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Biofuel Technologies and Policies

*Karel Janda– Ondrej Benes**

Abstract

This paper deals with technological and legislation features of biofuels development. We look at all 2nd generation (2G) end products, the three major conversion pathways and especially the feedstock, with differentiates 2G biofuels from the conventional, 1G fuels. In the legislation and policies review we provide a timeline pointing out the major changes and policies, as well as brief comments on their applications. We look at biofuels policies for the three top player in biofuels production, the U.S., Brazil and the European Union. Because the 1st generation is strongly associated with the food-fuel debate we then focus on its link to the 2G as well, showing how these links are weaker and manageable, although with some challenges still present.

Key Words: Ethanol; biodiesel; policies; technologies.

JEL codes: Q42, Q55, Q58

1. Introduction

The overall enthusiasm accompanying conventional (1st generation) biofuels in the early 21st century has later been noticeably reduced when the externalities accompanying these fuels came into the spotlight. Since the late 2000s the push away from these fuels towards more environment friendly alternatives has been clearly visible. Thus, came both academic support for 2nd generation (and advanced in general) biofuels, later followed by political and economic action. However, even though demand for the enhancement of their role was publicly accepted by political representation, volumes have not been growing as fast as necessary.

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In this paper we look at the specific workings of the advanced (2nd generation) biofuel industry and provide a well-structured overview of all factors in play from technological to legislative frameworks.

2. Biofuel generations

We typically distinguish between three¹ generations of biofuels. This distinction is based solely on the chemical, resp. technological, characteristics of each generation. However, from these purely process related aspects, legal, environmental and social externalities obviously arise. Nevertheless, we will not focus on these, right now.

The crucial difference between each generation is their respective feedstock. Conventional (1G) fuels are made from food-crops. These crops are ideal for biofuel production since they are rich in sugar, starch or vegetable oil, ensuring bulky oil yields for the following conversion process (see below). However, even though they have been heavily supported in the early stages (investments spiked in 2007, see below), the arising concerns – food-fuel debate, biodiversity or impacts on crop land and related emissions (Alalwan, Alminshid, and Aljaafari 2019) – highlighted by academics and NGOs later slowed down the enthusiasm. As most troublesome have proven to be the impact 1G fuels have on food prices as they generally compete with the food industry for land and feedstock.

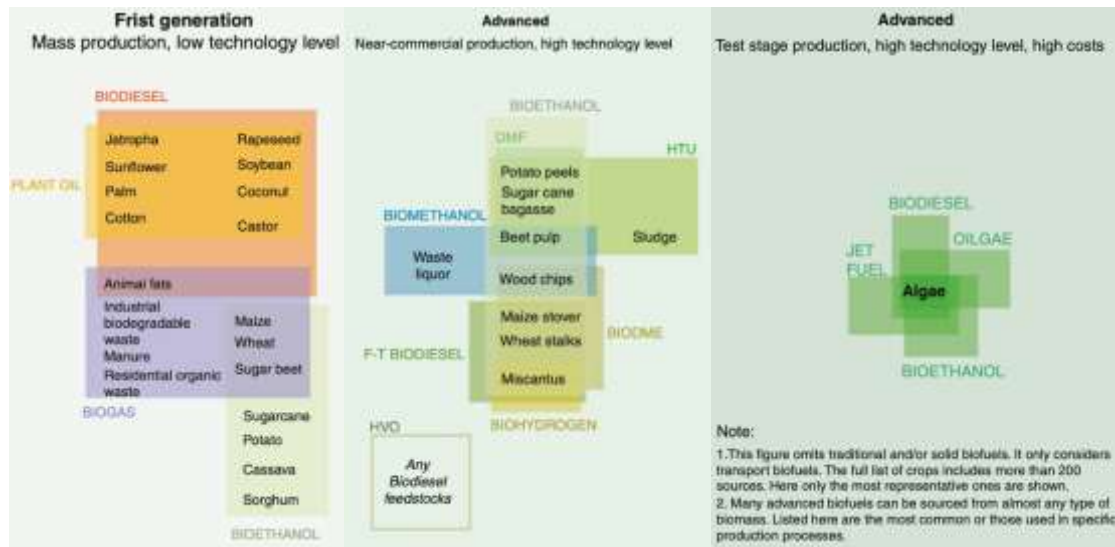
Because of this the 2nd generation (2G) are produced from the residual (non-food) parts of current food crops, such as leaves, stems or husks (agricultural residues), forage residues, other non-edible (energy) crops, recycled vegetable oil, used cooking oils (UCO) or waste (mostly municipal solid waste – MSW – used in various ways). Even though the food-crop absence lowers ties with the food sector, the two still interact, mainly through competition for land. Use of such feedstock is also more technologically challenging, raises production costs and lowers this generation's ability to go up against fossil and 1G (bio)fuels.

The third generation which uses algae or bacteria as feedstock is, considering the feedstock externalities, the most prominent. It allows producers to bypass certain production phases (the pre-treatment, enzyme degradation and microbial synthesis) leaving all of these to the algae and thus lowering costs. Given the nature of the production process (mostly using ponds) which doesn't require prime, agricultural land, this generation holds the largest potential to leave the food–fuel competition behind entirely. However, based on various studies (Alalwan

¹ All other biofuels, produced using different technologies than those by the stated three generations, are understood to be the fourth generation. They are purely experimental and have not yet been clearly defined (Janda, Kristoufek, and Zilberman 2012).

et al. 2019, Lackner 2017, Sims et al. 2010), the industry is in its early stages with high capital requirements and production costs. For an overview of the generations, see the figure below.

