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Size, space, and cost characteristics of potential bioreactors

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Abstract

New options are needed to reduce the impact of motor vehicles on climate change and declining fossil fuel resources. Cars which are fuelled by hydrogen could be a sustainable method of transportation if suitable technologies can be devised to produce hydrogen in an environmentally benign manner along with the provision of the necessary fuelling infrastructure. This paper assesses size, space and cost requirements of bioreactors as a decentralised option to supply hydrogen powered cars with biohydrogen produced from algae or cyanobacteria on a theoretical basis. Decentralised supply of biohydrogen could help to reduce the problems that hydrogen cars face regarding market penetration. A feasibility study for decentralised biohydrogen production is conducted, taking the quantity of hydrogen which is needed to fuel current hydrogen cars into account. While this technology is, in theory, feasible, sizes and costs of such reactors are currently too high for widespread adoption. Thus, more R&D is needed to close the gap and to approach marketability.

Key words

hydrogen, biohydrogen, decentralized reactors, algae, hydrogen cars, hydrogen economy

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Highlights

- hydrogen produced during photosynthetic processes could be a sustainable fuel for motor vehicles
- the minimum size for a decentralised supply using biohydrogen reactors is 47 cubic metres
- maximum yields of biohydrogen could be higher than for common energy crops when space used is the criterion
- with 26 € per 100 km in a hydrogen car, costs for biohydrogen production are currently very high

Introduction

The excessive use of motorised vehicles is a major source of atmospheric carbon dioxide and other harmful pollutants. In 2010, around 23% of the world's energy related CO_2 emissions resulted from the transport sector - with a tendency to grow (Sims et al., 2014). It is essential to reduce the emissions of greenhouse gases drastically in order to mitigate climate change and car use plays a key role. In addition, fossil fuel resources are finite and renewable alternatives have to be found to guarantee energy security in the long run (Campbell & Laherrer, 1998; Shafiee & Topal, 2009). There are only a limited number of possibilities to reduce the negative environmental impact that cars and other motor vehicles have on the environment in general and climate change in particular (Offer, Howey, Contestabile, Clague & Brandon, 2010; Sandy Thomas, 2009).

Alternatives to conventional vehicles are the use of electrically or hydrogen powered vehicles. In contrast to battery powered vehicles, hydrogen powered vehicles can be quickly refuelled and have large ranges. As well as road vehicles, hydrogen can also be used to power aircrafts and ships (Altmann, Weinberger & Weindorf, 2004; Anandarajah, McDowall & Ekins, 2013; Nojoumi, Dincer & Naterer, 2009). While hydrogen is completely "clean" during the combustion process, the production of hydrogen is normally based directly or indirectly on fossil energies, which leads to the emission of greenhouse gases. Currently, over 90% of hydrogen is produced through natural gas steam reforming. Alternatively, hydrogen can be produced through electrolysis of water with electricity as an energy source. However, if electricity from non-renewable resources is used for hydrogen production, it leads to significant emissions of greenhouse gases. Electrolysis can only be sustainable if hydrogen is produced with electricity from renewable resources (T. Abbasi & Abbasi, 2011; Koroneos, Dompros, Roumbas & Moussiopoulos, 2004; Levene, Mann, Margolis & Milbrandt, 2007).

Hydrogen can also be produced photoautotrophically or photoheterotrophically from algae or cyanobacteria. Such production routes could be feasible carbon neutral alternatives to current production methods. Algae and cyanobacteria are particularly interesting for both biohydrogen and biogas production because they grow faster and produce more biomass per hectare than conventional energy crops (Rodolfi et al., 2009). Apart from nutrients, photoautotrophic organisms only need sunlight and CO_2 to grow. Photoheterotrophic organisms can produce hydrogen with the help of nutrients, sunlight and organic carbon sources such as acids or sugars (Hallenbeck & Benemann, 2002; McKinlay & Harwood, 2010; Meher Kotay & Das, 2008). These processes lead to the sequestration of carbon dioxide and could therefore be a sustainable production process for hydrogen in the future. However, if photoheterotrophic processes are used, the production of carbon sources such as acids and sugars leads to emissions prior to the actual hydrogen production process.

One main challenge regarding hydrogen vehicles is the limited fuelling infrastructure for these cars (Alazemi & Andrews, 2015). In Europe, only around 95 hydrogen fuelling stations exist (Dallmeier, 2016). At the same time, the consumer demand for hydrogen is so low that it is often not economically feasible to build large-scale hydrogen fuelling stations. The decentralised production and fuelling of hydrogen cars, for instance by biohydrogen produced in bioreactors, could help lessen these problems. If it was possible to supply hydrogen cheaply and without the release of greenhouse gases, hydrogen cars could easily replace conventional vehicles since thy have no disadvantages during usage.

Biohydrogen production

Fuel-efficient hydrogen cars need around one kilogram of hydrogen to drive 100 km. While the technology for using hydrogen in motorised vehicles is quite mature, large scale conventional hydrogen production leads to an excessive release of greenhouse gases.

Hydrogen can also be produced through biological processes using algae or cyanobacteria. This can be done photoautotrophically which means that only (sun)light, carbon dioxide and nutrients, in particular nitrate, phosphate and potassium, for the organisms are needed. Specific fertilizers for algae or N-P-K fertilizers for common field crops can be used.

