Perspectives for global development of biofuel technologies to 2050

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Introduction

The perspectives for production and use of biofuels (alternative fuels) are based on the rationales listed below, assuming that biofuels should:

- be available in sufficient volumes
- have technical and energetic properties warranting their suitability to power engines or heating devices
- be cost effective in terms of manufacture and sales
- be more environmentally friendly than traditional fuels by reducing the emission levels of toxic substances and greenhouse gases in combustion of those fuels
- ensure acceptable financial ratios for engines or boilers, proper level of safety of use and reduce the operational costs of those devices
- improve energy independence.

It has been assumed that the resource for the production of biofuels will be the broadly defined 'biomass'. Thus far, there have been a number of complementary definitions of biomass. According to the European definition, set forth in the applicable Directive 2009/28/EC, biomass is "the biodegradable fraction of products, waste and residues of biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste". Therefore, establishing biomass as the primary resource for biofuel production, the European definition outlines two basic resource pathways and the corresponding treatment techniques, i.e. the processes of BtL (*Biomass to Liquid*), or BtG (*Biomass to Gas*) and WtL (*Waste to Liquid*), or WtG (*Waste to Gas*).

The aforementioned Directive also introduces the term *bioliquids*, defined as liquid biofuels used for energy purposes other than transport, including the production of electric power, heat and chill, and produced from biomass. Thus, the processes of producing bioliquid, using biomass as the resource, fall within the definition of BtE (*Biomass to Energy*) and WtE (*Waste to Energy*).

In consideration of the above factors, at the beginning of 2010 European Biofuels Technology Platform has prepared an update to the Strategic Research Agenda on biofuels. The update included the technological progress and the need to intensify the reduction of emission of greenhouse gases. The International Energy Agency (IEA) is working on an independent Biofuels Roadmap for transport, emphasising the need for sustainable development and reduction of GHG emission, i.a. by utilising carbon dioxide. Also the European Directive stipulates in the preamble that "*the Community should take appropriate steps (…) including the promotion of sustainability criteria for biofuels and the development of second- and third-generation biofuels in the Community and worldwide (…)*".

Given the previous experiences and development of production technology of biofuels or, more precisely, alternative fuels originating from biological and civilizational waste materials (xTL processes), the dominating trend at the moment focuses on the reduction of CO_2 emission or balancing the emission to reach optimum levels in the processes of fuel production and combustion. The introduction of the term "xTL processes" is the result of the confirmed shortages of biomass as the resource for fuel production, which would make it impossible to produce biofuels in volumes sufficient to reach the set ratio objectives, both in terms of the percentage participation in the total pool of transport fuels and significant reduction of carbon dioxide emission levels. The issue of shortages of biomass as the resource for fuel production is particularly visible in Europe, where the ratio objectives already require import of biomass and certain biofuels (ethanol, biodiesel and vegetable oils). The import directions are provided in Figure. 1.

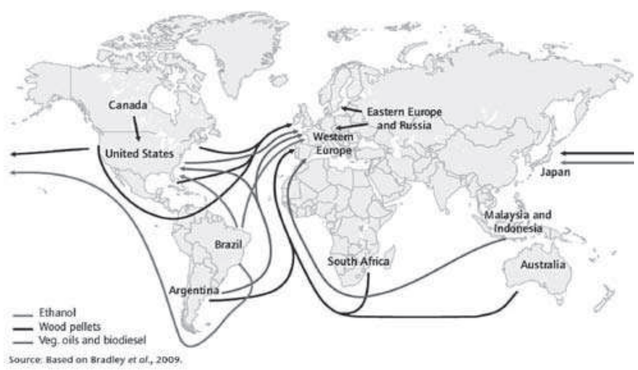

Fig. 1. Import directions of biomass and first-generation biofuels

Classification of biofuels

The basic classification of biofuels is based on the state of matter. According to Annex I to the Communication from the Commission no. 34 of 2006 COM(2006) 34 final, biofuels are classified as liquid, gaseous and other renewable biofuels. The Communication introduces the terms of first- and second-generation biofuels. Also, the Annex introduces the term "synthetic biofuels", defining them as "synthetic hydrocarbons or mixtures of synthetic hydrocarbons produced from biomass, e.g. Syngas produced from gasification of forestry biomass, or SynDiesel."

