotal</i>	$\text{CO}_2 + \text{H}_2\text{O}(\text{l}) \rightarrow \text{CH}_2\text{O} + \text{O}_2$	3420.6	7516.5	50%	91%	
7) To Hexose	$6 \text{CH}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6$	-615.8	313.2	83%	96%	Deng et al., 2013
<i>Chemistry total</i>	$6 \text{CO}_2 + 6 \text{H}_2\text{O}(\text{l}) \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2$	2804.8	7863.2	41%	87%	$\Delta E = \Delta H_{\text{glucose}}^{\text{f},0}$
<i>Power-to-food</i>	Electric energy → $\text{C}_6\text{H}_{12}\text{O}_6(\text{s})$	2921.9	9323.6	31%		
<i>Solar-to-food</i>	Solar irradiation → $\text{C}_6\text{H}_{12}\text{O}_6(\text{s})$			6%		for $\eta_{\text{SIP}} = 20\%$

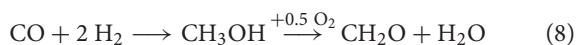
ΔE^{theo} give the theoretical energy demands of the process steps. ΔE^{prac} give the practically achieved energy demands of the process steps subject to non-perfect energy conversion efficiencies η and carbon yields γ . For the formose reaction, the energy conversion efficiency give the theoretical thermal efficiencies rather than technically demonstrated efficiencies. The step number corresponds to the indices *i* which are used in the mathematical notation in the text.



where the second process becomes exothermal at temperatures larger than 1100 K. This two-step process is well-established when using low-temperature electrolysis what comes, however, with the drawback of an overall energy conversion efficiency of just 40–80% (Thema et al., 2019).

In contrast, high-temperature co-electrolysis allows for the simultaneous synthesis of syngas from CO_2 and H_2O with an efficiency of 89% (Graves et al., 2011; Omojola, 2015; Zheng et al., 2017). Although high-temperature electrolisers are considered to be not yet economically competitive due to short electroliser lifetimes, their lifetime and therefore costs are expected to enhance in the near future (Schmidt et al., 2017). For instance, the German company Sunfire demonstrated a co-electroliser with an 82%-efficiency and a lifetime of >500 h (Sunfire, 2019a,b). We assume in the following that the technologically proven 89%-efficiency and the cost estimates for 2030 reported by Schmidt et al. (2017) as plausible key figures for the long-term performance of industry-scale high-temperature co-electrolysis.

The subsequent formaldehyde synthesis is industrially realized via the intermediate step of the methanol synthesis



with an energy efficiency of 56% and carbon yield of 91% (Spath and Dayton, 2003; Bahmanpour et al., 2014). The total energy efficiency of this quasi-mature formaldehyde synthesis scheme is then 50% and its carbon yield is 91%.

A direct one-step implementation of Equation (5) would omit energy-consuming intermediate steps and thus yield high energy conversion efficiencies. Research interest in such direct approaches has been reanimated recently (Bahmanpour

et al., 2015; Heim et al., 2017). In particular, Nakata et al. (2014) demonstrated on a lab-scale energy efficiencies of up to $\eta_{\text{CO}_2 \rightarrow \text{CH}_2\text{O}}^{\text{Nakata}} = 74\%$ for the synthesis of formaldehyde from a mixture of CO_2 and sea water.

Ultimately, we do not choose a particular reaction scheme for the synthesis of hexoses from formaldehyde but assume an energy conversion efficiency which equals the theoretical thermal efficiency of 83% and a carbon yield of 96% (see above).

The total energy demand for the hexose synthesis reads

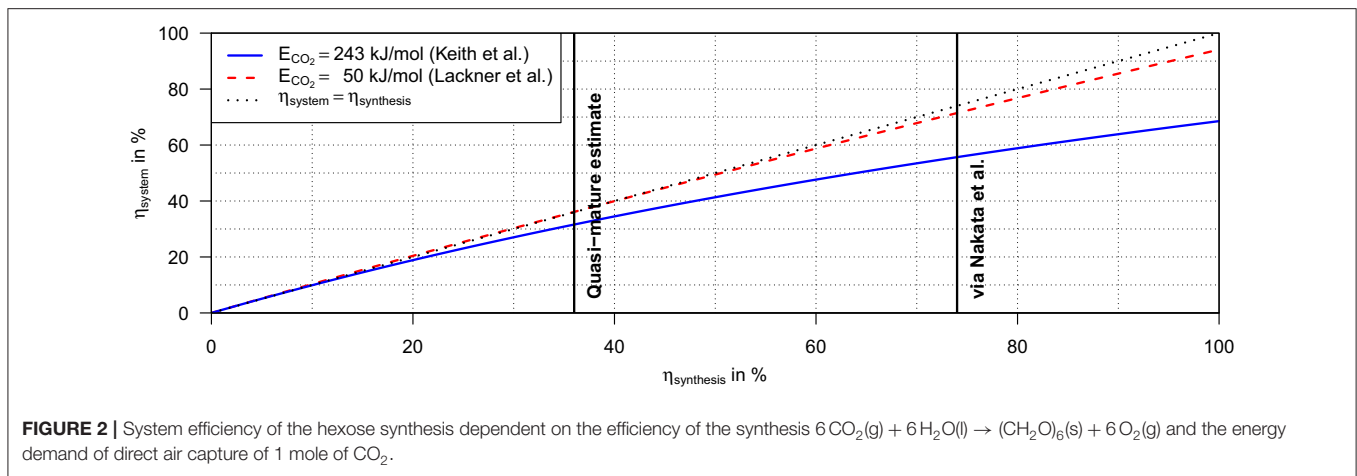
$$E_{\text{hexose}}^{\text{synthesis}} = \frac{\Delta H_{\text{hexose}}^{\text{f},0}}{\eta_{\text{synthesis}}} + 6 \cdot E_{\text{CO}_2} + 6 \cdot E_{\text{H}_2\text{O}} \quad (9)$$