Fig. 1 – The biofuel generations



The family of biofuels. HVO - hydro treated vegetable oil; HTU – hydrothermal upgrading, DMF - dimethylfuran, DME - dimethylether, FT - Fischer–Tropsch.

Source: Diagram copied from (Lackner 2017)

3. Biofuel technologies

In this section we start by looking at end products, then follow with introducing the respective conversion processes and finish with feedstock descriptions.

3.1 End products

We will concern ourselves mainly with transport biofuels that are commercially produced, those holding such potential, or biofuels that would be beneficial if commercialized. For a full list of end products² obtainable from biomass and usable for transport, see Tab. 1. Since some biofuels are generally used as blends, Tab. 2 offers given biofuel blend types along with whether or not they can be considered as “drop-in” fuels³. In all cases, the number denotes the percentage share of the biofuel.

Tab. 1 – Advanced biofuels with their respective 1G or fossil counterpart and production level

² For information regarding e.g. current ongoing projects, etc., regarding here stated fuels, visit: <http://www.etipbioenergy.eu/value-chains/products-end-use/products>

³ Usable in current engines without the need for engine modifications.

Conventional or Fossil counterpart	Advanced (2G or 3G)	Production scale level of advanced biofuel
1G bioethanol	Biobutanol	pilot
1G biodiesel	BioDME	demonstration
FAME (biodiesel)	HVO/HEFA	commercial
Gasoline, 1G bioethanol	Cellulosic Ethanol	commercial
LPG, CNG, 1G biogas	Biogas	commercial
LPG, CNG, bioethanol, biodiesel	Bio SNG	demonstration
Hydrogen (fossil)	Biohydrogen	pilot
Methanol (fossil)	Biomethanol	commercial
ETBE	Bio ETBE	commercial
1G SVO/PPO, diesel	2G SVO/PPO	decentralized use

HVO - Hydrotreated vegetable oils; HEFA - Hydro-processed esters and fatty acids; SVO - Straight veg. oil; PPO - Pure veg. oils; ETBE - Ethyl Tertiary Butyl Ether; BioSNG - Bio-Synthetic Natural Gas

Source: Own processing based on: (ETIP 2016a), (Alalwan et al. 2019), (EAFO 2020), (IRENA 2019), (ETIP 2016b)

Tab. 2 – Biofuel blends

Blending partner	Biofuel	Blend	Drop-in fuel?	Vehicle use by type
Diesel	FAME (1G)	B5 B7 B10 B20	Yes	Light duty Heavy duty Shipping (potentially)
		B99 B100*	No	
Gasoline	Bioethanol (1G & 2G)	E10 E15	Yes	Light duty Heavy duty (ED95) (limited)
		E85	Partially (FFVs**)	
		Methanol (1G & 2G)	M10 M85	Yes
	Biobutanol (1G & 2G)	85 % butanol	Yes	Light duty

* B100 is pure biodiesel,

**FFVs - Flex-flue vehicles

Source: ('Biofuel Blends: Ethanol, Biodiesel, Drop-in Fuels' 2020) ,(ETIP 2016a), (Alalwan et al. 2019), (EAFO 2020)

Biobutanol (C₄H₁₀O) is a higher member of the straight chain series of alcohol (ETIP 2016a) (carrying four carbons, C₄, ethanol has C₂) which increases the harvestable energy gains (around 25 % more heat energy than ethanol). Butanol's gross heat value is closer to that of diesel⁴ (110,000 BTU/gal.), it is less corrosive (help distribution) and it is also safer to handle than both ethanol and gasoline. During combustion it release only CO₂ and H₂O making it the more environmentally friendly choice (Alalwan, Alminshid, and Aljaafari 2019). Regarding feedstock there is no difference to ethanol. Butanol can be produced synthetically or by ABE (anaerobic conversion) fermentation (2G biobutanol), however today, the costs of this process disallow biobutanol to be produced commercially⁵ (EAFO 2020). However, due to its qualities, increasing interest surrounds biobutanol as a transport fuel. It is blended (85 %) with gasoline. (ETIP 2016a)

Bio DME (dimethyl ether, sometimes “wood ether”) is a colourless, slightly narcotic gas, which is highly flammable but handleable when pressured. It shares characteristics with Liquefied Petroleum Gas (LPG), is degradable in the atmosphere and it is not a greenhouse gas (GHG). Among other uses, bio DME can be a substitution for diesel – fuel equivalence 0.59 (diesel = 1) – but requires minor engine modifications (similar to those for LPG). An EU sponsored “BioDME” demonstration project (under FP7, see legislation chapter) in Sweden with positive results was run in 2013 (‘BioDME – Project Media’ 2013) . The plant used 100 % renewable feedstock while the fuel was tested and compared to diesel on a fleet of Volvo trucks. It is produced via gasification and further (2-step) synthesis (see below). (ETIP 2016a)

Bio-Synthetic Natural Gas (SNG, syngas) is produced by gasification of cellulosic materials (e.g. forestry residues, energy crops), whereas “*biogas*” is produced biologically, through anaerobic digestion – a well-established technology (13.4 Mtoe of EU PES in 2013) – of organic materials (e.g. manure, organic waste). With pre-treatment, biogas can also be produced from lignocellulosic feedstock. In the final stage, both gases are upgraded to (bio)methane which can be used in transport in the form of LPG or Compressed Natural Gas (CNG). BioSNG is also convertible to liquid advanced biofuels (biodiesel, bioethanol). BioSNG is currently in the demonstration phase. (ETIP 2016a)

⁴ Diesel's gross heat value = 115,000 – 138,700 BTU per gallon)

⁵ A demo plant in South Korea (GS Caltex) was announced to start production in 2016. Apparently not realized.