The European classification distinguishes the following types of biofuels according to their state of matter:

Liquid biofuels:

- ethanol produced from biomass and/or the biodegradable fraction of waste, for use as biofuel E5 containing 5% ethanol and 95% petrol, and E85, containing 85% ethanol and 15% petrol
- biodiesel, containing methyl-esters (PME, RME, FAME) produced from vegetable oil, animal oil or recycled (e.g. cooking) fats and oils of diesel quality, for use as biofuel B5 containing 5% esters and 95% petroleum-based diesel, B30 containing 30% and 70% respectively, and B100, which is non-blended biodiesel with properties in compliance with the applicable norms
- biomethanol as fuel or fuel component produced from biomass
- bio-ETBE, Ethyl-Tertio-Butyl-Ether produced from bioethanol, used as a fuel additive to increase the octane rating and reduce knocking. The percentage volume of bio-ETBE calculated as biofuel is 47%

- bio-MTBE, Methyl-Tertio-Butyl-Ether produced from biomethanol. MTBE is used as a fuel additive to increase the octane rating and reduce knocking. The percentage volume of bio-MTBE calculated as biofuel is 36%
- BtL as liquid fractions or mixtures of fractions, produced from biomass and used as biofuels or fuel components
- pure vegetable oils, produced from oil plants through pressing, extraction or comparable procedures, crude or refined but chemically unmodified, which can be used as biofuels when compatible with the type of engine involved and the corresponding emission requirements.

Gaseous biofuels:

- bio-DME, dimethylether produced from biomass, for use as biofuel in diesel engines
- biogas, a fuel gas produced from biomass and/or the biodegradable fraction of waste, which can be purified to natural gas quality
- biohydrogen produced from biomass and/or the biodegradable fraction of waste for use as biofuel.

Other renewable fuels as unspecified biofuels, originating from renewable energy sources as defined in Directive 2001/77/EC and used for transport purposes.

As mentioned above, the Communication specifies the distinction of biofuels into first- and second-generation biofuels. The distinction arises from the factors discussed above, but mostly from the assessment of the suitability of biofuels for the modern engine technology, the availability of resources and their environmental impact. The formal distinction between biofuel generations was published in the report "Biofuels in the European Vision, a Vision for 2030 and Beyond". The report introduces the division of biofuels into first-generation, i.e. the so-called conventional biofuels, and second-generation biofuels, i.e. advanced biofuels.

The first generation (conventional) biofuels include:

- bioethanol (BioEtOH, BioEt), understood as conventional ethanol produced by hydrolysis and fermentation from feedstock such as grains, sugar beet, etc
- PVO (pure vegetable oils), produced by cold pressing and extraction from oil crops
- biodiesel in the form of rapeseed methyl esters (RME), or fatty acid methyl (FAME) and ethyl (FAEE) esters from other oil crops, produced by cold pressing, extraction and transesterification
- biodiesel in the form of methyl and ethyl esters, produced by transesterification of waste cooking oils
- biogas produced by purification of wet landfill or agricultural biogas
- bio-ETBE produced by chemical processing of bioethanol.

The category of second-generation ("future") biofuels includes:

- bioethanol, biobutanol, mixtures of higher alcohols and their derivatives produced in the advanced processes of hydrolysis and fermentation of lignocellulose originating from biomass (excluding resources for food industry)
- synthetic biofuels produced by processing biomass through gasification and appropriate synthesis into liquid fuel components in BtL processes, and produced by processing biodegradable industrial and municipal waste, including carbon dioxide, in WtL processes
- diesel engine fuels, produced by processing lignocellulose from biomass using the Fischer-Tropsch process, including synthetic biodiesel from lignocellulose product compositions
- biomethanol produced by processing lignocellulose, including with the use of the Fischer-Tropsch synthesis and with the use of waste carbon dioxide
- biodimethylether (BioDME) produced by thermochemical processing of biomass, including biomethanol, biogas and syngases derived from biomass processing
- biodiesel as biofuel or fuel component for diesel engines, produced by hydrogen refinement of vegetable oils and animal fats (hydro-treatment)
- biodimethylfuran (BioDMF) produced by thermo- and biochemical processing of sugars, including cellulose
- biogas as a synthetic natural gas – biomethane (SNG), produced by gasification of lignocellulose and appropriate synthesis, and by purification of agricultural and landfill biogas and wastewater residues
- biohydrogen produced by gasification of lignocellulose and synthesis of the gasification products, or by biochemical processes.