For the alternative photoheterotrophic process route, organic carbon sources, such as sugars, alcohols or acids serve as the electron donor. While this complicates the overall set up, higher hydrogen yields can be achieved.

For biohydrogen production, anaerobiosis is essential because the enzyme hydrogenase, which catalyses the hydrogen production step, is sensitive to oxygen. Oxygen itself is produced during photosynthesis by the light-absorbing protein complex Phototsystem II (PS II). To avoid hydrogenase inactivation, organisms can be transferred to a sulphur deprived medium which inactivates PS II and thereby leads to anaerobiosis. However, this process is costly and labour-intensive. Alternatives include the cultivation of microalgae and their mutualistic bacterial partners (Wirth et al., 2015), genetic engineering to partially inactivate PS II or genetic engineering to increase oxygen consumption of algae (Allakhverdiev et al., 2010; Dubini & Ghirardi, 2015; Esquível, Amaro, Pinto, Fevereiro & Malcata, 2011).

Overall, research clearly showed that a production of biohydrogen can be achieved using algae or cyanobacteria. This process is possible using only sunlight, water, carbon dioxide and nutrients which can be easily supplied. However, special reactor plates and space is also needed to produce sufficient quantities of biohydrogen for practical applications. The required space and associated costs will be calculated in the following section and it will be discussed whether production of biohydrogen in decentralised reactors, for instance for the supply of private car owners, is a promising undertaking for the future and which mechanisms seem most worthwhile to achieve cost-effective biohydrogen production.

Assumptions, research Question and Method

Assumptions

A feasibility study is conducted to find out how far decentralised biohydrogen production for the fuelling of hydrogen cars is cost-effectively possible. "Cost-effective" means that the costs for driving 100 km in a hydrogen car should not be more expensive than the costs paid for 100 km in a conventional car. If the use of biohydrogen leads to higher costs it is unlikely that the technology will be embraced by private bodies or industries. At the current time, environmental benefits alone are not sufficient to guarantee market penetration of a new technology.

A decentralised reactor needs to produce a certain amount of hydrogen to supply a car with fuel. While the quantity must not compete with the quantity that needs to be supplied by large-scale hydrogen fuelling stations, the quantity should be sufficient to support a functioning infrastructure. Bioreactors could, for instance, be built in private gardens, on roofs or as part of the house structure, e.g. as a replacement of walls. This is particularly interesting for rural areas where the construction of hydrogen fuelling stations is often not economically sensible. In this study, the quantity that should be produced by reactors to allow a functioning decentralised fuelling infrastructure is determined as the quantity of hydrogen which can be produced in one hour to drive 100 km in a hydrogen car. Research from European countries indicated that the average daily driving distances in European countries is below 100 km (Pasaoglu et al., 2012). If not all produced biohydrogen is used in cars, excess biohydrogen could be used for the supply of heat in homes, could be blended into the natural gas pipeline networks or could be used through fuel cells to provide electricity for private applications.

It is also assumed that the laboratory results can be transferred to large outdoor bioreactor fields. In practice, this step is extremely difficult to achieve, as can be seen when comparing the result of the study by Lindblad et al. (2002) who uses outdoor reactors with similar studies (compare Table 1).

Research questions

The following questions shall be answered in the current paper:

(1) What space is needed for decentralised biohydrogen production for the supply of hydrogen vehicles?

(2) What are expected costs for a decentralised production of biohydrogen and which costs are consequently associated with using this hydrogen for fuelling cars?

(3) Is a decentralised production of biohydrogen for cars, for instance in gardens or roofs of private houses, a realistic scenario?

Method

To calculate total space and costs associated with biohydrogen production, experimental studies in which biohydrogen was produced from algae or cyanobacteria in a light dependent photoautotrophic or photoheterotrophic process are summarised. The organisms, volume used for the experiment, temperature, light intensity, electron donor and hydrogen yield are provided. It is also differentiated between experimental set-ups with or without a sulphur-deprived step. The studies were chosen to represent a vast range of different study approaches with varying boundary conditions. In cases where more than one study used the same organism and a similar approach, the study with the higher output yield was chosen. Since the units which are used in the different experimental designs concerning biohydrogen production differ, they are converted to the SI format: kilogram per litre of culture medium per hour [kg * l^{-1} * h^{-1}]. This allows for a better comparison of actual yields found in the different studies and allows for easy calculation of necessary reactor sizes to fuel hydrogen cars.

For this calculation, results which were published in millilitre per time span are converted to litres per cubic meter of culture medium per hour and are then multiplied with the density of hydrogen at 25 °C. This yields the mass of hydrogen which is gathered from one cubic metre of culture medium.

Results which are published in nanomole or micromole per time span are converted to mole per hour and are multiplied with the molar mass of hydrogen (M_{H2}=2,02 g/mole). This provides the mass in kg.

In cases where the results refer to the amount of chlorophyll, results are converted to kilogram per litre of culture medium through multiplying the hydrogen mass per chlorophyll unit with the amount of chlorophyll per litre.