The term *biodiesel* can refer to 1G biodiesel (FAME⁶ – fatty acid methyl ester) but also advanced HVO⁷ (hydrogenated vegetable oil). The physical properties of FAME are closer to those of diesel (than vegetable oils) and can be used pure (requires engine modifications) or blended (see Tab. 2). FAME is also non-toxic and biodegradable. Its production depends mainly on oil crops, the production of which makes up for 75 % of its production costs (Alalwan, Alminshid, and Aljaafari 2019). Biomass is converted to biodiesel (FAME) either chemically (transesterification, see below) or thermochemically (gasification with FT-synthesis⁸; pyrolysis). Hydrogenated Vegetable Oils (or HEFA, hydro-processed esters and fatty acids) on the other hand, are produced through hydro-processing resulting in a number of advantages. They are free of aromatics, oxygen and sulphur, plus have high cetane numbers. HEFA also offers a number of benefits over FAME (Fatty Acid Methyl Esters), such as reduced NOx emissions, better storage stability, and better cold flow properties. Having similar characteristics as biomass-to-liquid (BtL) diesel fuels produced by Fischer-Tropsch (FT) synthesis, HEFA can typically be used in all diesel engines, making HEFA a drop-in fuel. To date, both are produced at industrial levels. (ETIP 2016a), ('Hydrotreatment to HVO' 2020)

Second generation bioethanol ("cellulosic" ethanol, ethyl-alcohol) is colourless, volatile, flammable alcohol which is also biodegradable. In opposition to 1G ethanol, slightly different feedstock, and therefore conversion processes, are used. It is generally blended (see Tab.2) with gasoline and offers advantages like similar density, a higher octane number and lower temperature of combustion than gasoline. However, the fuel equivalence is 0.65 (gasoline = 1) and bioethanol is also more corrosive, volatile and can cause difficulties in cold conditions. Regarding feedstock, any biomass containing reasonable amounts of sugar (or sugar like material) can be considered⁹. The biochemical pathway (fermentation with respective distillation) is the predominant conversion process, however the thermochemical (gasification & synthesis) and biotechnological (synthetic bioethanol) are also possible. Along with biodiesel this fuel is globally most prolific (see below). For various reasons (1G and fossil subsidizing (IRENA 2019)) small amounts of 2G bioethanol is currently produced at commercial scale, however with flagship projects like the biorefinery in Crescentino, Italy (capacity 75 million p.a.) the increasing trend is clear. (ETIP 2016a), (EAFO 2020)

⁶ You may come across rapeseed methyl ester (RME), soybean methyl ester (SME) or palm methyl ester (PME) versions of FAME.

⁷ Referred to as "renewable diesel" in the U.S.

⁸ Fischer-Tropsch synthesis. Theoretically established e.g. to derive diesel from coal.

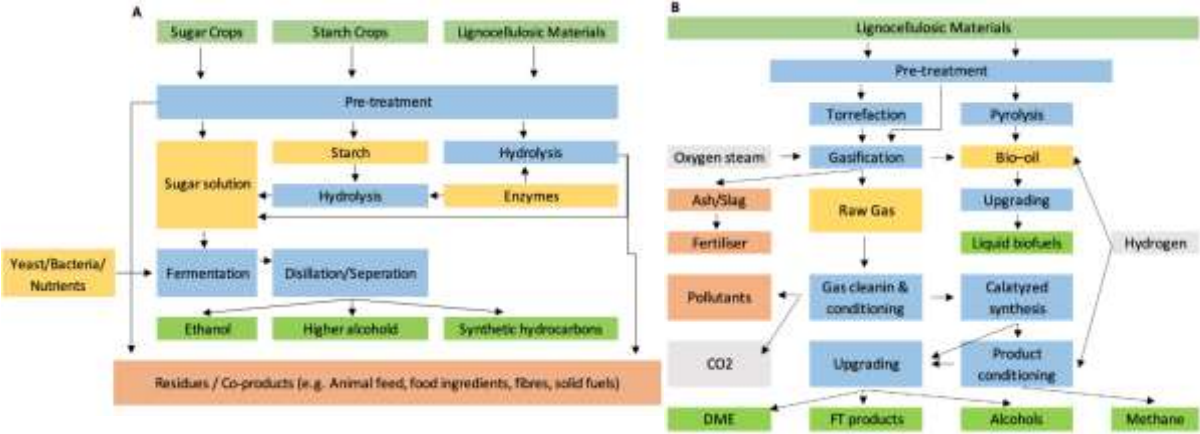
⁹ However, feedstock cost effectiveness can be a serious challenge (see below).