The above classification indicates that the processed first-generation biofuels cannot be classified as second-generation biofuels, which means that further processing of esters, e.g. by hydrogen refinement, does not produce a second-generation biofuel and is thus technically and economically unjustified. Basically, the concept of development of second-generation biofuels is based on the assumption that the resource for their production should be both biomass and waste vegetable oils, animal fats and any waste organic substances that are of no use to food or forest industry.

Former Directorate-General for Energy and Transport suggested adding the third generation of biofuels to include those, for which the technology of mass production and deployment will be developed by 2030 or later. Biohydrogen and biomethanol have been provisionally included in this category.

Due to the key factor enforcing the popularisation of biofuels, i.e. the reduction of GHG emission levels, mainly carbon dioxide, the definitions of third-generation biofuel terms have been clarified and the introduction of fourth-generation biofuels has been proposed. Both those groups are classified as advanced biofuels. The third-generation biofuels can be produced with the same methods as used for second-generation biofuels, but utilising the resource (biomass) modified at growing stage by molecular biology techniques. The purpose of those modifications is to improve the process of biomass conversion into biofuels (biohydrogen, biomethanol, biobutanol) by e.g. growing trees with low lignin content or the development of crops with genetically embedded appropriate enzymes, etc.

The proposition to distinguish a new, fourth generation of biofuels has arisen from the need to strike the carbon dioxide balance or eliminate its impact on the environment. Therefore, the production technologies of fourth-generation biofuels should provide for CCS (Carbon Capture and Storage) processes at the resource and technology production stages. The resources for those biofuels are to be plants with improved (also by way of genetic engineering) CO_2 assimilation capacities at the growing stage, while the technologies must provide for the capture of carbon dioxide in appropriate geological formations by carbonation or storage in crude oil and gas headings.

Perspectives for biofuels development in the USA

There is no biofuel categorisation in the US. According to the report by NREL (National Renewable Energy Laboratory), it is anticipated that biofuel production technologies will be developed and deployed gradually.

The NREL data indicate that at the moment the following biofuel technologies are being deployed:

- ethanol as biofuel component, with crop seeds and cellulose from agriculture and forestry as the resource
- biodiesel in the form of a mixture of esters of higher fatty acids from the processes of transesterification of vegetable oils and diesel

In the longer perspective the deployment of new biofuel technologies is anticipated:

- "Green Diesel and Jet Fuel", the so-called green diesel and universal fuel for turbine engines (mainly as fuel for military purposes), produced from fats, waste oils and pure vegetable oils, refined in oil refineries to very low sulphur content
- other products of biomass fermentation, such as: butanol, acetates (ethanates) and lactates (2-hydroxypropanoates), etc.

- post-pyrolytic liquids from biomass pyrolysis as the alternative resource for oil refineries or gasification processes
- synthesis gas produced from biomass by Fischer-Tropsch method, used as resource for production of methanol, dimethyl ether or alcohol mixtures
- "Algae-derived Fuels", or fuels produced from algae biomass, as the source of triglycerides for the production of biodiesel, "green diesel" and jet fuel, and as resources for the production of hydrocarbons
- biofuels produced from resources such as: jatropha, halophytes, gold-of-pleasure (*Camelina sativa*) for the production of diesels and jet fuels
- hydrocarbon fuels as the fuels of distant future, produced by biological processes or biomass hydrogenation, including fuels from xTL processes.

The latter biofuels group is becoming increasingly important, since in view of the rising need to reduce carbon dioxide emission levels it has been determined that new methods of striking the balance of this gas must be developed by finding new resources and processing methods. Therefore, in the US and Europe research on new, prospective technologies is under way, focusing on:

- the technology of biofuel production, including jet fuel, by sunless growing of algae from sludges originating from agriculture, grasses and waste substances, using carbon dioxide (the SOLAZYME technology)
- the technology of plasma gasification of waste biomass and municipal and industrial waste (BtG and WtG processes) and then processing the resulting gases into liquid biofuels (diesels and jet fuels) using the GtL process (SOLENA technology, deployed in Great Britain and Italy)
- the technology of using carbon dioxide in the production of energy carriers
- comprehensive biorefinement technologies.