To compare the produced biohydrogen quantities with the current needs of hydrogen cars, current hydrogen cars that use fuel cells (FC) or internal combustion engines (ICE) are identified with their key parameters. Next to the year of market introduction, the capacity of the tank, pressure or temperature in the tank, mass of hydrogen which can be stored in the tank, the vehicle's range, its energy consumption in kWh per 100 km and its hydrogen consumption per 100 km are given. In cases where the manufacturer does not provide all information, the missing values are calculated from the available data.

The specific requirements of bioreactors to allow an optimal utilisation of nutrients and sunlight are considered to calculate the minimum size of potential bioreactors to fuel different hydrogen vehicles. Firstly, the volume of bioreactors is calculated by dividing the amount of hydrogen needed by the different hydrogen cars to drive 100 km with the yield of different biohydrogen production methods. Thereby, the necessary volume to produce sufficient biohydrogen within one hour to drive a range of 100 km in different hydrogen cars is computed. This characteristic value can then be easily compared with the fuel and cost requirements of conventional cars, where fuel consumption is normally equally given per 100 km. Secondly, these volumes are used to calculate the lengths of potential vertical bioreactors with a theoretical height of 10 meters and a depth of 5 centimetres. While the heights of potential reactors may vary, the depths of bioreactors are limited by the need to supply the microorganisms with sufficient sunlight. Zhang et al. (2015) calculated that a depth of 5 cm is optimal for hydrogen production. In a third step, the space requirements of bioreactor fields on which bioreactor modules are built is calculated. Therefore, the length of vertical plate reactors with a hypothetical height of 10 meters and a depth of 5 centimetres is taken and multiplied with the distance that potential bioreactors need between them to avoid shading each other.

Finally, the number of kilometres which can be driven with the maximum yearly yield of one hectare of bioreactors is calculated and compared with the yield of well-established energy crops.

Costs for decentralised bioreactors are estimated based on known costs to produce algae in large reactor fields, the cost of nutrients, water filtration technologies, carbon sources and infrastructure. Additionally, the costs for a sulphur-deprived step is estimated.

The required space and costs for biohydrogen production through decentralised algae reactors are compared with costs for the powering of fossil-fuelled and electric vehicles. Considering the current need to find alternatives to the world's energy demand for the mobility sector, the results are discussed and an outlook of potential practical applications is given.

Feasibility study of decentralised reactors to produce biohydrogen for cars

Experimental studies of hydrogen production

Table 1 summarises current field studies in the area of photosynthetic biohydrogen production from algae and cyanobacteria. The table summarises the different external factors of the studies as well as the yields in kilogram per litre and hour. The complexity of the studies varies greatly. While some authors use simple experimental designs in which algae or cyanobacteria use light and different carbon sources to produce hydrogen (Howath & Codd, 1985; Lindblad et al., 2002; Tsygankov et al., 1998), some of the studies need a sulphur deprivation step after the growth phase for hydrogen production (Melis, Zhang, Forestier, Ghirardi & Seibert, 2000; Oncel & Kose, 2014; Oncel et al., 2015; Tsygankov, Kosourov, Tolstygina, Ghirardi & Seibert, 2006). Wirth et al. (2015) use a design in which algae are cultivated with mutualistic bacteria so as no sulphur deprivation is necessary. Song, Rashid, Choi and Lee (2011) use cells which were immobilised in agar gel, while Giannelli and Torzillo (2012) use a scattering light nanoparticle suspension to achieve better light penetration.

Table 1

Experimental conditions and hydrogen yield - in the original and standardised unit - of studies that use algae or cyanobacteria to produce biohydrogen

Organism	**Volume [l]**	**Temperature [°C]**	**Light intensity**	**Sulfur deprivation**	**Electron donor**	**H_2 yield [original unit]**	**H_2 yield [$kg*l^{-1}*h^{-1}$]**	**Additional information**	**Reference**
C. reinhardtii	110	28	2 x 1000 µmol photons $*m^{-2}*s^{-1}$	Yes	CO_2	0,61 $ml*h^{-1}*l^{-1}$	$5,48*10^{-8}$	Tubular photobioreactor; scattering light	Giannelli and Torzillo 2012

