HIGH RISK OF ABRUPT CLIMATE CHANGE REQUIRING CLOSELY ESTIMATE BIOFUEL GREENHOUSE GAS EMISSIONS BY LIFE CYCLE ASSESSMENT

Sandis Vilums
Latvia University of Agriculture
sandis.vilums@gmail.com

Abstract. The article focuses on a specific environmental evaluation method – Life Cycle Assessment (LCA) and it estimates biofuel greenhouse gas (GHG) emissions and compares to fossil fuels. It is mainly evaluated by the mean Global Warming impact indicator, expressed in grams of CO_2 equivalent per MJ of energy ($gCO_2eq \cdot MJ^{-1}$). Biofuels are highly relevant renewable energy options on a global scale. Comparing with fossil fuels, biofuels in some cases can be carbon neutral or even carbon negative and play an important role in the reduction of GHG emissions. A number of LCA have shown that first generation biofuels provide a little to no benefit for GHG reductions compared to fossil fuels, particularly when indirect effects are considered. LCAs of second and third generation biofuels exhibit great variability and uncertainty but are intended to achieve greater GHG reductions. Highly possible Arctic Ocean ice meltdown in the late summer as soon as in September 2015 and accelerated methane hydrate destabilization in the Arctic Ocean seabed via ocean warming could cause abrupt climate change in the following decade. Mitigation of climate change requires to use only biofuels with the global warming impact indicator close to 0 $gCO_2eq \cdot MJ^{-1}$ (Carbon Neutral) or – $gCO_2eq \cdot MJ^{-1}$ (Carbon Negative).

Keywords: abrupt climate change, life cycle assessment, biofuels.

Introduction

Scientific understanding of the cause of global climate change has been increasing. The fifth assessment (AR5 2013) of the Intergovernmental Panel on Climate Change (IPCC) reported with 95 % certainty that human activity is the dominant cause of the observed warming since the mid-20th century. The report confirms that warming in the climate system is unequivocal, with many of the observed changes unprecedented over decades to millennia: warming of the atmosphere and the ocean, diminishing snow and ice, rising sea levels and increasing concentrations of greenhouse gases. Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The globally averaged combined land and ocean surface temperature data show a warming of 0.85 ºC, over the period 1880 to 2012, when multiple independently produced datasets exist [1].

Human activity since the Industrial Revolution (1750) has increased the amount of greenhouse gases in the atmosphere, leading to increased radiative forcing, thereby the resulting changes in the Earth`s energy balance [2]. The major contributor to increases in radiative forcing due to increased concentrations of greenhouse gases since pre industrial times is carbon dioxide (CO_2) (61 %) with substantial contributions from methane (CH_4) (17 %), nitrous oxide (N_2O) (4 %) and chlorofluorocarbons (CFCs) (12 %) [1]. The atmospheric concentrations of major greenhouse gases as carbon dioxide (CO_2) [3], methane (CH_4), and nitrous oxide (N_2O) have increased to levels unprecedented. Carbon dioxide concentrations have increased by 43 % (from 280 ppm in 1750 [4] to 400 ppm in 2015 [5]), methane by 150 % (from 700 ppb in 1750 to 1803 ppb in 2011 [1], nitrous oxide by 20 % (from 270 ppb in 1750 to 324 ppb in 2011 [1]). The Global Warming Potential (GWP) provides a simple measure of the radiative effects of emissions of various greenhouse gases, integrated over a specified time horizon (20, 100), relative to an equal mass of CO_2 emissions. GWP of major greenhouse gases, lifetime (years) and increased radiative forcing are shown in Table 1.

The global carbon budget averaged over the last decade (2004-2013) is shown in Fig 1. For this time period, 91 % of the total emissions were caused by fossil fuel combustion and cement production, and 9 % by land-use change. The total emissions were partitioned among the atmosphere (44 %), ocean (26 %) and land (29 %). Fossil fuel and cement emissions over the last decade (2004-2013) had increased with an average of 2.7 $\% \cdot year^{-1}$ and all projections show that this tendency will remain the same or even increase in coming years [6].

