Recycling and Utilisation of Carbon Dioxide

Recycling and Utilisation of Carbon Dioxide in the European Union's Directives

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Abstract

In September 2015, the European Parliament and the Council adopted a new directive (2015/1513) that amended two existing directives in order to bolster the production of advanced fuels, biofuels, and "CO_2-fuels" in the transport sector. The combination of carbon dioxide and hydrogen (obtained by means of electrolysis with surpluses of renewable electricity) produces synthetic and renewable fuels that can easily be stored and transported in existing infrastructures. It is also possible to use CO_2-enriched microalgae as a feedstock for biofuel. To the extent these advanced fuels can be substituted for fossil energy, they could be helpful in the context of climate mitigation and energy transition, provided the regulatory framework is geared towards such an ambitious purpose.

Our comments address the relevance of legislative activity around such a strategy, mainly what kind of legal provisions are already taking shape at the European Union level. We discuss the ability of European directives to manage CO_2-fuels and biofuels made from microalgae with CO_2 enrichment. This subject is new, and the literature on related legal provisions is rare, thus the need to establish a reader's guide to the existing regulatory framework.

I. Introduction

The context in which the European Union (EU) addresses carbon capture and utilisation (CCU) is related to the challenges of energy transition and climate change mitigation. The growing interest in these technologies appears in an institutional context when the EU defines its objectives by stating it is committed to becoming "the world leader in renewable energy, the global hub for developing the next generation of technically advanced and competitive renewable energies".[1] The EU has set a target of at least 27 per cent renewable energy by 2030.[2]

For its part, the European Economic and Social Committee (EESC) advocates that renewable energy sources account for almost 45 per cent of power generation by 2030.[3] The EESC has unanimously bolstered the rise of renewable energy and the "absolute necessity" of energy storage, which amounts to "tens or hundreds of GW".[4] It envisages a wide array of different technological options such as "compressed air energy storage", "mechanical kinetic energy" (flywheel storage), "thermal energy" (heat), and "electrochemical energy" (batteries). It notably singles out "methanised hydrogen", a synthetic fuel (methane) produced from the combination of CO_2 and hydrogen.[5] Consequently, the EESC underlines that methanised hydrogen has by far the greatest energy storage potential in current gas infrastructures (for long periods) and can also form long-chain hydrocarbons with multiple applications (notably as substitutes for fossil resources in plastics).[6]

In academic literature, the term "methanised hydrogen" is usually replaced by other synonyms, including "CO_2 methanation" or power-to-gas (which defines the process) and "renewable power methane" (which defines the product).[7] In addition to methane,

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[1] Energy Union Package, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank, A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy Brussels, COM(2015) 80, 25.2.2015, p. 15.
[2] *Ibid.*
[3] EESC, Opinion of the European Economic and Social Committee on "Energy storage: a factor in integration and energy security" (own-initiative opinion), Rapporteur: Pierre-Jean Coulon, (2015/C 383/04), (OJ C383/19) 17-11-2015, p. 20.
[4] *Ibid.*, pp. 19-20.
[5] Cf. M. Sterner, *Bioenergy and renewable power methane in integrated 100% renewable energy systems*, Kassel University Press, 2009, 234 p.
[6] EESC (OJ C383/19) 17-11-2015, §4.4.
[7] Cf. M. Sterner, see note 5.

the combination of CO_2 and hydrogen can also provide liquid fuels such as methanol. To be exhaustive, we will also use the terms "CO_2 hydrogenation" (process) and "CO_2-fuels" (product). Whatever the terms, the EESC calls for more research and development in the field of energy storage and for a true investment push in order to ensure the development of this innovative sector.[8]

According to a Staff Working Document issued by the European Commission, a 10 per cent renewable energy target for fuel consumption for transport purposes within the EU is still possible by 2020.[9] Given that not many alternative fuels exist in the sectors of heavy-duty road transport and aviation, additional initiatives will be required.[10] Among them, as this document points out, greenhouse gas performance of biofuel can be improved "through the use of renewable energy as process input and through carbon capture and re-use".[11] Carbon dioxide as a feedstock for synthetic gas is also mentioned among other initiatives.[12]

When evaluating the carbon balance of CO_2 hydrogenation, the following combinations can be considered. First, CO_2 can come from the combustion of fossil resources or from biogenic sources (e.g. biogas produced from waste or energy crops). It can even be extracted directly from the atmosphere.[13] These sources of CO_2 can be reacted with hydrogen produced from different sources of electricity, for instance photovoltaic, wind turbines, or electricity surpluses. Indirectly, they have a different greenhouse gas emission (GHG) factor. Thus, the global GHG balance, expressed in carbon dioxide equivalent (CO_2-eq) per unit of energy contained in the fuel (Megajoule, MJ), depends on the origins of the CO_2 and electricity.

In the perspective of the legislative process related to these technologies, it is important to get a compelling evaluation of the CO_2 savings by unit of energy. According to Meylan *et al.*, the CO_2-eq emissions of natural gas (including indirect emissions caused by extraction) amount to 66.1 gCO_2-eq/MJ.[14] This amount can serve as a benchmark when comparing estimates of CO_2 savings from different kinds of CO_2 methanation. Emissions from CO_2 methanation (including the first use of carbon as well as the combustion of renewable power methane) range from 7.1 to 46.1 gCO_2-eq/MJ, depending on the sources of CO_2 and electricity.[15] CO_2-fuels can be of interest even when the CO_2 is issued from the combustion of fossil resources, provided that hydrogen from renewable electricity is used.[16]

The EU's interest in CO_2 recycling is quite recent and constitutes a possible complementary approach for CO_2 geological sequestration, which is already regulated by the Carbon Storage Directive 2009/31/EU (CSD).[17] If we are correct in assuming the necessity of these two approaches, renewable electricity production and renewable power methane could be substituted for fossil energy (thereby limiting fossil energy exploitation and combustion), while geological storage would limit CO_2 emissions when it is not yet possible to cut drastically the use of fossil energy. For instance, the Quality of Fuels Directive (QFD) opens the door to "carbon capture and storage" related exclusively to indirect emissions from the transport sector in order to reduce life-cycle greenhouse gas emissions from fuels.[18]

It is not our intention to discuss the relative virtues and drawbacks of CO_2 sequestration and utilisation, but the EU is developing and regulating these two approaches because they are complementary. That said, what are the legal provisions regulating and framing the development of CO_2 utilisation?

Directive 2015/1513[19] amends the Renewable Energy Directive (RED)[20] and the Quality of Fuel

[8] EESC (OJ C383/19) 17-11-2015, §1.6.

[9] Commission Staff Working Document, *Technical assessment of the EU biofuel sustainability and feasibility of 10% renewable energy target in transport*, Accompanying the document Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and The Committee of the Regions, *Renewable energy progress report*, Brussels, 15.6.2015. SWD(2015) 117, p. 11.

[10] *Ibid.*, p. 11.