with the total efficiency $\eta_{\text{synthesis}} = \prod_{i=4-7} \gamma_i \cdot \eta_i$ of the chemical synthesis (see process steps *i* in **Table 1**). The total system efficiency (where the energy demand for the water supply is neglected in the second line)

$$\eta_{\text{system}} = E_{\text{hexose}}^{\text{theo}} / E_{\text{hexose}}^{\text{synthesis}} \quad (10)$$

$$= \eta_{\text{synthesis}} \cdot \left[1 + \underbrace{\frac{6 \cdot (E_{\text{CO}_2} \cdot \eta_{\text{synthesis}} - E_{\text{CO}_2}^{\text{theo}})}{E_{\text{hexose}}^{\text{theo}}}}_{\sim 0.0-0.3} \right]^{-1}$$

is in first approximation linear in $\eta_{\text{synthesis}}$ and only weakly dependent on the energy demand for the CO_2 extraction. Applying the parameters from **Table 1**, we obtain $\eta_{\text{synthesis}} = 36\%$ and $\eta_{\text{system}} = 31\%$ for the quasi-mature technology. An upper limit for the system efficiency can be estimated by applying instead $E_{\text{CO}_2}^{\text{Lackner}} = 50 \text{ kJ mol}^{-1}$ and the reaction scheme demonstrated by Nakata et al. (2014) with $\eta_{\text{CO}_2 \rightarrow \text{CH}_2\text{O}}^{\text{Nakata}} = 74\%$ and assuming an addition perfect carbon yield of $\gamma_{\text{CO}_2 \rightarrow \text{CH}_2\text{O}}^{\text{Nakata}} = 100\%$; corresponding to $\eta_{\text{system}} = 73\%$ (**Figure 2**).



Accordingly, the power-to-food efficiency of the hexose synthesis range between $\eta_{\text{system}} = 31\text{--}73\%$. Assuming an electricity supply by solar panels with a solar-to-power efficiency of $\eta_{\text{StP}} = 20\%$, the total solar-to-food efficiency of the hexose synthesis would be $\eta_{\text{StF}} = \eta_{\text{StP}} \cdot \eta_{\text{system}} = 6\text{--}15\%$.

5. PRODUCTION COSTS OF ARTIFICIAL HEXOSES

In this section, we estimate the production costs to produce artificial hexoses. The only actual input resource consumed by the hexose synthesis plant is electric energy (the cost of CO_2 and H_2O is also expressed in terms of energy consumption, as explained above). Accordingly, the production cost C_{hexose} of artificial hexoses can be separated as

$$C_{\text{hexose}}[\text{€/G}] = \frac{C_{\text{el}}[\text{€/G}]}{\eta_{\text{system}}} + C_0[\text{€/G}] \quad (11)$$

with the electricity price C_{el} and the overall “fixed” non-material costs C_0 , that is the operation and maintenance costs and the levelized capital costs. The energy content of hexose is 4.5 MWh/t so Equation (11) reads in more handy units

$$C_{\text{hexose}}[\text{€/t}_{\text{hexose}}] = \frac{4.5 \cdot C_{\text{el}}[\text{€/MWh}]}{\eta_{\text{system}}} + C_0[\text{€/t}_{\text{hexose}}] \quad (12)$$

The fixed costs C_0 predominantly sum up the non-material costs of the CO_2 -DAC device, the electrolyser, the formaldehyde synthesis reactor, and the formose reactor and assuming a continuous full-load operation (Table 2). It is not the aim of this paper to give a detailed cost calculation but rather to find a rough estimate for the fixed costs. For the following estimates, the non-perfect carbon yields of the subsequent processes have been taken into account, that is the estimates contain already a multiplicative over-production correction factor of $\frac{1}{0.87}$ for the CO_2 -DAC device and the electrolyser and of $\frac{1}{0.96}$ for the formaldehyde reactor. Furthermore, a conversion factor of $1 \text{ €} = 1.12 \text{ US\$}$ is applied.

(1) The non-material costs for the CO_2 -DAC device are $C_0^{\text{DAC}} = 74 \text{ US\$}/\text{t}_{\text{CO}_2} = 110 \text{ €/t}_{\text{hexose}}$ for the device realized by Keith et al. (2018).

(2) The costs for high-temperature co-electrolysers have been estimated for 2030 as $C_0^{\text{electrolysis}} = 7\text{--}83 \text{ €/MWh}_{\text{el}} = 36\text{--}430 \text{ €/t}_{\text{hexose}}$ (retrieved from Schmidt et al., 2017, and assuming $\frac{\text{€}}{\text{MWh}} = \frac{\text{€}}{\text{MW}} \cdot \frac{1}{\text{lifetime}}$). For the following calculations we assume the lower estimate by Schmidt et al. (2017). For comparison, Graves et al. (2011) estimated costs for their integrated fuel synthesis facility corresponding to $C_0^{\text{DAC}} < 1 \text{ US\$}/\text{GJ}_{\text{fuel}}$ corresponding to $< 17 \text{ €/t}_{\text{hexose}}$ and $C_0^{\text{electrolysis}} = 1\text{--}4 \text{ US\$}/\text{GJ}_{\text{fuel}}$ corresponding to $17\text{--}67 \text{ €/t}_{\text{hexose}}$.