Another industrial level produced alcohol is *biomethanol* which is used for blending with gasoline. Similarly, to ETBE (ethyl tertiary butyl ether), it is also used as an additive and helps, e.g., reducing emissions. Methanol can be produced both thermochemically (gasification¹⁰ plus synthesis) and biochemically (anaerobic digestion from methane). It is a drop-in fuel and holds potential for heavy duty and shipping. (ETIP 2016a)

3.2 Conversion process

In advanced (especially 2G) biofuel production, there are two principle pathways, biochemical and thermochemical (Eggert and Greker 2014). In Fig.2 you may see a generalized scheme of these two pathways (conversion processes). Within these two, the majority of the listed above end products are produced, with differences depending on the given final biofuel. In addition, it is important to also mention the hydrotreatment production process of HVO/HEFA (hydroprocessing). Within these three pathways, some conversion processes are at commercial scale and some are not. Since the scope and topic of this thesis doesn't fully permit to describe each process within each pathway, we focus on the three above listed in a generalized manner.

Fig.2 – The biochemical (A) and thermochemical (B) pathway schemes



Source: Own processing based on (ETIP 2016a)

Before any feedstock undergoes the actual conversion, pre-treatment is required. Pre-treatment can be either mechanical, chemical, thermochemical or biochemical. For all currently used methods see Tab.3. Pre-treatment, especially of lignocellulosic biomass, is also very discussed in its relationship to final costs. Finding cost-effective methods has proven to be a

¹⁰ Of glycerine, a by-product of biodiesel production.

major challenge, however cost-reduction is attainable through research and development of certain techniques (Sasmal and Mohanty 2018).

Tab.3 – Currently used pre-treatment methods

Physical	Biological	Chemical
<i>Milling</i>	<i>Microbial</i>	Explosion
Ball milling	Funghi	Alkali
Two roll	Enzyme	Acid
Vibro energy		Gas
<i>Irradiation</i>		Oxidizing agent
Gamma ray		Solvent extraction
Micro wave		
<i>Thermo</i>		
Pyrolysis		
High pressure		

Source: Own processing based on (Sasmal and Mohanty 2018)

3.2.1 Thermochemical pathway

Any conversion process in which gasification plays a role can be labelled “thermochemical”. There are two value chains using the thermochemical pathway, biomass to liquid (BtL) and biomass to gas, the two processes differing only slightly. For both, any lignocellulosic biomass is suitable. The BtL value chain results in bio gasoline, bioDME, alcohols and FT products¹¹. Because it has been used to produce diesel from coal, this pathway is considered fairly explored, meaning further technical evolution and cost-effectiveness improvements are somewhat improbable (Havlík et al. 2011, Eggert and Greker 2014). The only way how to reduce costs in value chains using this conversion process is cheaper feedstock (will be discussed later.)

After passing pre-treatment biomass can go straight to gasification or, as visualized above, undergo torrefaction or pyrolysis. Torrefaction is actually thermochemical (250–300°C) partial decomposition (heating in absence of oxygen). Pyrolysis is chemical¹² decomposition by heating in absence of oxygen resulting in a liquid fraction¹³. Motivation for their use are the intermediates, bio-coal (“char coal”) from torrefaction and bio-oil (“bio-crude”) from pyrolysis.

¹¹ FT products = products resulting from FT (Fischer-Tropsch) synthesis.

¹² Thermal and catalytic is also possible.

¹³ The so-called “flash” (or fast) pyrolysis (up to 500°C) offers highest yields of liquid fraction.

Both forms of biomass make long distance travel easier and prevent decomposition of stored biomass, plus char-coal offers higher energy content per unit volume than if the biomass wasn't torrefied (ETIP 2016b).

Once size reduction is completed, the raw material is transported to the gasifier. Gasification is a thermochemical process at 800–1300°C run at under-stoichiometric conditions. Such conditions cause biomass to fragment into raw gas which consists of simpler molecules (hydrogen, CO, CO₂, H₂O or methane). Several gasification agents (oxygen, water/steam) are usable, the choice depending on the desired composition of the final raw gas. Both of these stages have by-products like char, ash and other impurities. There are also two ways how to obtain necessary process heat. Autothermally – partial combustion of the processed material in the gasification stage – or allothermally using heat exchangers or heat transferring media. In order to get the desired fuel, catalysed synthesis (e.g. FT synthesis) is used to upgrade the clean raw gas to fuel. (ETIP 2016b)

Transesterification¹⁴ of oils (vegetable, animal, waste cooking oil) is another, more straightforward conventional conversion process. The chemical reaction (transesterification) is carried out by mixing fatty acids, alcohol and a catalyst (strong acid like e.g. sodium). This gives raw biodiesel and raw glycerol. These enter the cleaning step, where methanol is used, FAME is the final product. Purified glycerol is used either in the food, cosmetic or oleochemical industries, or as a substrate for anaerobic digestion. ('Transesterification to Biodiesel' 2020)

3.2.2 Hydroprocessing to HVO (chemical)

HVO/HEFA production consists of two main parts. Firstly, fatty acid feedstock (oils) undergoes hydrotreatment which takes place at reaction temperatures of 300–390 °C. This consists of a transformation from unsaturated compounds such as alkenes and aromatics into saturated alkanes (paraffins) and cycloalkanes, which are more stable and less reactive. The result, paraffinic hydrocarbons enters the second stage involving isomerisation and cracking, bringing the biofuel to a quality that can in some cases be considered superior to standard petroleum fuel. ('Hydrotreatment to HVO' 2020)

¹⁴ Transesterification can be considered as a purely chemical conversion process. It is included in the thermochemical value chain for its end product, FAME.