Relative to the trends over the last few decades, warming in the Arctic Ocean has accelerated during the past several years, as observed by satellites and in situ measurements [7; 8]. In addition to the warming effect of current forcing and emissions, highly possible Artic Ocean ice meltdown in the late summer as soon as in September 2015 [7; 9] and consequent accelerated methane hydrate destabilization in the Arctic Ocean seabed via ocean warming could exacerbate warming and even lead to abrupt, catastrophic climate change in the following decade. Abrupt climate change describes changes in climate that occur over the span of years to decades, compared to the human-caused changes in climate that are occurring over the time span of decades to centuries. A release of 50 billion tonnes of methane would bring forward by 15 to 35 years the date at which the global temperature rise exceeds 2 °C above pre-industrial levels [10]. Recent studies show that significant quantities of methane had already escaped from the East Siberian Arctic Shelf (ESAS) as a result of degradation of submarine permafrost [11; 12].

Table 1

GWP of major greenhouse gases, lifetime (years) and increased radiative forcing [1]

Gas	Lifetime, years	GWP time horizon		Increased radiative forcing from 1750 to 2013, $W\cdot m^{-2}$
		20 years	100 years	
Carbon dioxide, CO_2	100 to 300	1	1	1.88
Methane, CH_4	12.4	86	34	0.49
Nitrous oxide, N_2O	121	268	298	0.17
Tropospheric ozone, O_3	hours-days	n.a.	n.a.	0.40
CFC-12, CCl_2F_2	100	n.a.	10200	0.169

Over the past two decades, skeptics of the reality and significance of anthropogenic climate change have frequently accused climate scientists of “alarmism”: of over-interpreting or overreacting to evidence of human impacts on the climate system. However, the available evidence suggests that scientists have in fact been conservative in their projections of the impacts of climate change. Calling this tendency “erring on the side of least drama” [13].

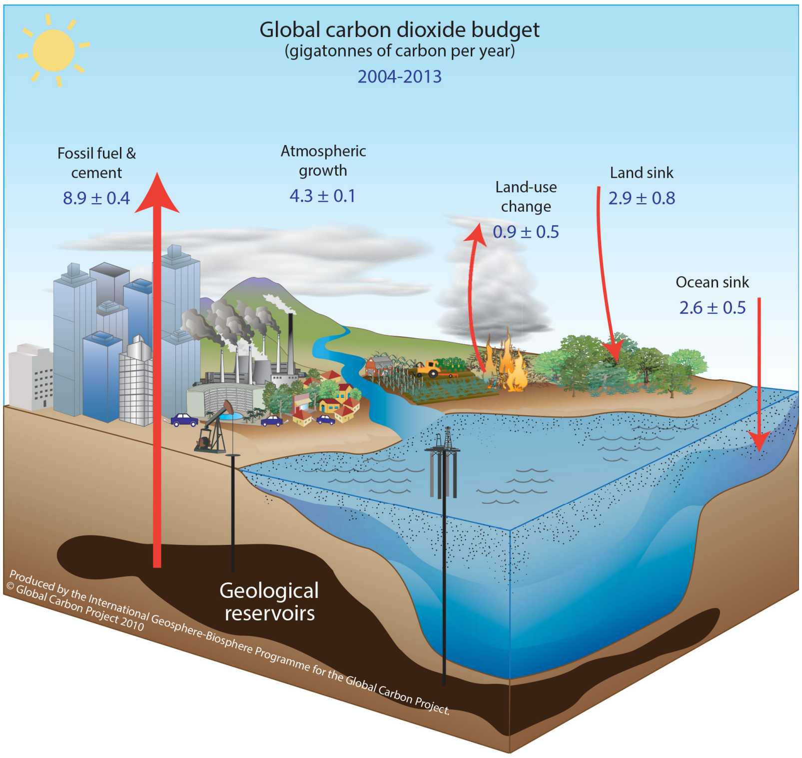

Fig. 1. **Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2004–2013:** all fluxes are in units of $GtC\cdot yr^{-1}$ [6].