(3) The costs for the industrial facilities for the formaldehyde reactor and the formose reactor could be estimated from the reported non-material costs of the two-steps production scheme *natural gas* \rightarrow *syngas* \rightarrow *methanol* of about $C_0^{\text{mature}} = 50 \text{ €/t}_{\text{CH}_3\text{OH}} = 2.2 \text{ €/GJ}_{\text{CH}_3\text{OH}}$ (Boulamanti and Moya, 2017). When we assume that C_0^{mature} is also a good estimate for the two-steps reaction scheme *syngas* \rightarrow *methanol* \rightarrow *formaldehyde*, the non-material costs of the formaldehyde reactor would be $C_0^{\text{formaldehyde}} = 38 \text{ €/t}_{\text{hexose}}$. As an intermediate results, our estimates indicate production costs of synthetic formaldehyde of $C_{\text{CH}_2\text{O}}^{\text{synthetic}} = 765 \text{ €/t}_{\text{CH}_2\text{O}}$ when assuming electricity costs of $C_{\text{el}} = 50 \text{ €/MWh}$. For comparison, the production costs of methanol from fossil methane are about $C_{\text{CH}_3\text{OH}} = 350 \text{ €/t}_{\text{CH}_3\text{OH}}$ (Bahmanpour et al., 2014) subject to a market price for fossil methane of roughly $C_{\text{CH}_4} = 16 \text{ €/MWh}$. Though the industrial conversion of methanol to formaldehyde adds further costs, it can be expected that the total production costs of “fossil” formaldehyde is significantly below our estimates for the costs of artificial formaldehyde. This comparison indicates that our estimates for the production costs of synthetic formaldehyde appears to be in a realistic range—and potentially the cheapest way to produce formaldehyde in a carbon-neutral future.

(4) The cost for the formose reactor can be separated into the facility costs for the synthesis of any hexose (or rather a mixture of hexoses) from formaldehyde and the additional costs

TABLE 2 | Fixed non-material costs of the required plant facilities and applying a conversion factor of 1 € = 1.12 US\$.

Plant facility component	Costs [€/t _{glucose}]	References and comments
1) CO ₂ Direct-Air-Capture device	110	Keith et al., 2018
2) High-temperature co-electroliser	36	Schmidt et al., 2017, lower estimate for 2030
3) Formaldehyde reactor	38	adopted from Boulamanti and Moya, 2017
4) Formose reactor	≤ 35	$\gamma_{\text{CH}_2\text{O}} \cdot C_0^{\text{formaldehyde}}$, see text
5) Targeted stereoisomer production	$C_{\text{target}}^{\text{glucose}} = ?$	see text
<i>total</i>	$C_0^{\text{glucose}} = 219 + C_{\text{target}}^{\text{glucose}}$	

for the targeted production of a particular hexose stereoisomer. Concerning the facility costs, the formose reactor design reported by Deng et al. (2013) appears to be at most as complicated as the formaldehyde synthesis reactor chain. Accordingly, we assume that the production of hexoses from formaldehyde may be (per carbon atom) at most as expensive as the production of formaldehyde from syngas. That is, we assume $C_0^{\text{formose}} \leq \gamma_{\text{CH}_2\text{O}} \cdot C_0^{\text{formaldehyde}} = 35 \text{ €/t}_{\text{hexose}}$.

(5) Concerning the targeted production technology, a cost estimate appears to be speculative. For instance, the production costs of glucose (referring to D-glucose) would read

$$C_{\text{glucose}} = C_{\text{hexose}} + C_{\text{target}}^{\text{glucose}} \quad (13)$$

For the sake of the argument, we assume in the following that appropriate and sufficiently cheap catalysts will be available in the mid-term future. That is, we tacitly neglect $C_{\text{target}}^{\text{glucose}}$ in the following economic comparison but highlighted this major source of uncertainty in **Table 2** and in the conclusions.

The artificial hexose synthesis does not cause significant externalities and thus its production costs represent also its total costs. For the range $\eta_{\text{system}} = 31\text{--}73\%$ in the system efficiency of the hexose synthesis plant estimated above, the total costs for artificial hexose (but exclusively the additive costs of the targeted stereoisomer production) would be about 0.5–1.0 €/kg or 0.8–1.6 €/kg for electricity costs of 50 or 100 €/MWh, respectively (**Figure 3**).

Another approach to arrive at an estimate of the production cost for artificial sugar would be to judge from present market prices for artificial sugars which are, e.g., 31 US\$/g for 25 g L-glucose and 350 US\$/g for 2 g L-fructose (prices taken from www.carbosynth.com). These prices most likely primarily reflect the salary for hand-crafted goods. For instance, a discount rate of roughly 10% for any doubling in purchased mass is effectively offered—indicating the drastically increasing returns to scale of the artificial sugar production. An industry-scale automatization of the sugar synthesis thus may plausibly reduce the production costs by the four to five orders of magnitude which would be required for economical competitiveness. In fact, all processes of the proposed synthesis plant outline appear to be automatable and thus relatively inexpensive compared to the electricity costs.