[11] *Ibid.*, p. 2.

[12] *Ibid.*, p. 10.

[13] Cf. F.D. Meylan, V. Moreau, S. Erkman, "Material constraints related to storage of future European renewable electricity surpluses with CO_2 methanation", *Energy Policy*, 2016, 94:366–376. doi: 10.1016/j.enpol.2016.04.012. Cf. M. Sterner, see note 5.

[14] F.D. Meylan, F.-P. Piguet, S. Erkman, "Power-to-gas through CO2 Methanation: Assessment of the Carbon Balance regarding EU Directives", (submitted to the *Journal of Energy Storage* in September 2016, in correction).

[15] *Ibid.* (The range is related to the recycling of CO_2 from natural gas.)

[16] A. Sternberg, A. Bardow, "Life Cycle Assessment of Power-to-Gas: Syngas vs Methane", *ACS Sustainable Chem. Eng*. 4, 2016, 4156–4165. doi:10.1021/acssuschemeng.6b00644

[17] European Parliament and Council, Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the Geological Storage of Carbon Dioxide, consolidated version, 17.02.2012 (GSD).

[18] European Parliament and the Council, Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC, consolidated text, 05.10.2015, Article 7a(2)(b)(ii).

[19] European Parliament and Council, Directive 2015/1513/EC of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources, L239, (AD).

[20] European Parliament and Council, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable

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Directive (QFD).[21] It adds to the RED, among other developments, an Annex IX(A) that lists 20 feedstocks dedicated to the production of advanced renewable fuels, four of which are characterized by CO_2 utilisation. These four feedstocks are:

- "Algae if cultivated on land in ponds or photobioreactors".[22] The growth of certain microalgae species is stimulated by the injection of concentrated carbon dioxide streams,[23] including flue gases.[24] The RED does not specify the origin of the CO_2 (biomass or fossil?).
- "Bacteria, if the energy source is renewable".[25] This item implies the use of renewable energy with "guarantees of origin".[26] Cyanobacteria, which are prokaryotic microalgae cultivated in open ponds and photobioreactors, are probably the species designated by this provision.[27] This provision does not specify the origin of the carbon dioxide.
- "Renewable liquid and gaseous transport fuels of non-biological origin".[28] This item fits the definition of hydrogen, but could also include the capture and hydrogenation of carbon dioxide.
- "Carbon capture and utilisation for transport purposes".[29] This item addresses the development of CO_2 hydrogenation.

These four types of feedstocks will complete the array of advanced renewable fuels, and the last two will be helpful in order to tackle the electricity storage challenge.[30]

More specifically, these four types of feedstocks imply the use of concentrated CO_2 in most cases, a feature that distinguishes them from the other 16 items of Annex IX(A) and from the two items of Annex - IX(B) RED. These 18 feedstocks pertain to the category of biomass,[31] and they are employed in the production of what the directive calls biofuels or bioliquids. They are somehow linked with the four feedstocks cited above, but there is a difference in the possibility of producing biofuels from these 18 categories of feedstock without artificially capturing and processing CO_2 (since the capture is performed by photosynthesis). In contrast, the production of CO_2 fuels requires specific flows of this gas. For instance, concentrated CO_2 is required to produce renewable power methane and is suited for cultivating microalgae and bacteria.

Depending on the origin of the CO_2 (biogenic, fossil, or atmospheric origins), which fuel falls into the categories of biofuels or synthetic fuels? This question is important insofar as pertaining to a category brings further juridical consequences regarding the target that shall be reached by advanced biofuels or bioliquids as outlined in section 3 below.

At first glance, algae and bacteria fall into the category of biofuels, while "renewable liquid and gaseous transport fuels of non-biological origin"[32] do not seem to fit into this category. These two statements will be widely ascertained in section 4. Nevertheless, the question remains open concerning "carbon capture and utilisation for transport purposes".[33] From a juridical viewpoint, the answer necessitates a systemic and teleological interpretation of the rules.[34] Thus, understanding the exact status and practical implications of the four types of feedstocks outlined earlier commits us to describing the legal context surrounding advanced renewable fuels and biofuels.

We endeavour in the next sections to tell why advanced renewable fuels and biofuels are a general concern for the EU (section 2); to present the different sustainability criteria that biofuels shall respect (section 3); to define more precisely the four advanced fuels based on CO_2 recycling and their possible

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sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (consolidated version of 05.10.2015).

[21] Directive 98/70/EC (consolidated text, 05.10.2015 – from that point onward we quote the consolidated version).

[22] Annex IX(A)(a), Directive 2009/28/EC (consolidated version of 05.10.2015).

[23] Chan Yoo, So-Young Jun, Jae-Yon Lee, Chi-Yong Ahn, and Hee-Mock Oh. "Selection of microalgae for lipid production under high levels carbon dioxide", *Bioresource Technology* (2010) 101 (1, Supplement 1) pp. S71–S74.

[24] Cf. Bei Wang, Yanqun Li, Nan Wu, and Christopher Lan, "CO_2 bio-mitigation using microalgae", *Applied Microbiology and Biotechnology* (2008) 79 (5) pp. 707–18.

[25] Annex IX(A)(t), Directive 2009/28/EC (consolidated text, 05.10.2015 – from that point onward we quote the consolidated version).

[26] Article 2(j) and Article 15, Directive 2009/28/EC.

[27] Bei Wang *et al.*, see note 24.

[28] Annex IX(A)(r), Directive 2009/28/EC.

[29] Annex IX(A)(s), Directive 2009/28/EC.

[30] Cf. F.D. Meylan *et al.*, see note 13.

[31] In addition to the four items related explicitly or implicitly to CO_2 utilization, Annex IX(A) lists the following 16 feedstocks: (b) Biomass fraction of mixed municipal waste, (c) Bio-waste, (d) Biomass fraction of industrial waste, (e) Straw, (f) Animal manure and sewage sludge, (g) Palm oil mill effluent and empty palm fruit bunches, (h) Tall oil pitch, (i) Crude glycerine, (j) Bagasse, (k) Grape marcs and wine lees, (l) Nut shells, (m) Husks, (n) Cobs cleaned of kernels of corn, (o) Biomass fraction of wastes and residues from forestry and forest-based industries, (p) Other non-food cellulosic material, (q) Other ligno-cellulosic material. Annex IX(B) lists the two additional feedstocks: (a) Used cooking oil, (b) Animal fats.

[32] Annex IX(A)(r), Directive 2009/28/EC.

[33] Annex IX(A)(s), Directive 2009/28/EC.