Due to high risk of abrupt climate change there is a necessity to evaluate closely all renewable biofuels by the Life Cycle Assessment (LCA) method to get the results for most appropriate biofuels for mitigation of climate change. Biofuels are highly relevant renewable energy options on a global scale [14]. Comparing with fossil fuels, biofuels in some cases can be carbon neutral or negative and play an important role in the reduction of greenhouse gas emissions. This article focuses on assessment of major greenhouse gas (CO_2) emissions of various generation biofuels in comparison to the emissions of fossil fuels.

Materials and methods

There is a broad agreement in the scientific community that Life Cycle Assessment (LCA) is one of the best methodologies for the evaluation of the environmental burdens associated with biofuel production, by identifying energy and materials used as well as waste and emissions released to the environment [15; 16]. LCA is a method based on the ISO standards 14040/14044. The objective of LCA is to describe and evaluate the overall environmental impacts of a certain action by analyzing all stages of the entire process from raw material supply, production, transportation and energy generation to recycling and disposal stages following actual use, in other words, "from the cradle to the grave". Moreover, it also allows an identification of opportunities for environmental improvement.

The methodological framework for LCA is divided into 4 steps:

1. **Goals and scope of the study:** This step deals with the definition of questions that the author wants to answer in the study. All methodological assumptions, i.e. the scope of the study (system boundaries, functional unit, method to account for co-products, environmental impact indicators, type of data, etc.) are described according to the goals of the study.
2. **Life cycle inventory:** Input and output flows of matter and energy as well as emissions to the environment (air, water, soil emissions and solid wastes) included in the system are listed.
3. **Life cycle impact assessment:** Inventory flows are converted into potential environmental impact categories using a characterization method. Impact categories and associated characterization methods are chosen in accordance with the goals and scope of the study.
4. **Interpretation of results:** The results are analyzed regarding the defined goal and scope of the study.

Results and discussion

This study shows the variations of LCA results for GHG emissions of different biofuel generations comparing with the reference fossil fuels. As CO_2 gas is major GHG that contribute to global warming, then only LCA reports and articles with included global warming impact indicator or carbon intensity (expressed in grams of CO_2 equivalent per MJ of energy) were selected.

First generation (G1) liquid biofuels are economically viable and produced in industrial scale nowadays mainly from crops such as wheat, sugarcane, sugarbeet, soybeans, corn, rapeseed, palm oil, sunflower, etc. The most representative categories of these biofuels are ethanol and biodiesel. These G1 biofuels have come up against sustainability issues mostly related to the use of agricultural commodities in their production processes. G1 biofuel global warming impact comparison is shown in Fig. 2. Bioethanol from sugarcane (37 $gCO_2eq \cdot MJ^{-1}$) has the best CO_2 emissions savings (56 %) comparing to the fossil reference (83,8 $gCO_2eq \cdot MJ^{-1}$) summing direct and indirect land use change emissions. Bioethanol from corn (55 $gCO_2eq \cdot MJ^{-1}$) and sugarbeet (53 $gCO_2eq \cdot MJ^{-1}$) emissions savings are about 36 % comparing to the fossil reference. Bioethanol from wheat has almost the same global warming impact (82 $gCO_2eq \cdot MJ^{-1}$) as the fossil reference and has only 2 % CO_2 emission savings. Biodiesel from soybeans (113 $gCO_2eq \cdot MJ^{-1}$), rapeseeds(107 $gCO_2eq \cdot MJ^{-1}$), sunflower (96 $gCO_2eq \cdot MJ^{-1}$) and palm oil (123 $gCO_2eq \cdot MJ^{-1}$) global warming impact has increased comparing with the fossil reference respectively, additionally 35 %, 28 %, 15 % and 47 % CO_2 emissions. Only biodiesel from waste vegetables (14 $gCO_2eq \cdot MJ^{-1}$) shows significant decrease of CO_2 emissions (83 %).