								nanoparticle suspension	
Gloeobacter 1421	0.005	25-30	30 µmol*m^{-2}*s^{-1}	No	CO_2	1,38 µmol * h^{-1} * mg chl^{-1}	6,9*10^{-12}		Howath and Codd 1985
Anabaena AMC 414	1	26	456 µE*m^{-2} *s^{-1}	No	CO_2	13,8 ml*h^{-1}*l^{-1}	1.24*10^{-6}	Air phase was replaced with argon	Lindblad et al. 2002
Anabaena AMC 414	4.35	avg. 21.8	-	No	CO_2	14,9 ml*h^{-1}*l^{-1}	3.21*10^{-7}	Outdoor experiment during the summer in London, UK	Lindblad et al. 2002
C. reinhardtii		25	200 µmol*m^{-2}*s^{-1}	Yes	CO_2	2 ml*h^{-1}*l^{-1}	1.8*10^{-7}		Melis et al. 2000
C. reinhardtii	5	27	150 µE*m^{-2}*s^{-1}	Yes	CO_2	1,3 ml*h^{-1}*l^{-1}	1.17*10^{-10}	Photobioreactor	Oncel and Kose 2014
C. reinhardtii D1-protein mutants	1	27	2 x 70 µE*m^{-2}*s^{-1}	Yes	CO_2	2,92 mg*h^{-1}*l^{-1}	2.92*10^{-6}		Oncel et al. 2015
Chlorella sp.	0.2	37	120 µmol*m^{-2}*s^{-1}	Yes	CO_2, 30 mM glucose	238 ml*h^{-1}*l^{-1}	2.14*10^{-5}	Immobilised cells in agarose gel	Song et al. 2011
Rhodoacter capsulatus B10	1	30	80 W*m^{-2}	No	CO_2, 32 mM lactate	97 ml*h^{-1}*l^{-1}	8.99*10^{-6}		Tsygankov et al. 1998
C. reinhardtii	1.2	28	~ 300 µE*m^{-2} *s^{-1}	Yes	CO_2	0.73 ml*h^{-1}*l^{-1}	6.56*10^{-8}	Day/night cycle	Tsygankov et al. 2006
Chlamydomonas sp.; Scendesmus sp.; mutualistic Bacteria	0.035	25	50 µmol*m^{-2}* s^{-1}	No	CO_2	1,91 ml * l^{-1} after 4 days	1.79*10^{-12}		Wirth et al. 2015

Hydrogen vehicles on the market

Several hydrogen cars have been developed during the last two decades. The vehicles differ considerably regarding the technology used, their weight and their engine power - and consequently their hydrogen consumption. In general, hydrogen fuelled cars can be divided into cars which use hydrogen directly in an internal combustion engine (ICE) and cars which use fuel cells (FC) to convert hydrogen into electricity and are propelled by an electric motor. While the former are restricted by the Carnot cycle, the latter can theoretically achieve high levels of efficiency (Farooque & Maru, 2001). Table 2 lists some of the better-known hydrogen cars. The Toyota Mirai, which was launched in 2014, is the first and only hydrogen car which is produced on a large scale. Next to the Toyota Mirai, only the Hyundai ix35 FCEV can currently be bought, all other vehicles are prototypes and not available for the public.

Table 2

List of hydrogen fuelled cars

Car	Year of market introduction	Type*	Capacity of tank [litre]	Physical condition of hydrogen	Pressure in tank [bar]	Temperature in tank [°C]	Mass in tank [kg]	Range of vehicle	Consumption [kWh/100 km]	Consumption [l/100 km]
Toyota Mirai	2014	FC	122	Gaseous	700	-	5	500	33	1
Hyundai ix35 FCEV	2013	FC	144	Gaseous	700	-	5.64	600	32	0.95
Honda FCX Clarity	2008	FC	171	Gaseous	350	-	4.1	460	30	0.91
BMW Hydrogen 7	2006	ICE	114 (H_2) 74 (petrol)	Liquid	-	-253	7.6	200	120	3.6
Mazda RX-8 Hydrogen RE	2003	ICE	110 (H_2) 61 (petrol)	Gaseous	350	-	2.4	100	80	2.4

* FC = fuel cell; ICE = internal combustion engine
Sources: BMW 2011; Honda 2009; Hyundai 2015; Mazda Global 2015; Toyota 2014

Results

Design of decentralised reactors

At the current time, there are few hydrogen vehicles and few hydrogen fuelling stations. While excess hydrogen can be easily converted into electricity by fuel cells or burned for heat production, too little of hydrogen can be a problem for a functioning infrastructure. Once more hydrogen vehicles are sold, the infrastructure and hence the amount of hydrogen provided at decentralised or large-scale fuelling stations needs to adapt to the higher demand.

Until then, a decentralised infrastructure for the provision of small quantities of hydrogen could help to increase market penetration of hydrogen vehicles.

Space requirement

To provide sufficient hydrogen within one hour for the different hydrogen cars to drive 100 kilometres, potential bioreactors would need the volumes shown in Table 3.

Table 3

Volume in square metres which would be needed to produce sufficient biohydrogen within one hour to drive 100 kilometres in different hydrogen cars

Studies	Hydrogen cars				
	Toyota Mirai	Hyundai ix35 FCEV	Honda FCX Clarity	BMW Hydrogen 7	Mazda RX-8 Hydrogen
Giannelli and Torzillo 2012	18,235	17,323	16,594	65,647	43,764
Howath and Codd 1985	144,927,536	137,681,159	131,884,058	521,739,130	347,826,087
Lindblad et al. 2002	806	766	734	52,914	1,935
Lindblad et al. 2002	3,116	2,960	2,835	204,543	7,478
Melis et al. 2000	5,562	5,284	5,061	365,110	13,348
Oncel and Kose 2014	8,556,516	8,128,690	7,786,429	561,707,121	20,535,638
Oncel et al. 2015	342	325	312	22,482	822
Song et al. 2011	47	44	43	168	112
Tsygankov et al. 1998	111	106	101	400	267
Tsygankov et al. 2006	15,238	14,476	13,866	54,855	36,570
Wirth et al. 2015	559,085,439	531,131,167	508,767,749	2,012,707,580	1,341,805,053

However, the volume alone does not provide sufficient information. For energy production, vertical flat plate reactors are used. The depth of such reactors should ideally not exceed 5 cm. Hypothetically, reactors with a depth of 5 cm and a height of 10 meters (which is higher than the current reactors in use) could be built. The length of such reactors to provide sufficient hydrogen within one hour to drive 100 kilometres in the different hydrogen vehicles is shown in Table 4.