[34] Cf. M. Poiares Maduro, "Judicial Adjudication in a Context of Constitutional Pluralism", *European Journal of Legal Studies*, December 2007, pp. 137-152. Cf. S. Besson, M.-L. Gächter-Alge, "L'interprétation en droit européen: quelques remarques introductives", in Besson, S., Levrat, N. & Clerc, E. (eds), "L'interprétation en droit européen—Interpretation" in *European Law*, Zürich: Schulthess 2011, pp. 3–35.

inclusion in the category of biofuels by European directives (section 4); to present and assess the relevance of the evaluation rules of the greenhouse gas emissions savings capacity as part of the directives (section 5); and finally to draw conclusions about the relevance of the first EU directives on CO_2-fuels.

II. Advanced Renewable Fuels and Biofuels as a General Concern in the EU

This section presents the general framework of the two directives that aim to promote and support advanced renewable fuels in order to overcome the issues of first generation biofuels.

According to Directive 2015/1513, advanced biofuels "provide high greenhouse gas emission savings with a low risk of causing indirect land-use change, and do not compete directly for agricultural land for the food and feed markets."[35] Thereby, the need exists to encourage further research in advanced biofuels made from algae or waste, among other feedstocks. According to Scarlat *et al.*, the issue is real since the share of renewables in transport (biofuels and renewable electricity) is expected to rise 19–20 per cent by 2030.[36]

The RED underlines the need for energy efficiency in the transport sector because the mandatory percentage target for energy from renewable sources that has to be achieved by all Member States "is likely to become increasingly difficult to achieve sustainably if overall demand for energy for transport continues to rise".[37] The directive confirms this statement while pinpointing the need to limit competition between biofuels and food production (risk of food shortage) and to assess regularly the effect on food prices in order to adapt the biofuels policy.[38]

Besides the risk of food shortage, the European Parliament was also aware of the need to restrain environmental impacts, notably for maintaining the integrity of carbon stocks in soils,[39] and the biological diversity of forests and other biotopes, as well as for maintaining soil, water, and air.[40] Article 17(3) protects biodiversity: "Biofuels and bioliquids . . . shall not be made from raw material obtained from land with high biodiversity value".[41] Furthermore, biofuels and bioliquids should also comply with the EU environmental requirements for groundwater and surface water quality, as well as with social requirements.[42] These provisions do not prevent the EU from criticising its own biofuel policy,[43] or to face criticism from non-governmental organizations[44] and the comments of scholars.[45] The RED limits first-generation biofuels to *only* 7 per cent of energy consumption for transport by 2020[46] (instead of 10 per cent for non-fossil fuels[47]). Hence, the urgent need to develop biofuels derived from different feedstocks like "waste and residues from biological origin" or "the biodegradable fraction of industrial and municipal waste",[48] algae, bacteria, and the other items listed in Annex IX RED, including synthetic fuels through CO_2 hydrogenation.

It must be noted that the 20 feedstocks listed in the Annex IX(A) RED have a target of 0.5 percentage points of the share of energy from renewable sources across all forms of transport by 2020.[49] This target is

[35] §7, Directive 2015/1513.
[36] N. Scarlat, J.-F. Dallemand, F. Monforti-Ferrario, M. Banja, "Renewable energy policy framework and bioenergy contribution in the European Union: An overview from National Renewable Energy Action Plans and Progress Reports", *Renewable and sustainable energy reviews* 51 (2015), p. 981. http://dx.doi.org/10.1016/j.rser.2015.06.062
[37] §18, Directive 2009/28/EC.
[38] §9, §71, Article 17(7), Directive 2009/28/EC.
[39] §71, §73, §85 and Article 17(4), Directive 2009/28/EC.
[40] Article 17(4)(5)(6)(7), Directive 2009/28/EC.
[41] Article 17(3), Directive 2009/28/EC.
[42] §74, Directive 2009/28/EC.
[43] According to a Staff Working Document of the European Commission, "biofuel production also impacts soil, water, and air quality, primarily during the production of biofuel feedstock. . . . Increased demand for biofuels also leads to increasing monoculture systems, which adversely affects soil quality. . . . Increased biofuel production also led to an increase in water consumption, with 14.0 km^3 of water used for EU biofuel production in 2012." *SWD*(2015) 117, 15.6.2015, p. 4.
[44] According to a study from Transport & Environment, "On average, biodiesels from virgin vegetable oil – which take almost 70% of the EU biofuel market – lead to around 80% higher emissions than the fossil diesel they replace. Palm and soy-based biodiesel is even three and two times worse respectively." "The EU 7% cap should fall to zero after 2020". Globiom: the basis for biofuel policy post 2020, Transport & Environment, April 2016, p. 8 and p. 11. https://www.transportenvironment.org/sites/te/files/publications/2016_04_TE_Globiom_paper_FINAL_0.pdf (accessed 29 June 2016).
[45] "A significant increase in the demand for biomass for bioenergy and the expected additional demand for bio-based materials will increase the competition for natural resources, in particular for land and water resources with potential negative impact on the land use patterns, biodiversity and environment. The increased use of forest and agricultural waste streams for bioenergy production could however have negative effects on soil fertility, soil productivity and biodiversity. The increased production of biomass can aggravate water scarcity in many areas of the world, because it puts additional pressure on water demand." Nicolae Scarlat *et al.*, see note 36, p. 983.
[46] Cf. Article 3(4)(d), Directive 2009/28/EC.
[47] Article 3(4), Directive 2009/28/EC & Article 7a(2), Directive 98/70/EC.
[48] Article 2(e) Directive 2009/28/EC.
[49] "A reference value for this target is 0.5 percentage points in energy content of the share of energy from renewable sources in all forms of transport in 2020 referred to in the first subparagraph, to be met with biofuels produced from

not aspirational from a quantitative viewpoint, but it focuses on new valorisation technologies for different feedstocks.

III. The 60 per cent Target and Other Sustainability Criteria

In view of the above drawbacks of biofuels, Article 7b QFD and Article 17 RED state that the "sustainability criteria" are compelling and further specify their characteristics. "The greenhouse gas emission saving from the use of biofuels [and bioliquids][50] ... shall be at least 60 per cent for biofuels [and bioliquids] produced in installations starting operation after 5 October 2015."[51] The directives on renewable energy (RED) and on the quality of fuels (QFD) display the 60 per cent savings target as a sustainability criterion, specifying that biofuels produced from waste and residues need only fulfil this criterion.[52] For the first and second generations of biofuels,[53] additional criteria are specifically linked to biodiversity and carbon stored in land: biofuels and bioliquids shall not be made from raw material obtained from land with high biodiversity value[54] or high carbon stock[55] and from land that was peatland in January 2008.[56] Finally, biofuels and bioliquids shall also fulfil the minimum requirements for good agricultural and environmental condition.[57]

According to a preliminary report from an agency in the United Kingdom, the 60 per cent threshold is too high and will discourage research and investment geared towards advanced biofuel production.[58] This remark is partially justified, for instance in the case of algae and bacteria, since a fair assessment should integrate the amount of CO_2 from fossil origin that is injected into ponds and photobioreactors. Such a calculation would make difficult to reach the 60 per cent target,[59] despite the fact that microalgae production could contribute to reduce competition with food and agricultural land.[60]

As will be ascertained later on, "renewable liquid and gaseous transport fuels of non-biological origin"[61] do not fall in the category of biofuels or bioliquids and consequently they do not need to reach that target.