6. TOTAL COSTS OF THE CONVENTIONAL SUGAR PRODUCTION

The average spot market price for conventional white sugar was 0.32 €/kg in 2018 (OECD and FAO, 2018) subject to a volatility span since 2015 between 0.22–0.52 €/kg (data from NASDAQ). The spot market price is a distorted proxy for the actual production costs and consumer prices due to politically motivated subsidies and market restrictions. As of today, the minimum achieved production costs for sugar are 0.29 €/kg based on corn milling, 0.19 €/kg based on sugar beet, and 0.41 €/kg based on sugar cane (Cheng et al., 2019). The minimum consumer price for sugar lies in Germany (exclusively the value-added tax of 7%) at around 0.55 €/kg for non-organic sugar and 2.4 €/kg for organic sugar (organic refers in the following to “organic farming”). This figure includes additive costs for transportation, retail, and marketing of about $C_{\text{retail}} = 0.23 \text{ €/kg}$ which are plausibly independent from the actual way of production (non-organic, organic, artificial) and an additive premium of 1.85 €/kg for the production and marketing in the case of organic sugar.

An estimate of the total costs of the conventional sugar production needs to add all externalities. In the following, we estimate the additional contributions to the sugar price from a series of externalities (**Table 3**). The most obvious ecological externalities are the water demand, the consequences of a non-organic agriculture, the CO₂ emissions, and the demand in land area.

1) The conventional production of 1 kg sugar requires 900_{-500}^{+1000} kg water for sugar beets and 1500_{-700}^{+1200} kg water for sugar cane (weighted global averages and the span of national extremes, Gerbens-Leenes and Hoekstra, 2009). In semi-arid regions such as the Western United States, the Middle East, or Northern India, the demand in additional groundwater for irrigation is on the order of 1,000 kg water per 1 kg sugar and even the most efficient semi-arid production (Spain) requires still 500 kg groundwater. These extreme amounts of water are today usually provided by an unsustainable extraction of ancient groundwater (Aeschbach-Hertig and Gleeson, 2012; Wada, 2016; Grogan et al., 2017), thus future agriculture can there only be maintained either by long-distance transport of fresh water from humid regions or by sea water desalination. The costs of sea water desalination are today as low as 1 €/t_{fresh water} when assuming electricity costs of 50 €/MWh from renewable

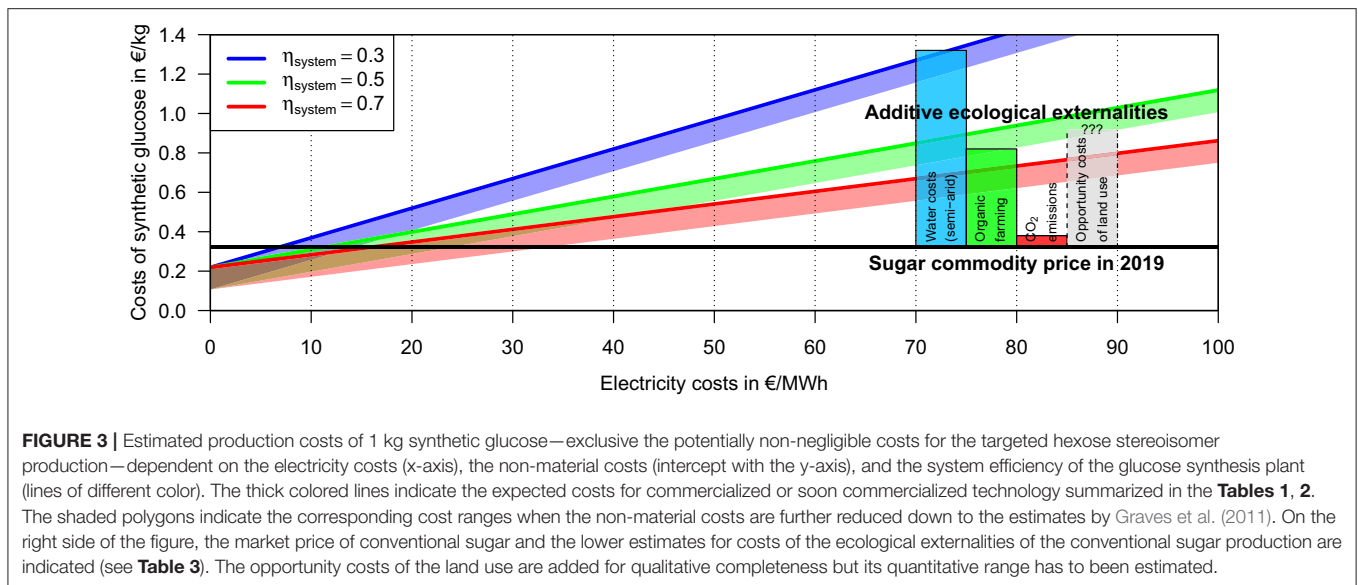


FIGURE 3 | Estimated production costs of 1 kg synthetic glucose—exclusive the potentially non-negligible costs for the targeted hexose stereoisomer production—dependent on the electricity costs (x-axis), the non-material costs (intercept with the y-axis), and the system efficiency of the glucose synthesis plant (lines of different color). The thick colored lines indicate the expected costs for commercialized or soon commercialized technology summarized in the **Tables 1, 2**. The shaded polygons indicate the corresponding cost ranges when the non-material costs are further reduced down to the estimates by Graves et al. (2011). On the right side of the figure, the market price of conventional sugar and the lower estimates for costs of the ecological externalities of the conventional sugar production are indicated (see **Table 3**). The opportunity costs of the land use are added for qualitative completeness but its quantitative range has to be estimated.

TABLE 3 | Externalities of the conventional sugar production.