As can be seen, the lengths are enormous. It is therefore not feasible to build such reactors in one connected row. Rather, shorter rows would need to be built next to each other on a bioreactor field. If sunlight is to be used primarily to promote the growth of the organisms, the reactors need to be built far enough apart to limit growth losses induced by shading.

Table 4

Length in meters which would be needed for bioreactors (depth = 0.05 m; height = 10 m) to produce sufficient biohydrogen within one hour to drive 100 kilometres in different hydrogen cars

Studies	Hydrogen cars				
	Toyota Mirai	Hyundai ix35 FCEV	Honda FCX Clarity	BMW Hydrogen 7	Mazda RX-8 Hydrogen
Giannelli and Torzillo 2012	36,470	34,647	33,188	131,293	87,529
Howath and Codd 1985	289,855,072	275,362,319	263,768,116	1,043,478,261	695,652,174
Lindblad et al. 2002	1,612	1,531	1,467	105,829	3,869
Lindblad et al. 2002	6,232	5,920	5,671	409,086	14,956
Melis et al. 2000	11,123	10,567	10,122	730,219	26,696
Oncel and Kose 2014	17,113,032	16,257,380	15,572,859	1,123,414,243	41,071,276
Oncel et al. 2015	685	651	623	44,964	1,644
Song et al. 2011	93	89	85	336	224
Tsygankov et al. 1998	222	211	202	801	534
Tsygankov et al. 2006	30,475	28,951	27,732	109,711	73,141
Wirth et al. 2015	1,118,170,878	1,062,262,334	1,017,535,499	4,025,415,159	2,683,610,106

Depending on the location of the bioreactors and the time of the year, space requirements differ. During the summer months in middle Europe, bioreactors would need to be built approximately 20 meters apart from one another to avoid shading of one module by another for approximately 10 hours during the day. This does not mean that 10 hours of sunlight are used. However, 20 meters between bioreactors would allow optimal utilisation of sunny hours throughout a 10-hour time span.

If bioreactors were built accordingly, the space that would be required is shown in Table 5.

Table 5

Land consumption in square meters which would be needed for bioreactors (depth = 0.05 m; height = 10 m) to produce sufficient biohydrogen within one hour to drive 100 kilometres in different hydrogen cars

Studies	Hydrogen cars				
	Toyota Mirai	Hyundai ix35 FCEV	Honda FCX Clarity	BMW Hydrogen 7	Mazda RX-8 Hydrogen
Giannelli and Torzillo 2012	72,941	69,294	66,376	262,587	175,058
Howath and Codd 1985	579,710,145	550,724,638	527,536,232	2,086,956,522	1,391,304,348
Lindblad et al. 2002	3,224	3,063	2,934	211,658	7,738
Lindblad et al. 2002	12,463	11,840	11,342	818,173	29,912
Melis et al. 2000	22,247	21,135	20,245	1,460,439	53,393
Oncel and Kose 2014	34,226,063	32,514,760	31,145,717	2,246,828,486	82,142,552
Oncel et al. 2015	1,370	1,301	1,247	89,927	3,288
Song et al. 2011	187	178	170	673	449
Tsygankov et al. 1998	445	423	405	1,602	1,068
Tsygankov et al. 2006	60,951	57,903	55,465	219,422	146,281

Additional electron donors are used in some cases. In the study by Tsygankov et al. (1998), the authors use a constant concentration of 32 millimolar (mM) lactate – which corresponds to 2.88 grams per litre and hour. Since around 111 cubic meters are necessary to provide sufficient biohydrogen to drive 100 km in the Toyota Mirai, this adds up to 320 kg of lactate.

Song et al. (2011) use around 30 mM glucose per 200 ml of culture medium every 70 hours, which corresponds to approximately 0.39 grams per litre and hour. While lactate is a by-product of the food industry, glucose must be produced through enzymatic hydrolysis of starch from maize or potatoes. Around 70% of the maize kernel is starch (The Corn Refiners Association, 2009), which can be almost completely converted to glucose. 5.4 grams of glucose can therefore be produced from 7.7 grams of maize. According to the results of Song et al. (2011), 47 cubic metres of culture medium are necessary (compare Table 3). Hence, around 25.85 kg of maize are necessary to produce sufficient glucose to drive 100 km in the Toyota Mirai. Overall, the land consumption is very high.