Given the same target, what would happen if we consider synthetic fuel made from hydrogen produced with renewable electricity and from CO_2 of biomass origin as biofuel? This possibility would not raise more concerns under the sustainability criteria than waste, residues, algae, and bacteria, and it ought to fulfil the 60 per cent target. At this stage of the analysis, this question remains open.

IV The EU Directive and Fuels Based on Carbon Dioxide Recycling

Shall we include or exclude from the category of biofuels and bioliquids the four fuels listed in Annex IX of Directive 2009/28/EC[62] when they are produced from CO_2 of biomass or fossil origin? The answer is important since the directive does not require biofuels and other advanced renewable fuels to meet the same objectives.

4.1 Algae

According to the RED, algae cultivated for energy purpose have to be processed in ponds or photobioreactors.[63] The growth of alguae can be stimulated by the injection of concentrated carbon dioxide. Microalgae (single-celled photosynthetic organisms) are usually cultivated for biofuel production. The difference between algae and bacteria depends on the evolution stage of the unicellular organism, algae being eukaryotes (with a nucleus) and bacteria being prokaryotes (without nucleus).[64] Whatever its exact and compelling definition, algae as a feedstock can be listed in the category of biomass insofar as they are biodegradable.

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feedstocks and with other fuels, listed in part A of Annex IX." Article 3(4)(e), Directive 2009/28/EC (consolidated version of 05.10.2015). The last 2.5% ought to be covered by renewable electricity, biofuels of the second generation not listed in Annex IX, and the two items from Annex IX(B) (7% + 0.5% + 2.5% = 10%).

50 The Directive on renewable energy differs from the Directive on the quality of fuels by two words since it adds the mention of bioliquids.

51 Article 7b(2), Directive 98/70/EC and Article 17(2), Directive 2009/28/EC.

52 Article 7b(1), Directive 98/70/EC.

53 Article 23(8)(a), Directive 2009/28/EC.

54 Article 7b(3), Directive 98/70/EC & Article 17(3), Directive 2009/28/EC.

55 Article 7b(4), Directive 98/70/EC & Article 17(4), Directive 2009/28/EC.

56 Article 7b(5), Directive 98/70/EC & Article 17(5), Directive 2009/28/EC.

57 Article 7b(6), Directive 98/70/EC & Article 17(6), Directive 2009/28/EC.

58 Arup URS Consortium, Advanced Biofuel Feedstocks – An Assessment of Sustainability, Framework for Transport-Related Technical and Engineering Advice and Research (PPRO 04/45/12), E4tech (UK), 2014, p. 32. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/277436/feedstock-sustainability.pdf (accessed 29.06.2016),

59 See subsection 5.2.

60 N. Scarlat *et al.*, see note 36, p. 983.

61 Annex IX(A)(a)&(r), Directive 2009/28/EC.

62 Annex IX.

63 Annex IX(A)(a).

64 We do not endorse the doubt of the Arup URS Consortium that states: "It is very unclear as to what 'Bacteria' is actually meant to encompass, and whether it is actually a process, not a feedstock." *Ibid.* p. 28. (See also page 13.).

Legal specifications do not exist to define the origin of the CO_2 injected into a culture. It is supposed to come from biomass or combustion of fossil energy (or from the calcination of limestone by the cement industry).

The origin of the energy used in the process is not legally specified. It obviously comes from the sun through photosynthesis, but there is also a need to mix the water and temper the ponds and photobioreactors with, for instance, waste heat from a nearby power plant.

Whatever the origin of the CO_2 used to stimulate their growth, algae cultivated in ponds or photobioreactors[65] fall into the category of biomass, and the fuels produced from these biodegradable organisms are considered biofuels or bioliquids.

4.2 Bacteria

The cultivation of "bacteria, if the energy source is renewable",[66] implies the use of renewable energy[67] with "guarantees of origin" according to specific RED provisions.[68] The use of renewable energy is specified for bacteria[69] and not for algae. To this extent, the cultivation of algae and the production of related biofuels would be less constrained with regard to energy origin than biofuels made from bacteria. However, like algae, some bacteria (cyanobacteria) can be cultivated in photobioreactors (a controlled, closed environment), a fact that does not make their cultivation very different from algae. The main difference, which probably explains the differentiation in the RED, is that some species of bacteria are not photosynthetic and can consume hydrocarbons or hydrogen (chemo-autotrophic bacteria),[70] or possibly electrons.[71] The cultivation of algae or bacteria can use waste heat coming from a nearby power plant or other industrial facility.

Cyanobacteria can be cultivated in photobioreactors with the injection of concentrated CO_2 from either fossil or non-fossil energy. Whatever the origin of the CO_2 used for stimulating their growth, bacteria are living organisms that fall into the category of biomass.

4.3 More indications on the origin of CO_2 stimulating the growth of algae and bacteria

No recent mention of the origin of the CO_2 can be found in eur-lex.europa.eu or in the report of a UK consortium (see note 58), but the issue is well known in the area of agricultural regulation. According to the Expert Group for Technical Advice on Organic Production (EGTOP) of the European Union Directorate-General for Agriculture and Rural Development, the use of CO_2 issued from fossil fuel combustion is not forbidden for cultivation under greenhouses.[72] In winter, this practice makes more sense because fuels are burned to heat greenhouses. However, the CO_2 used for rebalancing/enrichment should preferably come from processing or burning biomass.[73]

Concerning bioenergy production, using CO_2 derived from biomass would provide a more climate friendly biofuel than CO_2 from fossil fuel combustion. Since the volume of available CO_2 from biomass could face a shortfall, the contribution of CO_2 from fossil fuel combustion could be a transitory means of helping bacteria and algae capture more solar energy with the aim of increasing the share of advanced fuels for transport purposes, at least up to 2050.[74] Carbon dioxide from direct air capture could also become an eligible feedstock, but is currently expensive.[75]

[65] Annex IX(A)(a), Directive 2009/28/EC.

[66] Annex IX(A)(t).

[67] Article 2(a) of Directive 2009/28/EC specifies: "'energy from renewable sources' means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases".

[68] Article 2(j) and Article 15, Directive 2009/28/EC.

[69] Given the above definition of algae (see subsection 4.1), we can hypothesize that bacteria are unicellular prokaryotes, which is a valuable reason to distinguish them from algae.