Potential externality	Costs [€/t _{sugar}]	References and comments
<i>ecological</i>		
Unsustainable water supply	1,000	for semi-arid conditions, ≥ 20 € for humid conditions, see text
Consequences of non-organic farming	500	additive costs for organic farming, Degner, 2016; Südzucker, 2019
CO ₂ emissions	60	assuming a CO ₂ tax of 150 €/t _{CO₂} , see text
Occupation of valuable land	?	alternative use: nature reservation, other agricultural activities, ...
<i>socio-economic</i>		
Insecure food supply	?	lower starvation rates caused by natural fluctuation in the food supply
National food dependency	?	impact of external shocks on the domestic food supply
Fair trade premium	50	Fairtrade International (2019) contracts with +0.06 US\$/kg.
Rationalization of work force	?	less workers required in farming and processing
Value of non-sugar biomass	< 0	e.g., for bio power plants

energies (Advisian, 2019). Assuming that the water costs have not yet contributed significantly to the market price for sugar, the production costs of sugar would increase by 0.5–1 €/kg_{sugar} in semi-arid regions when the water costs are internalized.

In humid regions, the larger part of the water demand is supplied for free by precipitation, however, even the most efficient regions require at least 200 kg additional groundwater (or surface water) per 1 kg sugar for irrigation and subsequent processing. These still immense amounts of water are extracted usually for free, following the economical assumption that precipitation replenishes the extracted groundwater in a sustainable way. For instance, the common groundwater extraction fees are in Germany 0.05–0.12 €/t_{groundwater} ~ 0.02 €/kg_{glucose} (variation between German states excluding the city states, BUND, 2019). The German agriculture is even freed to pay these fees at all. The recent dry summers of 2018 and 2019 in Germany and Europe in general have, however, suggest that this practice may need to be changed. While today an internalization of the water costs would only negligibly increase the costs of sugar from humid regions, the climate change may

impose that the water extraction costs will rise also there to significant numbers and first political initiatives aim to stop the above mentioned water subsidy for the German agriculture (Government of Mecklenburg-Vorpommern, 2018).

2) The low production costs of conventional sugar are achieved also by the increase in per-area yield due to the massive use of fertilizer, pesticides, and herbicides. The accompanying ecological externalities such as groundwater pollution and the loss in biodiversity are severe (see above) and thus a drastic reduction of the non-organic production appears to be mandatory in near future. In consequence, only organic sugar should be supplied. The production costs of non-organic sugar beets in Germany has been estimated as 25–28 €/t_{beet} corresponding to 0.16–0.18 €/kg_{sugar} (Degner, 2016) and reported contract prices between beet farmers and the sugar industry have been in this range as well. In contrast to that, organic sugar beets have been contracted in Germany for the season 2019 for 105–115 €/t_{beet} (Südzucker, 2019). Assuming a mass yield of extracted sugar per beet of about 16% (Bundesinformationszentrum Landwirtschaft, 2018), this

indicates additive farming costs of about 0.5 €/kg_{sugar} for organic farming, at least in Germany. Remarkably, these additional farming costs are much lower than the additional consumer costs of 1.85 €/kg (see above) indicating that the marketing of organic sugar causes yet large costs due to, e.g., the smaller market volume.

3) The processing of sugar beets requires at the most efficient processing facilities about 1.3–1.5 kWh/kg_{sugar} causing CO₂ emission of 0.3–0.4 kg_{CO₂}/kg_{sugar} (German electric energy mix) but higher numbers for older facilities with larger emissions exist (Nordzucker, 2018a,b). The energy demand of farming is in Europe on average 0.13 tons of oil equivalent per hectare utilized agricultural area (that is about 0.13 kWh/kg_{sugar}, see next section) adding roughly another 0.05 kg_{CO₂}/kg_{sugar} (Eurostat, 2019). The removal of CO₂ from the atmosphere may currently cost at the very least 0.15 €/kg_{CO₂} (combined CO₂-DAC plus CO₂ storage costs). On the one hand, such a fully-compensating CO₂ tax add costs of 0.06 €/kg_{sugar} to the conventional sugar costs. On the other hand, the above assumption of renewable electricity costs of 50 €/MWh would imply for consistence that the conventional sugar production would also operate then carbon-free and with similar electricity costs as today.

4) Sugar beet plantation occupy about 1% of the area of Germany and starch-supplying crop (e.g., cereals, potatoes, maize) plantation occupy about 18% (Bundesinformationszentrum Landwirtschaft, 2017). An artificial carbohydrate production would free (at least parts of) these areas for other uses such as enhanced local recreation areas and nature reservation, which would allow a recovery of the local biodiversity, or a more generous area supply for the agricultural production of vegetables, fruits, or livestock cultivation.

In summary, the lower limit of the total costs of conventional sugar can be estimated at about 1 €/kg for humid regions and about 2 €/kg for semi-arid regions when including just the external costs of the water demand and the environmental pollution. The (difficult to estimate) opportunity costs of its land demand further increase the total costs. In addition, the conventional sugar production causes several socio-economic externalities:

- (1) Droughts and diseases can temporarily reduce the global carbohydrate supply possibly causing food commodity speculations. This temporary economical pressure can be severe to poor people in low-income countries. The yield of an artificial sugar production would be highly reliable and the installed capacities can be appropriately adopted to long-term changes in the food demand.
- (2) A reliable food supply for its population is a primary geopolitical goal of any nation. Many nations therefore support their domestic agriculture with unconditional subsidies and additional drought compensations rather than relying on potentially cheaper imports. An artificial sugar production would largely avoid these dependencies and subsidies.
- (3) Bad working conditions and poor pay for the employees probably also contribute to the low production costs of conventional sugar in developing countries. As quantitative

illustration, Fairtrade International has established a fair trade premium of 0.06 US\$/kg_{sugar} for conventional farming and 0.08 US\$/kg_{sugar} for organic farming (Fairtrade International, 2019).