As a consequence, second generation (G2) and third generation (G3) liquid biofuels from biomass residues, non-alimentary crops and wastes have been developed in the recent years. G2 and G3 biofuels are currently either in research and development or demonstration phase and still need further improvements to be commercially viable. These biofuels seem to be more efficient than G1 biofuels in terms of land use, food security, GHG emission reductions and other environmental aspects [17; 18]. G2 bioethanol is obtained from the biochemical conversion of lingocellulosic biomass. Synthetic biodiesel from biomass, also known as Biomass to Liquids (BtL), biomass FT-biodiesel (Fischer-Tropsch) or pyrolysis biodiesel is produced by thermochemical conversion of lignocellulosic biomass.

G2 biofuel global warming impact comparison is shown in Fig. 2. G2 bioethanol from corn stover (12 $gCO_2eq \cdot MJ^{-1}$), wheat straw (25 $gCO_2eq \cdot MJ^{-1}$), rapeseed straw (23 $gCO_2eq \cdot MJ^{-1}$), waste wood (22 $gCO_2eq \cdot MJ^{-1}$) and farmed wood (37 $gCO_2eq \cdot MJ^{-1}$) shows significant decrease in global warming impact comparing with the fossil fuel reference, respectively 86 %, 70 %, 73 %, 74 % and 56 % CO_2 emission reduction. G2 biodiesel from FT waste wood (4 $gCO_2eq \cdot MJ^{-1}$), FT farmed food (6 $gCO_2eq \cdot MJ^{-1}$), pyrolysis wheat straw (12 $gCO_2eq \cdot MJ^{-1}$) and pyrolysis rapeseed straw (17 $gCO_2eq \cdot MJ^{-1}$) also shows significant decrease in global warming impact comparing with the fossil fuel reference, respectively 95 %, 93 %, 86 % and 80 % CO_2 emission savings. G2 biogas biofuels from dry mature (15 $gCO_2eq \cdot MJ^{-1}$) and wet mature (16 $gCO_2eq \cdot MJ^{-1}$) are good energy sources with low carbon emission impact comparing with the fossil fuel reference, respectively 82 % and 81 % CO_2 emission savings.