Calculation of yearly maximum production of bioreactor fields

If it would be possible to use all sunlight during the year, the yearly production of bioreactor fields would be quite significant. For instance, in Central Europe, around 1,600 hours of sunshine can be used throughout the year (Osborn, 2016). Under these conditions and if the sun could be used optimally, one hectare of bioreactors could provide the amounts of hydrogen which are shown in Table 6. Dependent on the production method, these amounts are sufficient to drive over 850,000 km in the Toyota Mirai. With the bioethanol produced from one hectare of sugar cane, a reference car can drive approximately 65,280 kilometres (Dias De Oliveira, Vaughan & Rykiel, 2005). Bioreactors thereby outperform sugar cane, a very efficient energy crop, by over 1,300%. However, one hectare of solar panels provides between 400,000 and 500,000 kWh of electricity per year with which an economical electric vehicle can drive between 3 and 3.8 million kilometres (consumption 13 kWh/100 km). The energy output per area is therefore currently not competitive with electric vehicles. However, the advantages of hydrogen vehicles, namely the quick refuelling time and the large range, make hydrogen powered vehicle an important future technology.

Table 6

Number of kilometres which can be driven with the yearly yield of one hectare of bioreactors (depth = 0.05 m; height = 10 m) with approximately 1,600 hours of sunshine per year

Studies	Hydrogen cars				
	Toyota Mirai	Hyundai ix35 FCEV	Honda FCX Clarity	BMW Hydrogen 7	Mazda RX-8 Hydrogen
Giannelli and Torzillo, 2012	2,194	2,309	2,411	609	914
Howath and Codd, 1985	<1	<1	<1	<1	<1
Lindblad et al., 2002	49,625	52,237	54,533	756	20,677
Lindblad et al., 2002	12,838	13,513	14,107	196	5,349
Melis et al., 2000	7,192	7,571	7,903	110	2,997
Oncel and Kose, 2014	5	5	5	<1	2
Oncel et al., 2015	116,800	122,947	128,352	1,779	48,667
Song et al., 2011	856,000	901,053	940,659	237,778	356,667
Tsygankov et al., 1998	359,600	378,526	395,165	99,889	149,833
Tsygankov et al., 2006	2,625	2,763	2,885	729	1,094

As can be seen, the efficiency of the different production routes varies greatly. This can partly be explained by the experimental designs of the studies. However, the differences also indicate that a further improvement of current biohydrogen production methods is possible. As a range of authors have pointed out, improvement of external factors and genetic engineering could further increase hydrogen yield (Beer, Boyd, Peters & Posewitz, 2009; Radakovits, Jinkerson, Darzins & Posewitz, 2010; Vignais, Magnin & Willison, 2006).

Costs

One m² of photobioreactor plates costs between 40 and 100 Dollars (Richardson et al., 2014). We use the most optimistic estimation of around 37 Euros per m² and assume that no additional costs incur for loan interest because the initial investment is relatively small.

A reactor field with a volume of 5,000 litres needs 100 m² of plate reactors with a depth of 5 cm which need approximately 2,000 m³ of space to guarantee that during 10 hours, all sunshine can be used without shading of the reactors by one another. These reactors cost around 3,700 Euros. Next to these one-time costs, costs for nutrients, water, electricity, labour and transportation of CO_2 must be considered. As a source of CO_2, filtered flue gas can be used, which is available in large quantities from coal-fired power stations. This CO_2 is available free of charge and can potentially even generate monetary benefits because of saved carbon certificates. It is therefore assumed that the costs per months are as low as 20 Euros – or 240 Euros per year – to provide the necessary infrastructure for the provision of CO_2. We assume that the reactors can be used for 10 years during which maintenance costs, for instance for the replacement of pumps, filtration technologies and gas collection facilities, are about 5% of investment costs per year. The lease price for land is set at 1,000 Euros per hectare and year. This is very low compared to the value of farmland. However, it is assumed that the used land is low-value fallow land, land which cannot be used in any other value generating manner or that other land-uses can coexist such as livestock husbandry.

Efficient photobioreactors are designed in a way where CO_2 is introduced from the bottom of the reactor through perforated air tubing. The shape of the bioreactor, for instance through special constrictions in the interior, leads to an optimal distribution of CO_2 while at the same time, the algae solution is mixed continuously. By using this system, light-inhibition of algae and shading of algae by one another are reduced. Moreover, a reactor designed in this manner does not need a separate mixing application but only an airlift pump for the distribution of carbon dioxide. Additionally, a thermostat and a thermosensors are used to keep temperatures in an acceptable range.

The electricity price is set at around 12 cent/kWh, which was the average price paid per kWh of electricity by industry in the EU in 2016 (Eurostat, 2017). Water price is set at 0.50 Euros per cubic metre. It is assumed that the water in the 5,000-litre tank is completely replaced every 10 days and that 90% of water is recycled back into the system which is in accordance with Richardson et al. (2014). Labour costs are set at 20 Euros per hour.

Table 7 summarises the itemised and total costs per year.

Table 7

Costs for a 5,000 litre biohydrogen production reactor per year in Euros

Items	**Basis**	**Quantity**	**Price**
Purchase price	37 Euros / m²	10 reactors	370
Water	0.50 Euros / m³	292 litres	146
Price for land	1,000 Euros / ha	0.5	200
Growth medium	Containing nitrate, phosphate, potassium	-	1,560
CO_2	Transport and infrastructure	-	240
Electricity costs	12 cent/kWh	9000 kWh	1,080
Labour costs	20 Euros/hour	36	720
Maintenance costs	5% of investment costs per year	-	185
Total costs			**4,501**

Total costs per year for a 5,000-litre tank if it is used for 10 years therefore sum up to around 4,501 Euros. Electricity costs (1,080 Euros) and costs for growth medium (1,560 Euros) are the most expensive items. For processes which involve a sulphur deprived step, the costs are higher since additional labour and additional reactor space is needed. On the basis of the costs that are summarised in Table 7, it is assumed that for this step, no additional costs occur for the growth medium and for CO_2, while other costs are increased. The results are therefore multiplied with 1.6 to take this into account.