- (4) A fully automatized sugar production would not further require the agricultural work force. From an economic point of view, this exclusion of the production factor work would be another positive effect of the transition towards an artificial carbohydrate supply, however, from a social point of view it could be seen as thread for enhanced unemployment rates.
- (5) It has to be mentioned that the conventional sugar production leads also to additional, non-sugar biomass which has a real economical value. This positive (but relatively small) externality has to be subtracted from the total production costs.

7. COMPARISON OF BIOGENIC AND ARTIFICIAL SUGAR PRODUCTION

After we listed a large set of the negative externalities of the conventional agriculture, we want to focus on the comparison of the conventional and artificial sugar production on the three central ecological differences and its contributions to their economic competitiveness: (1) the demand in water, (2) the environmental pollution caused by non-organic farming (that is by the massive use of fertilizers, pesticides, and herbicides), and (3) the demand in (fertile) land area.

We compare the above derived figures for synthetic hexose (e.g., glucose or fructose) on the one hand and biogenic sucrose (a disaccharide which is composed of glucose and fructose) on the other hand. A comparison of one particular sugar species implies additional transformation costs (from synthetic monosaccharides to disaccharides or from biogenic sucrose to monosaccharides). Whether these costs have to be added to the synthetic or to the biogenic production costs depends on the subsequent food processing steps. Furthermore, all those sugars have basically the same physiological properties and are therefore used (within given limitations) as interchangeable substitutes in processed food products. For these two reasons, we here neglect the transformation costs for simplicity and treat those monosaccharides and disaccharides as the same macronutrient in the following economical comparison.

The very first knock-out criterion whether biogenic agriculture is competitive lies in the energetic and financial costs for the water supply. This criterion impeded the establishment of a significant agriculture in arid regions but may also frustrate the competitiveness of agriculture in semi-arid regions once the unsustainable extraction of groundwater becomes physically or politically impossible. Depending on sea water desalination as a water supply would at least quadruple the sugar production costs to more than 1.4 €/kg. In consequence, sugar production in semi-arid regions would obviously not be competitive to the conventional production in humid regions or an artificial sugar production. In humid regions, the water externality is typically not yet a major cost contribution. Brazil as the world's largest

sugar producer, however, faces water scarcity in some of the plantation regions (Bordonal et al., 2018) and increasing water costs there could have massive effects on the world sugar price. In summary, a future decline in the sugar production in semi-arid or otherwise water-scarce regions can be expected.

An undisputable advantage of an artificial sugar production is that it can be applied virtually anywhere. Particularly beneficial conditions appear to be—of all things—at the coastal regions of low-latitude deserts such as the Sahara. Effective energy costs are there expected to be extremely low because of (1) direct production costs of solar power by photovoltaic or solar thermal collector of less than 50 €/MWh, (2) basically no requirement of an energy storage besides the day–night contrast, (3) the coastal locations allow for a sustainable and relatively cheap water supply by desalination, (4) and the land required for the solar plants and synthesis facilities is typically cheap there because its ecological value and economical opportunity costs are typically low.

Second, while the artificial sugar production does not cause any environmental pollution, the imperative of a transition towards organic farming implies sugar production costs of above 0.8 €/kg (as illustrated at least in Germany). This is about the estimated costs for artificial sugar at electricity costs of 50 €/MWh, thus artificial sugar is already competitive to conventional sugar from humid regions even without considering the further externalities discussed above.

Third, these intermediate findings that conventional but organic sugar from humid regions may still be cheaper than artificial sugar does hold only for the today's balance in demand and supply. On the one hand, the above projections of a decline in the suitable land area for conventional agriculture as well as a potential reduction in the per-area yield due to a transition from non-organic to organic farming imply a reduction of the supply. On the other hand, the expected global population growth will cause an increase in the global sugar demand. Without an artificial sugar supply, this discrepancy would either result in an increase of the sugar price on the world market because the conventional sugar industry would nevertheless have to expand towards less fertile and therefore more expensive lands or in enhanced agricultural land use in humid regions.

The first scenario of an increasing world market price could imply that the production costs of artificial sugar may break-even with the rising world market price even if artificial production is less economical than the conventional sugar production in high-yield regions. The second scenario of an enhanced agricultural activity in humid regions is in concurrence with other land uses. Considering the severe loss in biodiversity in particular in humid regions, it appears possible that future environmental policy prohibits not only such an expansion but even demands a reduction of the agricultural land also in humid regions in favor for natural reservations. In fact, large land areas could be freed by the introduction of an artificial carbohydrate production as can be illustrated by the minimum area which is required to supply the average calorie intake for one adult human by biogenic or artificial calories, which we call in the following a human's "calorie-footprint" (CF). As above, we assume again an average calorie intake of $12 \text{ MJ d}^{-1} = 4.4 \text{ GJ a}^{-1}$ for an adult human.