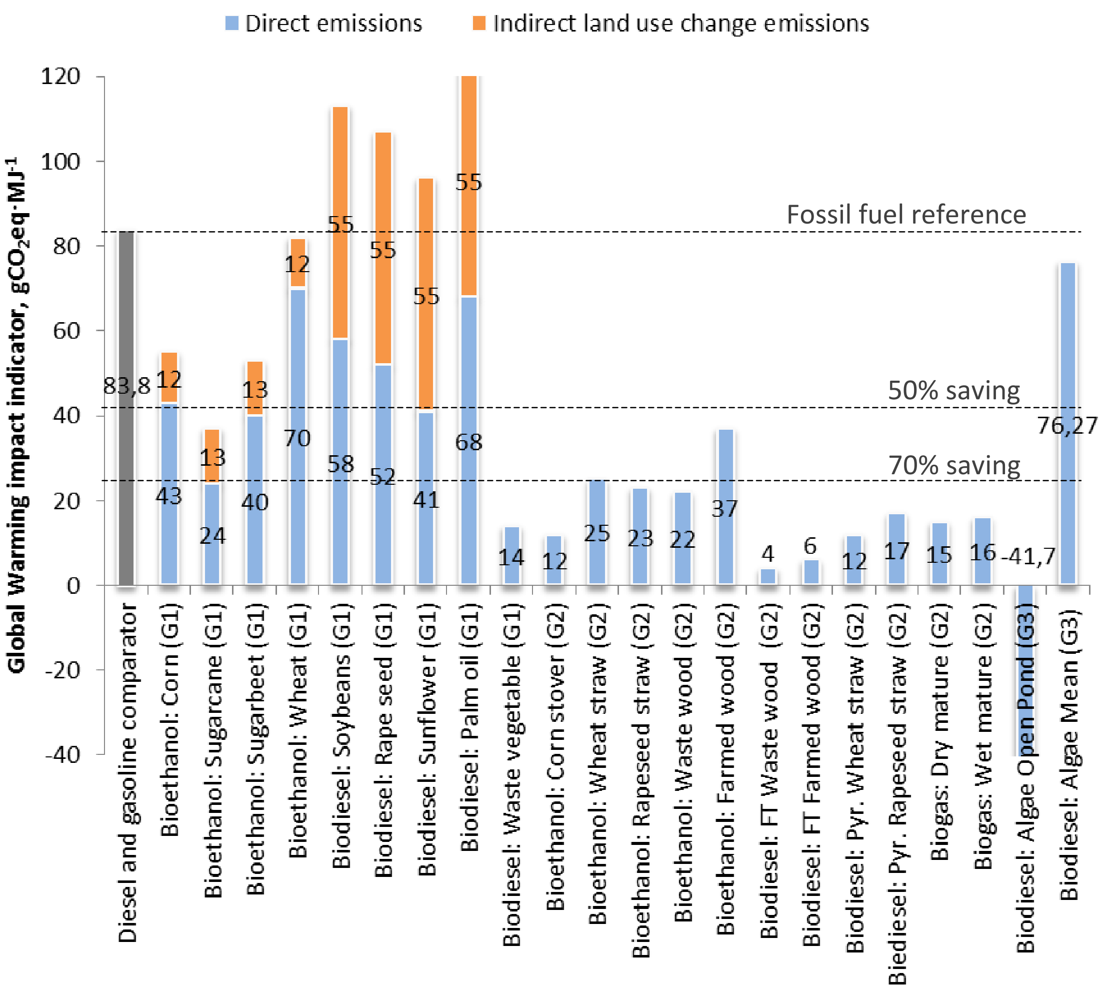

Fig. 2. **G1, G2 and G3 generation biofuel global warming impact indicator comparison by LCA method:** Almost all direct emission data of biofuels are taken from the EU Renewable Energy Directive [14] excepting Bioethanol: Corn stover(G2) [19], Bioethanol: Rapeseed straw(G2) [19], Biodiesel Pyr.: Wheat straw(G2) [19], Biodiesel Pyr.: Rapeseed straw(G2) [19], Biodiesel: Algae Open Pond(G3) [20] and Biodiesel: Algae Mean(G3) [21]. Indirect land use change (ILUC) emission data for G1 biofuels are taken from the EU Renewable Energy Directive ILUC proposal [22]

Microalgae offer great potential as a sustainable feedstock for the production of third generation (G3) biofuels, such as biodiesel and bioethanol. Microalgae are able to produce 15-300 times more oil for biodiesel production than traditional crops on an area basis. Furthermore, compared with conventional crop plants which are usually harvested once or twice a year, microalgae have a very short harvesting cycle (≈1-10 days depending on the process), allowing multiple or continuous harvests with significantly increased yields. Biodiesel production by microalgae will not compromise production of food, fodder and other products derived from crops [23]. G3 biodiesel biofuel global warming impact comparison is shown in Fig. 2. G3 biodiesel from algae in Open Pond by the LCA method shows excellent results (-41.7 $gCO_2eq \cdot MJ^{-1}$) and good potential in its application in climate change mitigation. A variety of researchers have constructed and presented LCAs of the microalgae biofuel process, however, inconsistencies in system boundaries and high-level process modeling with large uncertainties in sub-process modeling have led to a wide range of results[21; 24]. G3 biodiesel from algae mean value [21] (76.27 $gCO_2eq \cdot MJ^{-1}$) is similar to the fossil reference and leads only to 9 % CO_2 emission saving.