[70] Some bacteria can use other forms of energy, for instance chemical energy (fossil resources they can literally "eat"). Sugai Yuichi, Isty Adhitya Purwasena, Kyuro Sasaki, Kazuhiro Fujiwara, Yoshiyuki Hattori, and Komei Okatsu, "Experimental studies on indigenous hydrocarbon-degrading and hydrogen-producing bacteria in an oilfield for microbial restoration of natural gas deposits with CO2 sequestration". *Journal of Natural Gas Science and Engineering*, 2012, 5 (0): pp. 31–41. doi:10.1016/j.jngse.2012.01.011. In this case, the source of the chemical energy has to be carefully examined, as requested by the Directive, in order to avoid producing a "biofuel" made from petroleum. When cyanobacteria are considered, the guarantee of origins regarding renewable energy is not important because cyanobacteria are photosynthetic organisms using sun energy (i.e. a renewable energy).

[71] Xu, Heng, Kaijun Wang, and Dawn E. Holmes, "Bioelectrochemical removal of carbon dioxide (CO2): An innovative method for biogas upgrading". *Bioresource Technology*, 2014, 173 (0): 392-98. doi:10.1016/j.biortech.2014.09.127.

[72] European Commission, Directorate-General for Agriculture and Rural Development, Directorate H. Sustainability and Quality of Agriculture and Rural Development, Expert Group for Technical Advice on Organic Production (EGTOP), H.3. Organic farming, Final Report On Greenhouse Production (Protected Cropping), 2013, technical advice adopted at the 7th plenary meeting of 19 and 20 June 2013, EGTOP 6/13, §6.

[73] *Ibid.*, §6 (see also conclusion at subsection 3.8.5).

[74] Rogelj *et al.* determine that the carbon budget that could fit the 1.5°C is very tight as it implies achieving net negative CO_2 emissions after 2050. Rogelj Joeri *et al.*, "Energy System transformations for limiting end-of-century warming to below 1.5°C", *Nature Climate Change*, 2015, Vol 5, pp. 519–528.

[75] K. Zenz House, A. C. Baclig, M. Ranjan, E. A. van Nierop, J. Wilcox, and H. J. Herzog, "Economic and energetic analysis of capturing CO_2 from ambient air", *Proceedings of the National Academy of Sciences*, 2011, 108 (51): 20428-33. doi:10.1073/pnas.1012253108.

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In conclusion, we confirm that whatever the origin of the carbon dioxide, algae and bacteria cultivation is qualified to produce biofuel. Algae and bacteria producers are thus compelled to reach the 60 per cent target of greenhouse gas emissions savings as unique criterion for sustainability. The methodology for calculating GHG emissions savings from these biofuels is set forth in Annex V RED (see subsection 5.2).

4.4 Renewable liquid and gaseous transport fuels

"Renewable liquid and gaseous transport fuels of non-biological origin"[76] includes not only hydrogen for transport purposes, but also the capture and valorisation of CO_2 whose origin is not related to biomass and would come from the combustion of any fossil source. The definition given by EU directives does not provide further explanation: " 'Renewable liquid and gaseous transport fuels of non-biological origin' means liquid or 'gaseous fuels other than biofuels whose energy content comes from renewable energy sources other than biomass, and which are used in transport' ".[77] The exact signification remains unclear from the point of view of chemistry as it could refer to hydrogen or CO_2 hydrogenation strategies with fossil carbon dioxide.

Different preparatory works do not confirm hydrogenation of CO_2 as a possible process covered by this provision,[78] but these legal commentaries would not hinder Member States from including this strategy in the scope of this provision. It is also true that it is not absolutely necessary for the item "renewable liquid" to encompass CO_2-fuels insofar as the next item, "carbon capture and utilisation for transport purposes" seems to be geared towards all forms of CO_2 hydrogenation (see next subsection).

In any case, whether it is hydrogen or renewable power methane issued from fossil carbon dioxide, such synthetic fuel cannot be categorised as "biofuel". Thus, the directive would not compel producers of this kind of fuel to meet the 60 per cent greenhouse gas emissions savings[79] as a condition of the sustainability criterion. This kind of fuel has only to get energy from all renewable sources but biomass, and to obtain the related "guarantee of origin".[80]

4.5 Carbon capture and utilisation for transport purposes

Another type of feedstock is "carbon capture and utilisation for transport purposes, if the energy source is renewable".[81] This kind of feedstock opens room for the development of CO_2 methanation and more generally CO_2 hydrogenation strategies. The electricity required to produce hydrogen shall come from a renewable source and is compelled to obtain a "guarantee of origin".[82] Renewable energy from non-fossil sources includes: "wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogases".[83] The requirement of renewable energy to capture CO_2 does not create a problem because the hydrogenation of CO_2 usually produces a sufficient amount of heat for that purpose.[84]

Annex IX(A)(s) does not specify the origin of the CO_2 that can come from fossil resources, the atmosphere, or biomass. If the fuel is made from CO_2 coming from biomass, is it a biofuel based on this criterion? From the viewpoint of the RED: "'biofuels' means liquid or gaseous fuel for transport produced from biomass".[85] The key term in this provision is *biomass*, explained in Article 2(i), which "means the *bio*degradable fraction of products, waste and residues from biological origin from agriculture ..., as well as the *bio*degradable fraction of industrial and municipal waste".[86] By definition, carbon dioxide is not the "biodegradable fraction of products" and does not constitute a subcategory of biomass, even when it comes from biomass transformation. Biofuels are produced by concentrating "solar" energy contained in biomass. CO_2 does not contain useful energy. Therefore, CO_2 definitely cannot be considered biomass.

If a fuel is produced from energy of biological origin, is there any reason to consider that this feedstock enters in the production of biofuel? We can draw an analogy with the definition of fuels of non-biological origin in Article 2(10) RED.[87] The

[76] Annex IX(A)(r), Directive 2009/28/EC.

[77] Article 2(10), Directive 98/70/EC.

[78] First, the preparatory report that informed the UK's ongoing negotiations with other EU Member States on Directive 2015/1513 stated that this provision refers to hydrogen, not to power-to-gas (Arup URS Consortium, see note 58, p. 80). Second, according to one EU parliamentarian, "renewable liquid and gaseous fuels of non-biological origin" is a term that should be defined in this directive and be understood "as for example hydrogen or oxygen produced using wind or solar energy." (European Parliament, Committee on the Environment, Public Health and Food Safety, Amendments 364–482, 2012/0288(COD), Draft report Corinne Lepage (PE508.236v01-00), 3.6.2013, Amendment 382 (Sari Essayah), p. 15.)

[79] Article 7b(1), Directive 98/70/EC.

[80] Article 2(j) and Article 15, Directive 2009/28/EC; Article 2(10), Directive 98/70/EC

[81] Annex IX(A)(s), Directive 2009/28/EC.

[82] Article 2(j) and Article 15, Directive 2009/28/EC

[83] Article 2(a), Directive 2009/28/EC.

[84] "The heat released by the exothermic methanation (...) covers the requirements of CO_2 capture from biogas." (Meylan *et al.*, see note 13).

[85] Article 2(i), Directive 2009/28/EC

[86] Article 2(e), Directive 2009/28/EC (we underlined "*bio*" before degradable).