For lactate which is used in the study of Wirth et al. (2015), around 1 Euro per kilo must be paid. Glucose, which is used in the study of Song et al. (2011) as an electron donor, can be purchased for around 0.4 Euros per kg. It is assumed that the agarose gel is replaced every 4 months. Considering that the costs which are mentioned here are the minimum costs, it becomes clear that the production process is very expensive. While it was assumed that such reactors could be integrated in private houses or built in gardens, the current costs indicate that such an approach is unrealistic. This becomes even clearer when total costs of the different production methods are summarized. These costs can be seen in Table 8.

Table 8

Total costs and driving costs per 100 km in a Toyota Mirai for a 5,000-litre bioreactor when different experimental designs are used during a year with 1,600 hours of sunshine

	Costs in Euro					
	Basic	Sulphur deprivation step	Additional costs	Total	Amount of hydrogen [kg]	Costs for 100 km in Toyota Mirai
Giannelli and Torzillo, 2012	4,501	2,700	0	7,201	0,438712	16,414
Howath and Codd, 1985	4,501	0	0	4,501	5,52*10^{-5}	81,539,855
Lindblad et al., 2002	4,501	0	100 (use of argon instead of air)	4,601	9,92	464
Lindblad et al., 2002	4,501	0	-	4,501	2,57	1,753
Melis et al., 2000	4,501	2,700	0	7,201	1,44	5,006
Oncel and Kose, 2014	4,501	2,700	0	7,201	9,35*10^{-4}	7,701,934
Oncel et al., 2015	4,501	2,700	0	7,201	23,36	308
Song et al., 2011	4,501	2,700	0.78 (electron donor) 3,000 (agarose gel)	10,202	171,2	60
Tsygankov et al., 1998	4,501	0	14.4 (electron donor)	4,515	71,92	63
Tsygankov et al., 2006	4,501	2,700	0	7,222	0,53	13,756
Wirth et al., 2015	4,501	0	0	4,501	1,43*10^{-5}	314,555,445

Despite the high costs of the design of Song et al. (2011), it is still the cheapest option. Total costs are around 60 Euros per 100 km in the Toyota Mirai. However, electricity costs could be reduced by using excess electricity from wind turbines or solar panels. Once sufficient overcapacities exist, these overcapacities will be cheaply available. Moreover, Dalrymple et al. (2013) showed that nutrient-rich wastewater can also serve as a source of nutrients for algae. This would further reduce the costs drastically. Nevertheless, costs of around 26 Euros per 100 km would still occur even in a setting where electricity and nutrients could be supplied without any costs. In addition, costs will arise as a result of the compression process – which is a vital step if hydrogen is used in cars. According to Bossel, Eliasson, and Taylor (2003), 17 MJ of electricity are needed to compress 1 kg of hydrogen to 800 bar. This corresponds to approximately 12% of the hydrogen's energy content. Considering a price of 12 cent/kWh, this leads to total costs of 57 cent/kg of hydrogen. Overall, the costs for a cultivation of algae and cyanobacteria in photobioreactors is at the current time too high to compete in any way with conventional fuels.

Discussion

The use of motorised vehicles leads to excessive emissions of greenhouse gases, particularly CO_2. These emissions must be reduced in order to mitigate climate change. There are currently only very few alternatives to conventional vehicles. Electric cars, which could be a sustainable solution are not competitive in terms of range and fuelling time. New technologies are therefore urgently needed to reduce the impact that motorised vehicles have on climate change. Cars which are fuelled with hydrogen could be a sustainable alternative that allows equal ranges and fuelling times as conventional vehicles. However, the production of hydrogen is not environmentally benign and the necessary fuelling infrastructure does currently not exist.

Currently, natural gas steam reforming is the primary used production method for obtaining hydrogen. This production process leads to the release of large quantities of CO_2. The same is true for hydrogen which is produced through electrolysis using electricity generated from fossil resources. Since there are currently not sufficient overcapacities of electricity produced from renewable resources, the production of hydrogen from solely green energy is not a sustainable possibility.