Conclusions

1. Due to high risk of abrupt climate change there is a necessity to evaluate closely all renewable biofuels by the Life Cycle Assessment (LCA) method to get the results for most appropriate biofuels for mitigation of climate change. Climate change mitigation requires to use globally only biofuels with the global warming impact indicator close to 0 $gCO_2eq \cdot MJ^{-1}$ (Carbon Neutral) or – $gCO_2eq \cdot MJ^{-1}$ (Carbon Negative).
2. Comparison of the LCAs data has shown that G1 biofuels provide a little to no benefit for GHG reductions compared to fossil fuels (diesel and gasoline comparator), particularly when indirect land use change effects are considered. Less global warming impact is from bioethanol from sugarcane (37 $gCO_2eq \cdot MJ^{-1}$) and biodiesel from waste vegetable (14 $gCO_2eq \cdot MJ^{-1}$) with CO_2 emission saving 56 % and 83 % comparing to the fossil reference (83.8 $gCO_2eq \cdot MJ^{-1}$).
3. Almost all G2 biofuels achieved 70 % or better CO_2 emission savings comparing to the fossil reference excepting bioethanol from farmed food (56 %).
4. G3 biodiesel from Algae Open Pond (-41.7 $gCO_2eq \cdot MJ^{-1}$) achieved carbon negative result, however, the mean value of different G3 biofuels LCAs was similar to the fossil reference with only 9 % CO_2 saving.

References

1. Stocker M.T.F., Qin D., Plattner G.-K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V., Midgley P.M. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013, p. 1535.
2. Hansen J., Kharecha P., Sato M., Masson-Delmotte V., Ackerman F., Beerling D.J., Hearty P.J., Hoegh-Guldberg O., Hsu S.-L., Parmesan C., Rockstrom J., Rohling E.J., Sachs J., Smith P., Steffen K., Van Susteren L., Von Schuckmann K., Zachos J.C. "Assessing 'dangerous climate change': required reduction of carbon emissions to protect young people, future generations and nature.," PloS one, vol. 8, no. 12, p. e81648, Jan. 2013.
3. Luthi D., Le Floch M., Bereiter B., Blunier T., Barnola J.-M., Siegenthaler U., Raynaud D., Jouzel J., Fischer H., Kawamura K., Stocker T.F., "High-resolution carbon dioxide concentration record 650,000-800,000 years before present.," Nature, vol. 453, no. May, pp. 379-382, 2008.
4. Etheridge D.M., Steele L. P., Langenfelds R.L., Francey R.J., Barnola J.M., Morgan V.I. "Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn," Journal of Geophysical Research, vol. 101, no. 95, p. 4115, 1996.
5. Pieter T. "National Oceanic & Atmospheric Administration Trends in Atmospheric Carbon Dioxide," 2015. [Online][11.10.2014]. Available: http://www.esrl.noaa.gov/gmd/ccgg/trends. [Accessed: 01-Jan-2015].
6. Le Quere C., Peters G.P., Andres R.J., Andrew R.M., Boden T.A., Ciais P., Friedlingstein P., Houghton R.A., Marland G., Moriarty R., Sitch S., Tans P., Arneth A., Arvanitis A., Bakker D.C.E., Bopp L., Canadell J.G., Chini L.P., Doney S.C., Harper A., Harris I., House J.I., Jain A.K., Jones S.D., Kato E., Keeling R.F., Klein Goldewijk K., Kortzinger A., Koven C., Lefevre N., Maignan F., Omar A., Ono T., Park G.-H., Pfeil B., Poulter B., Raupach M.R., Regnier P., Rodenbeck C., Saito S., Schwinger J., Segschneider J., Stocker B.D., Takahashi T., Tilbrook B., Van Heuven S., Viovy N., Wanninkhof R., Wiltshire A., Zaehle S. "Global carbon budget 2013," Earth System Science Data, vol. 6, pp. 235-263, 2014.