Prospective biofuel technologies according to European Strategic Research Agenda

In view of the shortages of biomass available for use as resource, as well as significant flaws of first-generation biofuels related mainly to food competition and CO_2 imbalance, the European strategy set forth in "European Strategic Research Agenda Update 2010" defines the following biofuels as prospective, also providing the technological paths for their production:

- synthetic fuels/hydrocarbons from biomass gasification (application: renewable transport fuels for aircraft engines and diesel engines)
- biomethane and other gaseous fuels from biomass gasification (substitutes of natural gas and other gas fuels), (application: engine fuels and high-efficiency energy generation)
- biofuels (bioliquids) from biomass, produced by other thermochemical processes, such as pyrolysis (application: heating fuels, energy generation or, indirectly through xTL processes, for transport fuels)
- ethanol and higher alcohols from sugars, containing biomass (application: renewable transport fuels or as petrol components, E85)
- hydrocarbons from biomass, extracted from sugars or produced by biological and/or chemical processes (applications: renewable transport fuels for aircraft engines and diesel engines)
- biofuels originating from the use of carbon dioxide in the production of microorganisms or from direct carbon dioxide synthesis of natural origin in thermo- and biochemical processes (applications: renewable transport fuels and aviation).

Those terms also include the production of biofuels that have already been defined in terms of type, such as BioDME, BioDMF and other furan derivatives, FT-diesel, HTU-diesel, fuels produced by hydrogenation of vegetable oils and animal fats that are of no use to the food industry. Distinguishing between biofuel generations might not be necessary, since the definition of biomass set forth in the Directive clearly defines the resource capabilities, recommending the bio- or thermochemical processing thereof. However, due to the fundamental purpose of introducing biofuels as standalone fuels or fuel components, which arises from the need to reduce carbon dioxide emission levels, it appears as a certain novelty that the fuels produced by synthesis or using waste carbon dioxide to produce energy carriers for transport purposes are also considered biofuels. The International Energy Agency defines the fuels produced with those methods as *solar fuels*.

Prospective biofuels according to IEA Technology Roadmap – Biofuels for Transport

The above considerations on the classification of biofuels and the increasing number of biofuel types point to the need to determine optimal and reasonably uniform technologies of production in order to ensure the sufficient production capacities to meet the requirements of modern combustion engines. Therefore, the biofuel production technologies, while taking into consideration the development trends of power supply and combustion systems for the motor engines, must ensure safe operation of those engines, at the same time reducing the emission levels of toxic fuel components, as required by relevant "EURO" classes in Europe and US/California ULEV classes in the US. Also, due to engine requirements, it is important that biofuels with comparable composition and properties be available in all countries.

Therefore, the biofuels roadmap for transport, prepared by the International Energy Agency ("Technology Roadmap – Biofuels for Transport"), outlines the global perspectives for biofuel technology development by 2050, taking into consideration the above requirements and global resource capacities. Due to the understandable need to limit the number of biofuel types, at the same time ensuring proper development of production technologies without the need to introduce further generations, it is proposed to distinguish biofuels only into conventional and advanced. Figure 2 illustrates the classification and advancement level of specific biofuels in both groups, according to IEA.