3.2.3 Biochemical (biological) pathway

The biochemical pathway generally consists of four stages: pre-treatment, enzymatic hydrolysis, fermentation (or catalytic reforming), and distillation (fractionation). The pre-treatment is done so that the cellulose and hemicellulose are chemically accessible, meaning separate from the lignin (“woody”) component. Like in the thermochemical process, various approaches are possible, but the principles depicted above remain. During the enzymatic hydrolysis the pre-treated biomass is transformed into fermentable sugars using proper enzymes. The added enzymes are added to lower viscosity of the biomass slurry so that it can be pumped into saccharification tanks. The substance dwells in these tanks for a significant amount of time. This is so that the cellulose and hemicellulose (lignin has been dealt with in the pre-treatment phase) are broken up into other sugars with lower concentration. Finally, the saccharification is followed by simultaneous fermentation. Here, strains of yeast are used, commonly genetically modified brewer’s yeast. The goal is to obtain alcohol from designated sugars (e.g. xylose or glucose) generated in the previous phases. However, in order for the alcohol to be usable as fuel, it must be distilled. Ergo, distillation is the last stage of the whole conversion process. (Antizar-Ladislao and Turrion-Gomez, 2008), (ETIP 2016b)

Here again, feedstock quality plays a big role in the cost-effectiveness of this process. Since the end products are alcohols (ethanol, butanol, methanol), high percentages of sugar content (e.g. glucose, xylose) must be reachable. Depending on various oil content of given feedstocks (e.g. sugar or starch crops, lignocellulosic) and the level of necessary pre-treatment the final costs may vary. Most sugar and starch crops are used in the food industry, therefore 2G producers focus on lignocellulosic materials. Here, algae (3G) offer much potential. The by-product of both processes is lignin, which is usually dried and can be used as fuel for either process heat or heat generation elsewhere. Also, intermediate products can be obtained, such as furanics (blended with diesel and gasoline) and farnasene (feedstock for renewable diesel. (ETIP 2016b)

In order to summarize, Tab. 4 offers all conversion processes with their respective end product, by-products and intermediates. It is also worth mentioning that in contrast to bioethanol or FAME, bio gasoline, renewable diesel and biokerosene have the same combustion properties as their fossil based equivalents, gasoline, diesel or kerosene. They can thus be used without adaption or blend-limits in conventional engines. (ETIP 2016a)

Tab. 4 – Conversion process with respective end products, by-products and intermediates

Pathway	Value chain	Conversion process	End products	By-products, Intermediates
Thermochemical (chemical)	Biomass to Liquid (BtL)	Gasification & FT synthesis	Renewable diesel Biogasoline Biomethanol BioDME Biokerosene (jet fuel)	Glycerol, Naphta
		Steam Reforming, Fermentation	Biohydrogen	-
		Hydroprocessing	HVO/HEFA	-
	Biomass to Gas	Gasification & further synthesis	Bio SNG	Biochar, Bio-crude oil
		Anaerobic digestion	Biogas	
Biochemical	Sugar to alcohol	Yeast fermentation Microbial fermentation	Biobutanol	Lignin
			Bioethanol	
	Sugar to hydrocarbons	Microbial fermentation Catalytic reforming	Biogasoline	Lignin
			Bio crude oil	
			Isobutanol Renewable diesel Biokerosene (jet fuel)	

Source: Own processing based on: (ETIP 2016b), (ETIP 2016a), (Prasad and Ingle 2019), (Alalwan, Alminshid, and Aljaafari 2019), (EAFO 2020),

3.3 Feedstocks

It is known that 2G biofuel feedstocks hold a considerably more sustainable production protocol (Alalwan, Alminshid, and Aljaafari 2019). That is what makes them stand out when compared to conventional biofuels and fossil fuels. Along with the necessary upgrades in conversion processes, it is also what makes 2G biofuels pricier, compared to the 1st generation. In this part we will only focus on feedstock types and their pros and cons. Yield evaluation (for some) and potential cost-reduction areas will be discussed later as part of the cost-reduction potential. 2G feedstock can be divided into four groups:

- energy crops,
- agricultural and woody residues,
- organic waste,
- traditional breeding and genetically modified crops and
- vegetable oils. (Antizar-Ladislao and Turrion-Gomez 2008)

The majority of this biomass may also be used to generate heat, electricity or in wastewater treatments, but having the potential to be a cheaper and more ecological source of transport fuels makes them very attractive. Especially in times of oil price uncertainty or scarcity, and emission reduction need.