We illustrate the CF for the conditions in Germany: The average solar irradiation which reaches the Earth surface is about $95 \text{ W m}^{-2} = 3.0 \text{ GJ m}^{-2} \text{ a}^{-1}$ in Germany (Wild et al., 2013). Accordingly, a perfect solar-to-food conversion would imply a theoretical calorie-footprint of $\text{CF}_{\text{Germany}}^{\text{theoretical}} = 1.5 \text{ m}^2$. We estimated above a solar-to-food efficiency of $\eta_{\text{StG}} = 6\text{--}15\%$ for the artificial sugar production which implies a calorie-footprint of $\text{CF}_{\text{Germany}}^{\text{artificial}} = 10\text{--}25 \text{ m}^2$. In contrast, crop plants are only able to convert several tenth of a percent of the incoming solar irradiation to carbohydrates. For instance, the maximum possible sugar yield from sugar beets in Germany is estimated as $2.4 \text{ kg m}^{-2} \text{ a}^{-1}$ when assuming optimum growth conditions (Hoffmann and Kenter, 2018); corresponding to a solar-to-sugar conversion efficiency of 1.4%. The practically achieved sucrose yield is lower, e.g., in Germany the average sucrose yield from sugar beets is $1.1\text{--}1.3 \text{ kg m}^{-2} \text{ a}^{-1}$ (Zuckerverbände Deutschland, 2019). Accordingly, sugar beets yield $18\text{--}21 \text{ MJ m}^{-2}$ which corresponds to a solar-to-food conversion efficiency of about 0.7% and $\text{CF}_{\text{Germany}}^{\text{conventional}} = 213 \text{ m}^2$.

On a global average, the calorie-footprint is lower for artificial sugar $\text{CF}_{\text{global}}^{\text{synthetic}} = 5\text{--}13 \text{ m}^2$ but orders of magnitude higher for biogenic sugar because of the in average much less fertile land when compared to Germany. Accordingly, while the conventional agriculture may fail in the long-term to provide enough food for the current 8 billion humans, covering the one third of the Earth's land area which is currently use for agriculture with solar panels and assuming a solar-to-food efficiency of 15% for artificial sugar would provide (in form of pure sugar) the total calorie demand of 10 trillion humans or about 1,250 times the present world population.

8. BEYOND MONOSACCHARIDES

The replacement of conventional sugar in our food supply by artificial monosaccharides would have already direct positive impacts on the sustainability of our food supply as shown above. The biogenic sugar production, however, contributes only several percent to the ecological externalities of our food supply while the production of polysaccharides such as starch (amylose, amylopectin) contributing the largest part (e.g., as mentioned above, 18% of the territory of Germany are occupied by plantations of starch-supplying crops while only 1% of its territory is occupied by sugar beet plantations). Accordingly, a much more important implication of an artificial monosaccharide production would be to provide a foundation for a more sustainable production of polysaccharides. Such a subsequent, synthetic production of polysaccharides could be achieved via a polymerization of synthetic monosaccharides. A crucial advance in this direction would focus on the synthesis of starch. Another advance could be the synthesis of cellulose, e.g., in order to supply sustainable feedstock for livestock breeding or the paper industry. We note that (essentially pure) starch (from agricultural production) in the form of flour has been the main ingredient of many types of food like bread, pasta, or beer. Many other products of the modern food industry also contain starch

as basic ingredient. A techno-economic investigation of those possible subsequent food production steps is beyond the scope of this paper.

Another advance beyond the scope of this paper would be an at least partially artificial production of fats, proteins, and other nutrients. Digestible fats could be as well entirely synthetically produced from atmospheric CO₂ and water via a combination of glycerol ((CH₂O)₃H₂) synthesized, e.g., by the formose reaction and fatty acids synthesized, e.g., by the Fischer–Tropsch process. We note that fat synthesis may allow for a targeted production of healthy or else desired fats. Furthermore, synthesized products could be supplied as sustainable feedstock for biogenic agriculture of microorganisms, fungi, insects, and livestock in order to significantly reducing the environmental externalities of their associated biogenic products.

We here want to highlight again the underlying rationale that artificial and biogenic macronutrients are chemically identical. Thus, processed food such as bread, pasta, mashed potatoes etc. can be in principle produced with the same properties such as appearance, taste, and smell when the biogenic macronutrients are substituted by their artificial complements. Because a good fraction of the human macronutrients uptake is nowadays already supplied by processed food, a large part of the ecological externalities currently caused by the biogenic production of, e.g., cereals, rice, potatoes, and fat- and protein-supplying plants could in fact be avoided by using synthetic ingredients.

An estimation of the production costs of synthetic starch appears to be premature, but there are good reasons to be convinced that also for starch a synthetic production could be economically competitive with biogenic production: On the one hand, the production costs of synthetic starch will be most likely above the costs for synthetic monosaccharides estimated in this manuscript due to the additional costs for the monosaccharide polymerization, but these additional costs may be of the order of the costs of the formose reactor (+0.04 €/kg_{starch}) and thus negligible in comparison to the other costs factors. On the other hand, the production costs of biogenic starch are usually lower than for biogenic sugar but not much. For example, the production costs of conventional wheat flour are in first approximation given by the spot market price for conventional wheat, which was on average 0.22 €/kg_{wheat} in 2016–2018 (OECD and FAO, 2018), plus the grinding costs. Accordingly, the conventional production costs of conventional flour and conventional sugar should be roughly the same. Furthermore, also the ecological externalities of both biogenic products (use of water and pesticides etc.) are roughly the same. In consequence, it is plausible to assume that the total costs of biogenic starch does not deviate much from the totals costs for biogenic sugar.