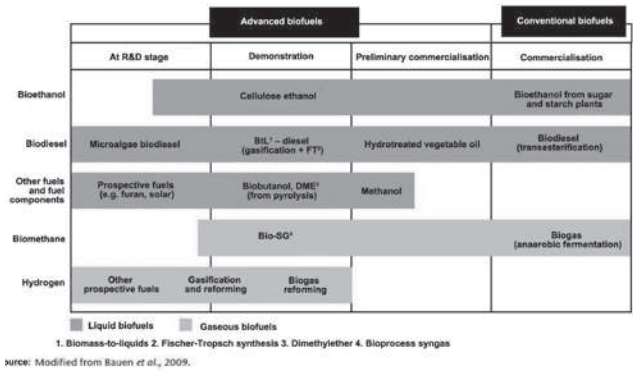

Fig. 2. Classification of biofuels and their production advancement level

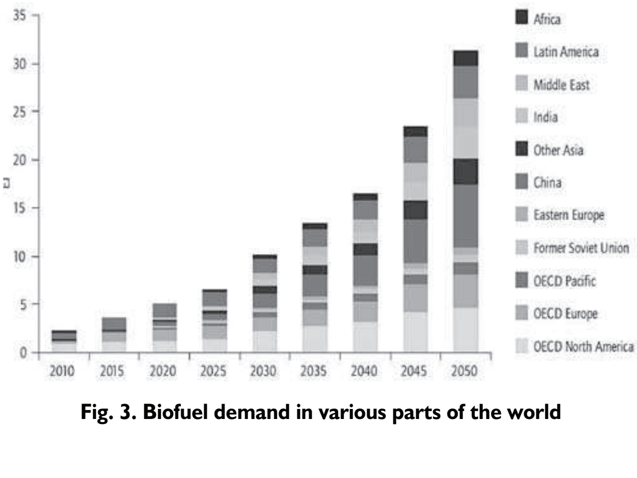

Fig. 3. Biofuel demand in various parts of the world

According to IEA's roadmap, due to the adopted ratio objectives the demand for biofuels will remain on the rise by 2050 (Fig. 3).

Securing the anticipated volumes of biofuels in 2050 will require resources with the total energy potential estimated at approx. 65 EJ, which is the equivalent of 100 million has. of crops in 2050, assuming that 50% of resources for the production of advanced biofuels will originate from waste substances (xTL processes). This means that the acreage for growing biomass for energy purposes must be increased. The planned rise in demand for biofuels is followed by the demand for farmland (Fig. 4). Assuming that strict requirements for the popularisation of xTL processes will be followed, the optimistic version ascertains that by 2050 a total of 145 EJ of energy will be secured from biomass and various waste substances, designated both for liquid energy carriers for transport (65 EJ) and processing into heating and electric power by polygeneration processes (80 EJ) Some estimations assume that with the anticipated increase of agricultural production and utilisation of wastelands, the total potential of the so-called "bioenergy" may reach 475 EJ by 2050. The estimated reduction of CO_2 emission levels should reach 2.1 Pg annually, with the biofuel share in the total transport fuel pool amounting to 27% (v/v).

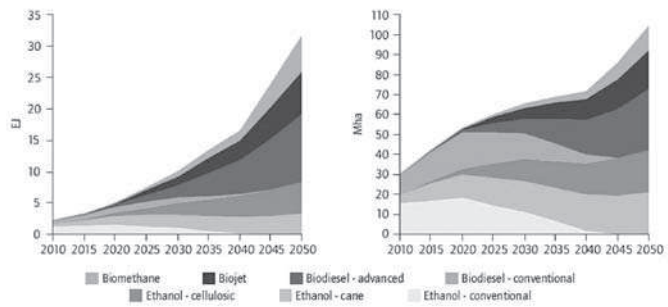

Fig. 4. Energy demand for biofuels (left) and the corresponding demand for agricultural land (according to IEA)

Considering the demand for biofuels that meet the requirements of future power sources for transport, including aviation, as well as the restrictions on the emission levels of CO_2, according to IEA the following biofuels and technological paths are preferred as advanced biofuels:

- **BtL biofuels** (compositions of synthetic hydrocarbons), produced by fast pyrolysis, i.e. heating biomass to temperatures in the range of (400°C… 600°C) and then rapid chilling, whereby unstable compounds may be liquefied (HTU process) as the HTU-diesel, or deoxygenated (HDO process), distilled and refined into fuel compositions. The by-product, so-called Bio-char (charcoal), may be used as solid fuel or in carbon sequestration and soil fertilisation
- **Diesel from BtL processes**, the so-called FT-diesel, produced by conversion into syngas and catalytic Fischer-Tropsch (FT) synthesis, applicable to a broad range of liquid hydrocarbons, including synthetic diesel and jet biofuels
- **Hydro-treated vegetable oil (HVO)** as fuel for diesel engines or heating oil, produced by hydrogenation of vegetable oils and animal fats (non-food and waste) First large production plants were launched in Finland and Singapore, but the process has not yet been fully commercialised
- **Cellulose bioethanol** produced from lignocellulose resources by biochemical conversion of cellulose and hemicellulose, resulting in sugar fermentation (IEA, 2008a). Cellulose ethanol has a better energy balance and improved properties in terms of GH emission levels and area requirements than starch ethanol
- **Biogas** produced by anaerobic fermentation of resources such as organic waste, animal faeces, wastewater residue and/or energetic plants. Biogas is purified to obtain **biomethane** (SNG) by removing CO_2 and hydrogen sulphide (H_2S), and may be used as engine fuel or hydrogen source, also for fuel cells
- **Dimethyl ether (BioDME)** can be used as gaseous fuel for diesel engines and is synthesised from methanol by catalytic dehydration, or from syngas by gasification of lignocellulose and other biomass. The production of BioDME by biomass gasification is still at demonstration stage (September 2010 in Sweden [Chemrec])
- **Biobutanol** has higher energy density and is more favourable than ethanol in engine petrols (EP). Biobutanol can be distributed via the existing EP network. It can be produced by fermenting sugars with *Clostridium acetobutylicum* bacteria. Pilot plants already operate in Germany and the US, with more under construction
- **Furan fuels**, with polysaccharides such as cellulose and starch as the resources, are produced by fragmentation of polysaccharide chains, thus obtaining glucose which is then transformed into fructose by isomerisation with the use of enzyme catalysts. In the dehydration process fructose is transformed into HMF (5-hydroxymethylfurfural), which then undergoes hydrogenolysis in the presence of copper-ruthenium catalyst and is transformed into DMF (dimethylfuran), used as fuel for petrol engines. It has considerable advantage over ethanol, having none of the latter's flaws as the fuel component
- **Solar fuels**, produced by gasification of biomass into syngas with the use of heat from concentrated solar power, which improves conversion efficiency and ensures higher reduction of greenhouse gases emission levels. Solar fuels can also be produced by water decomposition (vapour) and using carbon dioxide for producing syngas, which is then transformed by catalysis into fuel fractions. This fuel technology may also include the so-called artificial leaf technologies
- **Biorefinery systems** of producing liquid fuels and chemical intermediate products are too broad and complex subject to discuss in this paper.

In terms of the most promising resources for producing advanced biofuels, taking into consideration the so-called ground competition and the CO_2 emission levels reduction, the preferred crops include algae, gold-of-pleasure, jatropha and halophytes. In order to improve the volume of biomass resources available for fuel production, new technologies are being developed, such as: sunless (dark) photosynthesis, marine membrane systems for producing algae and technologies for producing ethanol as the resource.

Conclusions

Meeting the objectives outlined herein will require coordinated actions by all developed countries in the world. According to IEA Technology Roadmap, the next 10 years should see the implementation of the following tasks:

- Create stable, long-term political framework for biofuels in order to increase the investors' trust and allow a sustainable development of production of those fuels
- Ensure stable mechanisms of funding and supporting on the level required for the development of advanced technologies in order to achieve commercial mass production of biofuels within the next 10 years
- Agree on the international level the criteria of sustainable development as the foundation for implementation of biofuel certification systems and related policies on national level, without creating unnecessary trade barriers, especially for developing countries
- Establish binding schemes of financial support for sustainable production of biofuels in order to ensure 50% savings in LCA for all biofuels and provide incentives for the use of waste and residuals as biofuel resources

- Increase research engagement in improving resource capacities and determining the availability of agricultural land, along with the identification of the most promising resource types and locations for future production plants
- Reduce and eventually abolish duties and other trade barriers in order to reinforce the market of "sustainable" biomass and biofuels, and secure new resources
- Reinforce international cooperation on development and potential transfer of technology in order to popularise the concept of sustainable biofuel production on a global scale
- Develop and accept a system for sustainable use of agricultural and forest lands in order to avoid unfavourable sector changes in terms of land use
- Create national bioeconomy systems for consistent management of renewable power sources and processing technologies in developed countries.

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