Non-edible energy crops are probably the most straightforward. They can be grown on marginal land, lowering the food-fuel competition, however, they can still compete with feeding purposes (see below). We may divide them into two types, herbaceous energy crops and short-rotation coppice (SRC). Herbaceous crops are mostly types of grass (e.g. grass, rye, switchgrass) and can be used as hay or fresh. SRC are woody species previously grown for fibre used in e.g. pulp industries (e.g. eucalyptus, Salix, poplar, bamboo). Ethanol from these crops can produce 75 % less CO₂ than petrol, BtL fuels up to 90 %. Compared with food-crops, a wider range is available, making them suitable for various regional conditions. (Antizar-Ladislao and Turrion-Gomez 2008)

Another possible feedstock are *agricultural and woody residues*. Compared to energy crops, which specialized cultivation requires additional inputs such as land, fertilizer and harvest costs, residues in their first stage, carry very low production costs (Antizar-Ladislao and Turrion-Gomez 2008). However, rather low fractions (only about 15%) of total agricultural residues are available for energy purposes, due to various reasons like soil conservation, feeding needs or seasonal inconstancy. In opposition, woody residues are available in larger quantities and have one paramount upper hand. Trees can achieve a lignocellulosic energy conversion factor of 16 (corn has 1–1.5, sugarcane between 8–10) and they do not require prime land in order to grow

leaving space for food crops. Yet, significant challenges are also present. Carbon mitigation objectives, ecosystem services and biodiversity needs must all be balanced in relation to the possible widespread use of forest biomass in the transport sector. (Antizar-Ladislao and Turrion-Gomez 2008)

Organic waste such as animal fats and by-products, recycled cooking oils and many others are a heavily underused source of biomass for energy purposes, even though MSW generally averages approx. 65% biodegradability, which promises high yield sources for bioethanol and biogas production. Furthermore, its use will have positive effects on landfills¹⁵, plus collection mechanisms are already in place, the amount of needed investment should be reasonable¹⁶. However, unsystematic feedstock accumulation, conversion efficiency or further development needs are just some of the defined obstacles (Stephen and Periyasamy 2018). Still, viable projects are currently in place – e.g. in Northern Ireland, bioethanol is produced from potato peelings from chip plants – motivation for using these sources should be elevated. (Antizar-Ladislao and Turrion-Gomez 2008)

There are certain ways how to boost the crucial characteristics of crops. The two main ones are *traditional breeding*, which offers lower costs, but needs longer time periods to prove worthy or *genetical modification*, where costs are nowhere near low and the time period may be uncertain. In short, these approaches focus on the plant’s durability in various conditions (pesticides, unfavourable land, etc.), its ability to transfer larger amounts of energy from the sun (photosynthesis) or its oil yield percentages. As this may sound tempting, the introduction of modified crops into the environment may pose some risks. (Antizar-Ladislao and Turrion-Gomez 2008)

Tab. 5 – List of feedstocks

Energy crops	Agricultural and wood residues	Organic waste	Traditional breeding & genetical modification	Sustainably sourced vegetable oils
Amaranth	Barn	Animal fats	Miscanthus	Azadirachta indica
Bamboo	Citrus waste	Farm waste	Switchgrass	Calophyllum inophyllum
Energy maize	Corn stover	Food waste	Willow	Castor bean
Eucalyptus	Green waste	MSW	etc.	Cotton seed
Grass	Industrial waste	Olive pulp		Jatropha
Miscanthus	Sugarcane bagasse	Recycled cooking oil		Jojoba
Oilseed rape	Sawdust	Sewage sludge		Linseed

¹⁵ Lowering inflow of material

¹⁶ Mostly for separation technologies.

Poplar trees	Wheatstraw	Wastewater	Maduca indica
Reed canary grass	Waste ricestraw	etc.	Pongamia pinnata
Salix	Wood		Rubber seed
Sugarbeet	Wood chips		Tobacco
Sweet sorghum	etc.		etc.
Switchgrass			
Willow			
Winter triticade			
Winter wheat			
Wood			
Wood chips			
etc.			

Sources: Own processing based on (Antizar-Ladislao and Turrion-Gomez 2008), (Ashraful et al. 2014), (Stephen and Periyasamy 2018)

Sustainably sourced *vegetable oils* (2G) are supposed to be non-edible. If gained from dedicated energy crops, they become quite pricy and evoke most of the traditional 1st generation biofuels problems. Some oil-bearing shrubs, like *Jatropha*, castor bean oil (Brazil) or soybean oil (US), are already being used. They stand, however, against certain challenges regarding mainly cost-efficiency, land competition¹⁷ or handling obstructions (some tend to be poisonous). Waste oil projects also hold some potential, like Argent Energy’s biodiesel plant at Newarthill, Motherwell, Scotland. Here they use waste cooking oil from fast food and catering industry as biodiesel feedstock. (Antizar-Ladislao and Turrion-Gomez 2008)

Tab. 5 shows selected second generation feedstock based on various sources. Also, Tab. 6 contains an overview of the main advantages and disadvantages for all five feedstock groups.

Tab. 6 – Advantages and disadvantages of listed feedstock groups

Advantages	Disadvantages
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¹⁷ Like all energy crops, they can be grown on marginal land. However, on such land they tend to offer lower yields and to reach sensible oil yields they often require prime land.