[87] We could make an analogy with "renewable liquid and gaseous transport fuels of non-biological origin", which are not biofuels provided their energy content does not come from biomass: " 'Renewable liquid and gaseous transport fuels of non–biological origin' means liquid or gaseous fuels other than biofuels whose energy content comes from renewable energy sources other than biomass, and which are used in transport". Article 2(10), Directive 98/70/EC.

question remains open, but it would concern only a very limited number of CO_2-fuels.[88]

We recall that, if CO_2-fuels fall into the biofuel category (a different interpretation from ours), it would be difficult to fulfil the purposes of the Directive on renewable energy (RED). This statement is confirmed when looking at the framework and objectives of the directive. The recycling of CO_2 does not jeopardize biological diversity insofar as it does not rely directly on biomass exploitation. Moreover, the item "carbon capture and utilisation for transport purposes" does not compel the producers of this kind of fuel to meet the 60 per cent target[89] of greenhouse gas emissions savings as a feature of the sustainability criteria, nor does it require the respect of the other criteria of sustainability designed for biofuels and bioliquids. Yet it must be highlighted that CO_2-fuels usually respect these criteria much more than biofuels.[90] Additionally, the carbon balance assessment of power-to-gas (section 1 *supra* and subsection 5.3 *infra*) demonstrates that CO_2 methanation has a CO_2 savings potential that would contribute to increasing the share of renewable advanced fuels in the transport sector. As long as these objectives are important, our systematic and teleological interpretation of the RED finds there is no reason to categorize as "biofuel" the fuels made through the CO_2 hydrogenation process.[91]

V. EU Evaluation Rules for Greenhouse Gas Emissions Savings

There is a pending question about the ability of fuel producers that use algae and bacteria to reach the 60 per cent target[92] as a feature of the sustainability criteria. This target is of no importance regarding the evaluation of advanced fuels of non-biomass origin. We will nevertheless envisage the case where any assessment body would employ it when analysing the GHG performance of CO_2 hydrogenation (see note 117).

Our main question is whether the calculation formulae included in the RED (and QFD) generate some bias and whether they favour one approach over another without scientific justification? Doubts about their suitability exist because the formulae on carbon storage and carbon capture and replacement date back to the RED of 23 April 2009,[93] six years before the adjunction of Annex IX and the items related to CO_2 recycling.[94] In order to clarify this point, we present first the main elements of the calculation and then we endeavour to describe how it works regarding CO_2 recycling.

5.1 Annex V RED and Annex IV QFD

Life-cycle evaluation rules are set forth in Annex V of the Directive on Renewable Energy (RED),[95] and in Annex IV of the Directive on the Quality of Fuels (QFD).[96] Annex IV QFD concerns solely biofuels, while Annex V RED concerns biofuels and bioliquids, as well as their fossil fuel comparators, with letter C specifying the calculation of "greenhouse gas emissions from the production and use of transport fuels, biofuels, and bioliquids".[97] We interpret both annexes as the rules for evaluating biofuels made from algae[98] and bacteria;[99] however, the rules do not seem to address CO_2 hydrogenation (see subsection 5.3).

We have aggregated some variables of the formula in order to make it shorter.[100] According to Annex V(C),[101] greenhouse gas emissions from the production and use of transport fuels, biofuels, and bioliquids shall be calculated as:

$E = e_p + e_u - e_{ccr} - e_{ccs} - e_{op}$;

E = total emissions from the use of the fuel;

e_p = emissions from production (extraction or cultivation of raw materials, carbon stock changes caused by land-use change, processing, transport, and distribution);

e_u = emissions from the fuel in use;

e_{ccs} = emission saving from carbon capture and geological storage;

e_{ccr} = emission saving from carbon capture and replacement;

e_{op} = emission saving from other processes (excess electricity from cogeneration, soil carbon accumulation via improved agricultural management).

The formula is not independent of energy concerns since "greenhouse gas emissions from fuels (E), shall be expressed in terms of grams of CO_2 equivalent per MJ of fuel, gCO_2eq /MJ."[102]

Additionally, "greenhouse gas emission saving from biofuels and bioliquids shall be calculated as: $SAVING = (E_F - E_B)/E_F$".[103] Where:

[88] This configuration would rarely occur since CO_2 hydrogenation is suited for storing intermittent electricity (wind and sun), whereas biomass itself is a form of energy storage.
[89] Article 7b(1), Directive 98/70/EC.
[90] Cf. F.D. Meylan *et al.*, see note 13.
[91] The question remains open if the energy of CO_2 hydrogenation comes from biomass (see note 87).
[92] Article 7b(1), Directive 98/70/EC.
[93] Annex V, Directive 2009/28/EC, (OJ L 140/16, 5.6.2009).
[94] Annex IX, Directive 2015/1513 (OJ L 239/1, 15.9.2015).
[95] Annex V, Directive 2009/28/EC of 23 April 2009 (OJ L 140/16, 5.6.2009).
[96] Annex IV(C), Directive 98/70/EC (since its amendment by Directive 2009/30/EC of 23 April 2009 (OJ L 140/88, 5.6.2009).
[97] Annex V(C), Directive 2009/28/EC.
[98] Annex IX(a), Directive 2009/28/EC.
[99] Annex IX(t), Directive 2009/28/EC.
[100] In the following presentation, e_p and e_{op} represent different variables that are less relevant to our discussion.
[101] The following footnotes mention only the Annex V RED and not the similar Annex IV of QFD.
[102] Annex V(C)(2), Directive 2009/28/EC.
[103] Annex V(C)(4), Directive 2009/28/EC.

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E_B = total emissions from the biofuel or bioliquid; and
E_F = total emissions from the fossil fuel comparator.

The last formula is the one through which it is appropriate to assess whether the 60 per cent target has been reached by a biofuel. For biofuels, the default value of the fossil fuel comparator E_F should be 83.8 gCO_2eq /MJ – among other figures – if no other accurate figure is available.[104]

The definitions of e*p* and e*op* do not generate specific difficulties concerning our discussion and can be understood through the above definition.

However, the following specification is important: "Emissions from the fuel in use, *eu*, shall be taken to be zero for biofuels."[105] The explanation lies in the capacity of biomass to extract atmospheric carbon dioxide, according to its purported CO_2 neutrality.[106]

The directive puts forth a provision related to the evaluation of emission savings from carbon capture and geological storage (e*ccs*) "of emitted CO_2 directly related to the extraction, transport, processing, and distribution of fuel."[107] The same kind of provision is available for CO_2 re-use: "Emission savings from carbon capture and replacement, e*ccr*, shall be limited to emissions avoided through the capture of CO_2 of which the carbon originates from biomass and which is used to replace fossil-derived CO_2 used in commercial products and services."[108] The formula does not differentiate between the geological sequestration of CO_2 (e*ccs*) and the replacement of CO_2 (e*ccr*), even though the latter will be emitted again within a short span of time, whereas the former will not.