7. Parkinson C.L. "Global Sea Ice Coverage from Satellite Data: Annual Cycle and 35-Yr Trends," Journal of Climate, vol. 27, pp. 9377–9382, 2014.
8. Johnson M., Proshutinsky A., Aksenov Y., Nguyen A.T., Lindsay R., Haas C., Zhang J., Diansky N., Kwok R., Maslowski W., Hakkinen S., Ashik I., de Cuevas B. "Evaluation of Arctic Sea Ice Thickness Simulated by Artic Ocean Model Intercompariaision Project models," Journal of Geophysical Research, vol. 117, no. C00D13, pp. 121, 2012.
9. Maslowski W., Kinney C.J., Higgins M., Roberts A. "The Future of Arctic Sea Ice," Annual Review of Earth and Planetary Sciences, vol. 40, pp. 625-654, 2012.
10. Whiteman G., Hope C., Wadhams P. "Vast costs of Arctic change.," Nature, vol. 499, pp. 401-403, 2013.
11. Shakhova N., Semiletov I., Salyuk A., Yusupov V., Kosmach D., Gustafsson O. "Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf.," Science (New York, N.Y.), vol. 327, no. 2010, pp. 1246-1250, 2010.
12. Shakhova N., Semiletov I., Leifer I., Salyuk A., Rekant P., Kosmach D. "Geochemical and geophysical evidence of methane release over the East Siberian Arctic Shelf," Journal of Geophysical Research: Oceans, vol. 115, no. June 2009, pp. 1-14, 2010.
13. Brysse K., Oreskes N., O'Reilly J., Oppenheimer M. "Climate change prediction: Erring on the side of least drama?," Global Environmental Change, vol. 23, no. 1, pp. 327-337, Feb. 2013.
14. European Parliament, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009," Official Journal of the European Union, vol. 140, no. L, pp. 16-62, 2009.
15. World Energy Council, "Comparison of energy systems using life cycle assessment," London, UK, 2004.
16. United States Environment Protection Agency, "Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis," Renewable Fuel Standard Program. p. 1109, 2010.
17. Cherubini F., Bird N. D., Cowie A., Jungmeier G., Schlamadinger B., Woess-Gallasch S., "Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations," Resources, Conservation and Recycling, vol. 53, no. 8, pp. 434-447, Jun. 2009.
18. Benoist A., Dron D., Zoughaib A. "Origins of the debate on the life-cycle greenhouse gas emissions and energy consumption of first-generation biofuels - A sensitivity analysis approach," Biomass and Bioenergy, vol. 40, pp. 133-142, 2012.
19. Baral A., Malins C., "Assessing the Climate Mitigation Potential of Biofuels Derived From Residues and Wastes in the European Context." International Council on Clean Transportation, Washington, p. 30, 2014.
20. Quinn J.C., Smith T.G., Downes C.M., Quinn C. "Microalgae to biofuels lifecycle assessment - Multiple pathway evaluation," Algal Research, vol. 4, pp. 116-122, 2014.
21. Menten F., Chèze B., Patouillard L., Bouvart F. "A review of LCA greenhouse gas emissions results for advanced biofuels: The use of meta-regression analysis," Renewable and Sustainable Energy Reviews, vol. 26, pp. 108-134, Oct. 2013.
22. Council of the European Union, "Note from the Permanent Representatives' Committee to the Council: Proposal for a Directive of the European Parliament and of the Council amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC," no. June, pp. 1-51, 2014.
23. Dragone G., Fernandes B., Vicente A., Teixeira J. "Third generation biofuels from microalgae," Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology, pp. 1355-1366, 2010.
24. Quinn J.C., Davis R. "The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling," Bioresource Technology, vol. 184, pp. 444-452, 2015.