2G generally	<p>Hold a stronger "problem free" potential to be cost-competitive with fossil fuels.</p> <p>Expected to reduce net carbon emissions, energy dependency, and increase energy efficiency.</p> <p>Net carbon (emitted-consumed) from combusting 2G is neutral or even negative.</p> <p>Have the overall potential to overcome 1G limitations.</p>	<p>Demand further technological evolution.</p> <p>Tend to have higher cost-benefit ratios.</p> <p>Can have trouble with providing steady supply of feedstock.</p>
Management	Farmers already familiar with given feedstock management (growth, harvesting, storage, market).	
Non-perennial woody crops	<p>Land can be put back into crop rotation after harvest.</p> <p>High yield potential.</p> <p>Wide geographical distribution.</p> <p>Relatively low levels of input needed.</p> <p>Reduce erosion and improve soil properties.</p> <p>Provide better wildlife habitat.</p>	Compete for land with food if not installed on marginal land.
Perennial forage crops	<p>Low water and nutrition input requirement.</p> <p>Adaptability to low quality land.</p> <p>Positive environmental impact</p> <p>Native to North America</p>	<p>Competition with other industries.</p> <p>Takes 2-3 years to start full production.</p> <p>Limited availability of genotype.</p> <p>Important losses over winter.</p>
Energy crops (generally)	<p>Potentially more favourable GHC balance (compared to 1G and fossil fuels).</p> <p>Wider variety of non-edible feedstocks, meaning lesser food-fuel competition.</p>	Compete for land if not installed on marginal land.
Agricultural and wood residues	<p>Low production cost.</p> <p>Large in amount and widely used sources.</p> <p>Removal of excess woody material improves forest health and productivity (also helps to prevent wildfires).</p> <p>Have minimal direct impact on food prices.</p>	<p>Small volumes available for transport fuel purposes (due to other forms of use like soil conservation, feed, general season variation).</p> <p>Limited accessibility.</p> <p>Competes with current uses.</p> <p>Need special harvest and storage equipment.</p>

	Avoid GHC emissions associated with (in)direct land use changes.	
Organic waste (MSW, etc.)	Currently heavily underused, thus, quantitatively hold great potential. Promise of high yield sources for bioethanol and biogas. Positive effect on landfill land. Collection mechanism already in place.	Uncertainty about initial investment volume which would be sufficient.
Traditional breeding and genetic modifications	Potential great improvement to plant characteristics, especially their ability to withstand crude conditions, and oil yield percentages.	Uncertain or high time requirements in order to prove targeted utility. Unknown risks regarding the introducing of modified crops to given environments.
Vegetable oil yielding crops	Yielding high oil content. Can grow in poor soil and dry climate (e.g. Jatropha).	Potential food-fuel competition, especially concerning prime arable land. Consistent high yields are hard to achieve with low input costs. Need to develop optimal production practice.

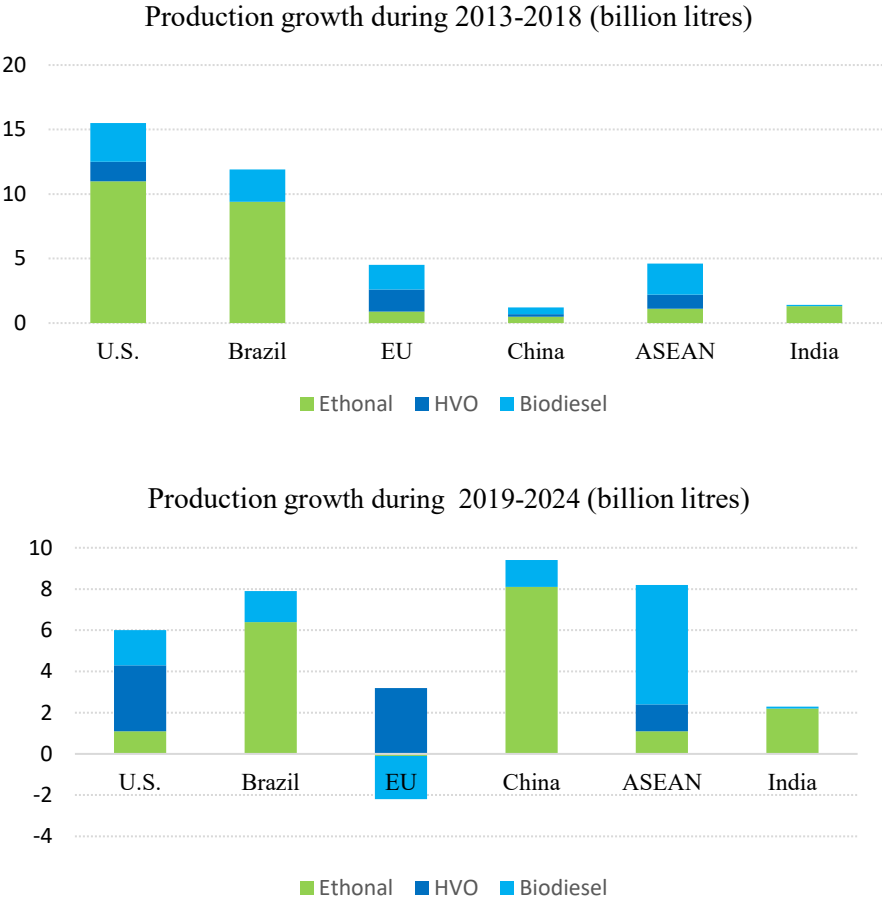
Sources: Own processing based on (Antizar-Ladislao and Turrion-Gomez 2008), (Alalwan, Alminshid, and Aljaafari 2019), (Carrquiry, Du, and Timilsina 2011)

4. Biofuel production volumes and capacities

Global production of all biofuels in 2018 increased by nearly 7 % from 2017, reaching 153 billion litres (3.8 EJ). Together, the U.S. and Brazil dominate production, sharing 69 %, and

with EU (8 %)¹⁸ and China (3.4 %) trailing. The U.S., Brazil and EU produce 77 % of global biofuels. The main fuels are ethanol (63 %), FAME (31 %) and HVO (6 %). In addition, in some countries biomethane production is quickly rising, nevertheless still representing less than a 1 % share. Other advanced biofuel (aside from 2G ethanol, FAME and HVO) hold a lower than 0.5 % share. For advanced biofuels as a whole, cellulosic ethanol accounts for 60 % of production in the sector (Transport Renewables Analysis, 2018). The main driver and influence of the markets are policymakers and regulators. (REN21, 2019)