Hydrogen produced from algae and cyanobacteria could be a sustainable production route since this process only needs (sun)light, nutrients and CO_2 if it is achieved photoautotrophically. Moreover, a decentralised supply of biohydrogen could be possible through the installation of photobioreactors. This could help to introduce a functioning, decentralised infrastructure for hydrogen which would lessen the barriers that hydrogen vehicles face regarding market penetration. However, the current paper showed that this approach is currently impractical. Photoautotrophic biohydrogen production results in very low yields. Over 340 cubic metres of culture medium would be needed to produce sufficient hydrogen to drive 100 kilometres in the Toyota Mirai if the photoautotrophic production method of Oncel et al. (2015) was used. Photoheterotrohic production methods lead to higher yields. Nevertheless, even if the highest biohydrogen production rates, which were found by Song et al. (2011), could be applied to large scale production plants, 47 cubic meters of culture medium would be needed to provide sufficient hydrogen within one hour to power a journey of 100 kilometres in a Toyota Mirai. The length of the bioreactors would be immense and the resulting space requirements are beyond what is currently feasible. While decentralization is a useful approach to guarantee energy security and reduce energy loss through transportation, it is not feasible for biohydrogen production processes through algae or cyanobacteria. The output is too low while the costs are too high. Available space on private property is more cost-effectively used through other energy-generating approaches such as solar cells or solar heat. Moreover, introducing a relatively new technology, such as bioreactors for biohydrogen production, is extremely difficult and associated with a range of problems besides costs: marketing is probably very expensive considering that the advantages are primarily found in the environmental sector. Next to biohydrogen production facilities, consumers also need to invest in technologies to use the produced hydrogen, such as hydrogen vehicles. Skilled workers is needed to install and service the reactors. Potential fears could arise regarding the safety of decentralized hydrogen production facilities.

The option of building bioreactors in gardens, on roofs or in the façade of houses is therefore difficult to implement at the moment.

The picture changes, however, when the maximal annual output of bioreactor fields is considered. 856,000 km could be driven with the yearly biohydrogen yield of one hectare with 1,600 hours of sunshine if the result of Song et al. (2011) could be transferred to large bioreactor fields. The yield of biohydrogen could be even higher if it was produced in countries with a higher number of sunshine hours per year. Biohydrogen production could also be interesting for countries which have large, mostly unused sunny areas which are not suitable for regular crop production such as in northern Africa, Australia, China and the United States. However, in such a scenario, the production is very unsteady and highly dependent on the weather. On cloudy days, the production would be very low or even non-existent.

While this outlook is optimistic, current research indicates that biohydrogen production is very low under outdoor conditions (Lindblad et al., 2002) and that the day/night cycle further reduces hydrogen yield (Tsygankov et al., 2006).

The analysis of the costs revealed that even under very optimistic conditions, the costs for hydrogen production through algae or cyanobacteria are extremely high and cannot compete with conventional fuels. While this dampens the current chances of biohydrogen becoming a major supplier of motor fuel it is likely that the biohydrogen production rate can be further increased through genetic engineering of algae or the optimisation of the experimental set ups. To further reduce the price for biohydrogen, the production could be linked to other value generating options. Algae that produce biohydrogen could also be used as a source of biogas, animal fodder, dietary supplements or in the cosmetic industry. However, these options need to be analysed in depth and future research needs to identify the most cost-effective options. This could make the process more attractive from an economic point of view.

Limitations and future research

In the current paper, the size, space and cost requirements of bioreactors for hydrogen production were calculated on a theoretical basis. However, a range of limitations apply: The hydrogen production rates of the different studies were found in small experimental designs with quantities of a few decilitres to litres of culture medium. It is questionable whether these results can be transferred to volumes of several cubic meters. Moreover, in the current study the reported maximum yields of the different studies were used. These yields were, however, reached at different time intervals and with the help of varying external factors. While some authors measured the production within one hour, Zürrer and Bachofen (1982) measured the hydrogen production during one day, Kim, Ahn and Yoon (2004) during 48 hours. All the cited studies used artificial lighting except the outdoor experiment of Lindblad et al. (2002). Light and temperature conditions were adjusted to the organisms' needs. It will be the main challenge of the future to analyse in how far the results can be reproduced in large outdoor bioreactor farms with sunlight as the sole source of light.

While in theory, large bioreactor volumes could be feasible in scarcely populated regions, the whole approach is only reasonable if large scale production is fundamentally possible. Especially the question as to how far the yearly sunshine hours could be used and how hydrogen yield can be further increased is of importance to find out whether the high yields that were calculated in the current study are a realistic scenario. This might open solutions not only for the mobility sector but also for all energy related areas.

Conclusion

Emissions from motor vehicles are a global environmental problem. Hydrogen could be a solution for this problem if sustainable options for biohydrogen production exist and the necessary infrastructure could be easily supplied. The technologies primarily used today for hydrogen production are associated with high rates of greenhouse gas emissions. Biohydrogen produced from algae or cyanobacteria was presented as a possible alternative which is not associated with high greenhouse gas emissions. These organisms can be grown relatively easily in bioreactors. They therefore need no fertile soil and are no competitor to food crops. In theory, they only need sunlight, nutrients and carbon dioxide to produce hydrogen. No carbon dioxide is produced during the process. The opposite is the case: carbon dioxide is taken up during the growth process of the microorganisms. Moreover, bioreactors could serve as a decentralised production facility for the implementation of a hydrogen fuelling infrastructure. The size and space requirements of bioreactors used for biohydrogen production to supply different hydrogen cars with hydrogen was calculated for the first time in this paper. While in theory biohydrogen could be a sustainable option for hydrogen production in general and hydrogen cars in particular, space and cost requirements of such production methods are very high. It will be a main challenge of the future to improve production methods and reduce costs for biohydrogen production through algae and cyanobacteria so that this production method could be used for a decentralised supply of hydrogen.

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