The term "replacement" does not encompass exactly all types of CO_2 recycling. We can get its exact meaning by examining how the above formula can evaluate the CO_2 performance of ethanol (a biofuel made from feedstocks like sugar cane).[109] The transformation process leading to ethanol releases a significant amount of CO_2 that can be easily captured and used as a co-product in another process that requires this gas (CO_2-fuels, welding under CO_2 atmosphere, polymers, urea production, etc.).[110] It is correct to deduce the "replacement" of CO_2 when it is really occurring, insofar as the biofuel production plant could conversely release it directly into the atmosphere. However, this subtraction is restricted to the amount of CO_2 related to the co-product of the biofuel. When the CO_2 comes from natural gas combustion, it would not be possible to share this amount between any advanced renewable fuel and the power plant since the formula does not provide a holistic and comprehensive approach to CO_2 hydrogenation (see subsection 5.3).

5.2 Algae and bacteria

Fostering the growth of algae or bacteria by means of CO_2 enrichment can be done whatever the origin of the CO_2 (fossil or biomass) and can lead to the production of biofuels (or bioliquids). The question is whether and how the injection of CO_2 into ponds or photobioreactors will be taken into account by the formulae of Annex V(C) RED?

First, this kind of biofuel – like other biofuels – will not take into account emissions from the fuel in use (e*u* = 0). This is justified for conventional biofuels that absorb atmospheric CO_2 through photosynthesis (such biofuels are deemed to be carbon neutral; see note 106). However, in the case of biofuels derived from algae and bacteria, the evaluation does not account for the origin – possibly fossil – of their carbon content.

Second, the variable e*ccr* (carbon capture and replacement) concerns the CO_2 released from the transformation of algae or bacteria, for instance when residues are anaerobically fermented. When CO_2 is captured and used in a co-product, the variable e*ccr* is subtracted from the total emissions of the biofuel.

Third, CO_2 enrichment with fossil CO_2 is not in the scope of the variable e*p* since a mandatory provision states, "Capture of CO_2 in the cultivation process of raw materials shall be excluded".[111] In other words, the calculation will exclude the capture of carbon dioxide. However, emissions of fossil CO_2 occur physically in the process without having to be assessed and attributed to algae or bacteria. This provision, together with the exclusion of the CO_2 emitted by the fuel in use, could advantage the algae and bacteria industry and help these types of biofuels hit the 60 per cent target. However, the evaluation is not fair as it does not take into account the origin (possibly fossil) of the carbon content of algae and bacteria.

Fourth, how to calculate and to whom to allocate the amount of CO_2 (originating from a fossil power plant) injected into open ponds or photobioreactors but not absorbed by microalgae? Should we consider that the power plant has continued to emit these amounts? If this is the case, what kind of motivation does the power plant industry have to recycle CO_2?

The last question blurs the picture because it lacks a

[104] Annex V(C)(19), Directive 2009/28/EC.
[105] Annex V(C)(13), Directive 2009/28/EC.
[106] The assumption about carbon neutrality "is not correct and results in a form of double-counting, as it ignores the fact that using land to produce plants for energy typically means that this land *is not producing plants for other purposes*, including carbon otherwise sequestered". European Environment Agency Scientific Committee, Opinion of the EEA Scientific Committee on Greenhouse Gas Accounting in Relation to Bioenergy, 15 September 2011, 10 p.
[107] Annex V(C)(14), Directive 2009/28/EC.
[108] Annex V(C)(15), Directive 2009/28/EC.
[109] L. Xu, "Adding value to carbon dioxide from ethanol fermentations", *Bioresource Technology*, vol. 101, Issue 10, May 2010, pp. 3331–3319.
[110] *Ibid.*
[111] Annex V(C)(6), Directive 2009/28/EC.

clear answer, but there is no doubt the evaluation rules of the directives do not provide a comprehensive and *fair assessment* (from cradle to grave) of these two biofuels.

5.3 Carbon dioxide hydrogenation for transport purposes

Evaluation of the emissions of CO_2 hydrogenation and related synthetic fuels is not encompassed by Annex V RED, which is dedicated to biofuel. However, an evaluation can be found in the European Commission Directive 2015/652 on Calculation Methods (CMD), which gives the default values expressed in gCO_2-eq/MJ of a CO_2-fuel or, more precisely, of "compressed synthetic methane in a spark ignition engine" "through the Sabatier[112] reaction of hydrogen from non-biological renewable energy electrolysis".[113] The life cycle GHG intensity amounts to 12.4 gCO_2-eq/MJ for the whole power-to-gas process.[114] This is the only mention of this approach and no other evaluation is cited despite the fact that – depending on the source of energy and CO_2 inputs – the total emissions of the fuels can vary dramatically.

Furthermore, the default value is in the lower range of the results of Meylan *et al.*, which range from 7.1 to 46.1 gCO_2-eq/MJ (see section 1).[115] The value is also in the lower range of the results of Reiter and Lindorfer who calculated a range of 6 to 53 gCO_2-eq/MJ,[116] depending on the sources of CO_2 and electricity. This discrepancy with the EU's default value is significant and raises doubt about the relevance of Council Directive 2015/652 on that specific point.

A little doubt still exists about whether formulae of Annex V(C) RED are dedicated to the assessment of synthetic fuels made through CO_2 methanation. Nonetheless, if we were wrong on the non-classification of CO_2 methanation in the category of biofuels, these formulae would not be streamlined for that purpose,[117] whereas the default value for the whole power-to-gas process in Directive 2015/652 (CMD) is definitely not able to report with confidence the CO_2 savings depending on the origins of the energy and the carbon dioxide.

VI. Conclusions

This article aims to describe and organize the provisions on carbon capture and utilisation related to advanced renewable fuels and biofuels. Since September 2015 these technologies have given rise to a specific EU directive that amends the Renewable Energy Directive (RED) and the Quality of Fuels Directive (QFD). We recall that these technologies would be useful for climate mitigation, not by themselves, but on condition that the broad legal framework is geared toward that purpose, which is presently not the case.

The ambition of this article is limited to understanding the provisions of the directives related to advanced renewable biofuels and related texts. We raise a discussion on the ability of the EU directives to manage the advantages and drawbacks of CO_2 hydrogenation, as well as biofuels made from algae or bacteria enriched with carbon dioxide. To shed light on the purposes of these directives, we present some key questions on energy transition, the limitations and drawbacks of biofuels, and the expected advantages of advanced renewable fuels and biofuels. CO_2-fuels are very important for the future of transport, as well as for energy storage on a seasonal basis, two key developments recognised by the EU.

Our questioning does not tackle the provision on

[112] The Sabatier reaction: $CO_2 + 4\,H_2 \Rightarrow CH_4 + 2\,H_2O +$ heat.

[113] Council Directive (EU) 2015/652 of 20 April 2015 laying down calculation methods and reporting requirements pursuant to Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels, OJ L 107/26, 25.4.2015, Annex I(2)(5). (The Sabatier reaction produces a synthetic methane, and water, and heat.)