9. SOME WORDS ON ANTICIPATED SOCIETAL CHANGES

A large-scale supply of artificial carbohydrates and other products would nevertheless not result in a total displacement of biogenic agriculture but rather disburdens the current agricultural system from the need to allocate resources

such as fertile area and groundwater to the production of macronutrients. In consequence, the biogenic agriculture could enhance its activities in those production sectors where a synthesis is not economically or not possible at all. This applies, first of all, to the production of micronutrients such as taste producing substances and vitamins. In addition, it can be expected that even in a world where a healthy human diet could be produced entirely synthetically, there would be still a demand in non-processed, biogenic food products such as a real turkey with real potatoes and real cranberries.

The transition towards an (entirely) artificial food supply would mark another milestone of human's long-lasting desire to become less dependent on nature. Like for the neolithic and industrial revolutions, the societal, political, and cultural system may change significantly and irreversibly.

Getting rid of the production factor soil in favor of the production factor capital paired with increasing returns to scale in the chemical industry could possibly result in food production becoming an industry as any other industry, with the danger of extreme concentration of market power in the hands of an international oligopoly. If unchecked, such a development could bring most direct and potentially most devastating impacts on society similar to those of the early industrial revolution. It would be a crucial challenge for policymakers to accompany this transition on the one hand by political-economic reforms, which ensure that the national sovereignty does not become subdued by corporate market power, and on the other hand by appropriate social-political reforms, which avoid a division of society in people which can still afford biogenic food and those which can no more satisfy such a demand.

Getting rid of agriculture as one of the oldest achievements of civilization may lead to mankind further growing away from its roots and traditions. As one aspect of many, mankind then needs to reinvestigate its relation to life. For example, if a “vegan+” food supply is possible, where neither animals nor plants need to be killed or else abused, would it be ethically tolerable to continue so?

Getting rid of an Earth-bound food supply would remove the most fundamental limitation of long-term manned space missions and may thus mark the starting point of mankind colonizing the galaxy.

10. CONCLUSIONS

We compiled a reaction scheme which allows the artificial synthesis of monosaccharides—exemplified for hexoses—from atmospheric carbon dioxide, water, and electric energy via the formose reaction. All process steps have been demonstrated and described in the literature. The subsequent step of a targeted production of, e.g., pure D-glucose, either via suitable catalysts or a subsequent separation from the mixture of hexoses has not yet been demonstrated in the literature but has been made plausible within this paper. While this paper focused on monosaccharide, it has been highlighted that the artificial monosaccharide production would in principle allow also for the artificial production of starch.

We estimate a solar-to-food energy conversion efficiency of at least 6–15% which implies an at least 10-times higher per-area yield of sugar compared to conventional agriculture. We estimate (total) production costs of 0.5–1.6 €/kg for artificial glucose when produced on an industrial scale and subject to renewable energy costs of 50–100 €/MWh (but exclusively the yet speculative costs for the stereoisomer separation via a catalyst or subsequent processing). We estimate that the production costs of conventional sugar increase at least to ≥ 0.9 €/kg for humid conditions and ≥ 2 €/kg for semi-arid conditions when including the costs of its most obvious ecological externalities such as an unsustainable water demand and environmental pollution. Accordingly, the artificial sugar production may already today have lower total production costs than the conventional sugar production.

In conclusion, the artificial carbohydrate production can provide an affordable and secure food supply for a multiple of the today's world population, while at the same time lowering the ecological and climatological externalities of the conventional agriculture. In addition, the artificial carbohydrate production would avoid socio-economic externalities such as

an insecure food supply, national food dependencies, need of human work force, and occupation of valuable land. A transition towards such an at least partially artificial food supply appears not only to be smart but may be the only possibility to avoid future global conflicts on food resources. In addition, the freed land area could be used to extenuate other man-made degradations of the ecological system, for instance, by the establishment of nature reserves for endangered species, by afforestation programs to mitigate the climate change, or simply by enhancing sustainable organic farming.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to the conception and realization of the study. FD wrote the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDIX

A. ENERGY DEMAND FOR THE EXTRACTION OF CO₂ AND H₂O FROM THE LOCAL ATMOSPHERE

Given a gas mixture which contains component A with a molar mixing ratio $\chi \ll 1$, the absolute temperature T , and the universal gas constant $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$. The mixing entropy ΔS_M relative to the component A for one mole of mixture is given by (see any textbook on thermodynamics, e.g., Atkins et al., 2018)

$$\Delta S_M = -R \cdot [\chi \cdot \ln(\chi) + (1 - \chi) \cdot \ln(1 - \chi)] \quad (\text{A1})$$

and the mixing entropy ΔS_M relative to the component A for one mole of the component A is given by

$$\Delta S_A = \frac{\Delta S_M}{\chi} \stackrel{\chi \ll 1}{\approx} -R \cdot \ln(\chi) \quad (\text{A2})$$

The minimum required energy to separate 1 mole of the component A from the mixture is given by

$$\Delta W_A = \Delta S_A \cdot T \stackrel{\chi \ll 1}{\approx} -R \cdot T \cdot \ln(\chi) \quad (\text{A3})$$

Assuming $T = 300 \text{ K}$, the energy demand for the extraction of 1 mole of CO₂ or H₂O from the local atmosphere reads

$$\Delta W_A(\chi_{\text{CO}_2} = 4 \cdot 10^{-4}) = 19.5 \text{ kJ mol}^{-1} \quad (\text{A4})$$

$$\Delta W_A(\chi_{\text{H}_2\text{O}} = 1 \cdot 10^{-2}) = 11.5 \text{ kJ mol}^{-1}. \quad (\text{A5})$$