[114] The life cycle GHG intensity of the Sabatier reaction amounts to 3.3 gCO_2-eq/MJ, a value we probably should add to emissions caused by the electrolysis step since 9.1 gCO_2-eq/MJ is indicated for "electrolysis fully powered by non-biological renewable energy". Thus, the Directive 2015/652 estimates an amount of 12.4 gCO_2-eq/MJ (3.3 + 9.1) for the whole power-to-gas process. (Annex I(2)(5), Council Directive (EU) 2015/652)

[115] Cf. F.D. Meylan *et al.*, see note 14. The results of recycling CO_2 from coal range from 38.9 to 56.9 $gCO_{2\text{-eq}}$/MJ, well above the range produced by recycling CO_2 from natural gas or biogas origins.

[116] G. Reiter, J. Lindorfer, *Global warming potential of hydrogen and methane production from renewable electricity via power-to-gas technology*, Int J Life Cycle Assess 20: pp. 477–489 (2015). doi: 10.1007/s11367-015-0848-0

[117] The question is whether and how this formula accounts for the source of carbon dioxide? For instance, in the case of a methanation plant that uses CO_2 captured from a natural gas power plant (i.e. fossil), the emissions from the fuel in use (*eu)* will be taken to zero, and the CO_2 that enters in the methanation process will not be subtracted through the variable e*ccr*. If the methanation plant uses CO_2 from a renewable source (for instance CO_2 from an ethanol plant), only the ethanol plant can subtract the amount of CO_2 replaced with regard to the variable e*ccr*. In both cases, the formula does not encompass the energy contributions of the methanation process together with the energy contained in the initial fuel (i.e. natural gas or ethanol), nor does it calculate their global CO_2/energy ratio through their common emissions of CO_2 and common energy production. If the above advanced fuels were categorised as biofuels by lack of comprehensive and holistic evaluation, the assessment of the CO_2/energy ratio by the Annex V RED would not be balanced nor able to support the "best' technological option.

double counting the energy content of advanced fuels.[118] This provision aims to ease the 10 per cent renewable energy target to be reached by Member States by artificially multiplying energy content.[119] The idea is to incentivize the use of feedstocks with low, indirect land-use change.[120] This point would deserve a specific paper.

Regarding our conclusions, algae and bacteria are biomass feedstock, and the fuel derived from this feedstock shall be included in the category of biofuels. No legal requirement for the origin of the CO_2 exists, hence the possibility of obtaining CO_2 flows either from biomass transformation or from fossil energy combustion. CO_2 from biomass would result in a more climate friendly biofuel than fossil carbon dioxide. However, the volume of available CO_2 from biomass could fall short, creating the possible need – during the first period of energy transition by 2050 – to recycle CO_2 from fossil origin, keeping in mind that this source ought to be cut in the second part of the century in order to implement negative emissions schemes.

Bacteria cultivation shall use renewable energy to avert the risk of consuming hydrocarbons or non-renewable electricity, but algae should not, insofar as energy from the sun is their main source of energy (besides waste heat from a nearby industrial facility). The valorisation of waste heat and CO_2 from fossil energy could be a transitory option up to 2050.

Concerning the evaluation of algae and bacteria biofuels, it has been shown that the formula applied to these kinds of advanced biofuels is not adequate and can even be misleading. Nevertheless, this evaluation method would help these biofuels reach the 60 per cent target despite the fact that fossil CO_2 would be emitted within a short span of time. More accurate formulae would reveal these biofuels are unable to reach the 60 per cent target when using CO_2 derived from fossil resources. This fact challenges the pertinence of this target with regard to algae and bacteria fuels, which would deserve a specific legal regime apart from other biofuels.

Renewable liquid and gaseous transport fuels of non-biological origin can refer to hydrogen or CO_2 hydrogenation strategies. These fuels are not biofuels (unless maybe when the renewable electricity source employed in hydrogen production comes from biomass). They are thus exempted from the 60 per cent target about greenhouse gas emissions savings. It is also true that there is no absolute necessity to make this item of Annex IX encompass CO_2 hydrogenation insofar as "carbon capture and utilisation for transport purposes" of the same Annex seems to be clearly geared towards this strategy.

Carbon capture and utilisation for transport purposes is oriented to the development of CO_2 hydrogenation, particularly CO_2 methanation. Whatever the origin of the CO_2 and considering that intermittent renewable electricity of non-biological origin should be used for hydrogen production, there is no formal reason to consider that this process generates a biofuel. Thereby it is not subject to the 60 per cent criterion (which otherwise would be out of reach). The default values of the CO_2-eq emissions from the electrolysis process together with the Sabatier reaction, as part of Council Directive 2015/652, are largely underestimated and do not reflect the wide range of possible figures.

The formulae for CO_2-eq assessment set forth in Annex V(C) RED are definitely not suited to assess algae – and bacteria – based biofuels cultivated with CO_2 injection. They are not fair since they do not provide a comprehensive and holistic assessment of CO_2 savings (from cradle to grave).

There is no doubt that CO_2 hydrogenation and CO_2 enrichment of algae and biofuels constitute very interesting technological options for renewable advanced fuels as well as – considering hydrogenation only – for seasonal electricity storage. The EU has set forth the first rules related to this domain, thereby confirming the growing interest in the environmental and economic advantages of CO_2 recycling. On the one hand, strengthening these technological trajectories and their benefits will require a revision of EU directives in order to assess fairly these advanced fuels. On the other, relaxing or even abandoning the 60 per cent target for algae, bacteria, and CO_2-fuels would be necessary to encourage the development of these technological options.

The hydrogenation of carbon dioxide from fossil origin could constitute a relatively climate friendly strategy in the context of energy transition by 2050 (not later). Within that time period – and on condition of implementing alternative regulations – the provision binding CO_2 methanation to renewable electricity may need to be relaxed, insofar as guarantees of origin could constitute a hindrance to storing surpluses of electricity that are likely to grow. Nevertheless, the practical effect of such orientation should be assessed carefully in the perspective of new binding rules channelling disinvestment in the fossil energy sector.

The carbon capture and utilisation of CO_2 of different origins (including fossil) could be conceived as an important step towards reducing emissions before the utilisation of biogenic and atmospheric CO_2 foster the creation of an (almost) anthropogenic carbon cycle.

[118] Article 3(4)(f), Directive 2009/28/EC.

[119] Jana Polakova, David Baldock, Bettina Kretschmer, "Pursuing change in biofuels policy and developing alternatives: Leaked proposal Commission on indirect land use change", *Institute for European Environmental Policy*, 2012, p. 3 http://www.ieep.eu/assets/993/Biofuel_Exchange_briefing_note_Sept12_-_ILUC_Proposal_is_leaked.pdf (accessed 29 June 2016)

[120] *Ibid.*, p. 3.