Fig. 3 – Growth of produced volumes for given periods ¹⁹



Source: Own processing based on IEA, Biofuels production growth by country/region, IEA, Paris

Fig. 3 shows production volume growth for all major biofuels markets for 2013–2018 and 2019–2024 (forecast). The share of U.S., Brazil and EU by the end of the first period was 46.6 %, 24.2 % and 13 % respectively. When looking at the EU, we can see the effects of the

¹⁸ The EU however leads HVO production, accounting for 50 % (3.5 billion litres) globally, followed by U.S. (31 %, 2.2 billion litres).

¹⁹ Underlying value table can be found in appendix H

pull away from conventional towards advanced biofuels (in this case, from biodiesel to HVO), by downsizing the whole sector of biodiesel (-2.2 billion litres).

Even though electric mobility is rapidly expanding, biofuels still hold an almost 90 % share in the transport sector regarding renewables, with passenger vehicles playing the first fiddle, accounting for more than 60 % of that ('IEA, Transport Biofuels Analysis' 2019). In 2020 they are forecasted to account for 82 Mtoe (68 %), with heavy duty vehicles (HDVs) holding 29 % (35 Mtoe) and shipping only 3.3 % (4 Mtoe). The cry for increased usage of biofuels in aviation (less than 0.01 % of aviation fuel demand in 2018) is eminent, since it is the fastest growing emitter of CO₂, with 2020 levels predicted to be 70 % higher than in 2005²⁰ and having potential to rise past 300 % in 2050 ('Reducing Emissions from Aviation' 2016).

Regarding investment serious improvements need to be achieved. 1G biofuel investment spiked in 2007 at roughly over 25 billion USD. Since then they have fallen to around 3 billion USD in 2018 (IRENA 2019). This could be sign of a shift to 2G fuels, if only those investments were growing. 2G related invest figures spiked in 2011 at around 3 billion USD, falling under 1 billion by 2018 (IRENA 2019). According to IRENA the overall new investment attitude within the biofuels sector is "*at best moderate*" (IRENA 2019), which is paradoxical, since 68 countries have already enacted blending mandates, a rapid increase from 36 in 2011. The minor volumes (when compared to 1G) flowing into 2G biofuels are also partially caused by e.g. public support and attitude uncertainty, for which some governments (U.S.) are being criticized (see below).

Another way how to evaluate the status of 2G (advanced) biofuels is by number of biorefineries. Tab. 7 shows the numbers for advanced biorefineries in 2016. However, numbers from a different study in from 2017 (Nguyen et al. 2017) offer slightly different numbers, stating for example, that there are only 6 commercial scale plants in the EU. Even though the numbers differ, it is clear that globally, 1G biofuel refineries still account for the majority. E.g. in Brazil, there are 360 ethanol plants, two of which produce 2G ethanol (Nguyen et al. 2017). In the EU there are 363 plants focusing on liquid fuels, but only 19 (Nguyen et al. 2017) produce 2G biofuels. Fig. 4 shows locations of biofuel refineries worldwide. The visualisation supports numbers stating that the U.S., EU and Brazil currently hold the largest production capacity, with China and Southeast Asia running up.

Tab. 7 – Advanced biofuel plants as of 2016

²⁰ If aviation was a country, it would rank in the "TOP 10" emitters globally.

Region	Commercial plants	Demonstration plants
North America	12	11
Europe	9	7
South America	3	0
Asia	2	2
Oceania	0	1

Source: Own processing based on data from Statista²¹

Fig. 4 – Global biorefineries²² as of 2017



Source: Available in Google Maps, based on (Nguyen et al. 2017)

5. Biofuel policies

This chapter is meant to familiarize the reader with the legislative framework in place, currently affecting the biofuels industry. Because this sector holds high ecological and

²¹<https://www.statista.com/statistics/686698/number-of-commercial-and-demonstration-advanced-biofuel-plants-worldwide/>

²² Blue markers = operational plants; Yellow markers = plants in development; Red markers = suspended plants

economic potential, along with potentially high social and environmental negative externalities, it has found itself under close scrutiny of not only the academic groups, but mainly the political representation of many countries. As stated before, we look at three regions, the European Union, the United States and Brazil.

5.1 The Paris Climate Agreement and the IEA's Sustainable Development Scenario

In 1996 the EU Environment Council became the first to define²³ a global mean temperature increase limit of 2°C (above pre-industrial levels). Eventually, this cap-like attitude was taken in also by the G8 in 2009. The long-term temperature goal (LTTG) is one way of expressing the dangerous anthropogenic interference (DAI). Preventing DAIs is the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC). Gradually greater numbers of global institutions, both national and supranational, have in various ways pledged to deal with climate change (global warming). (Schleussner et al. 2016)

These tendencies have most recently shown themselves in the Paris Climate Agreement²⁴ adopted during the UNFCCC's conference of parties in Paris, December 2015. The agreement states the objective as *“holding the increase in the global average temperature to below 2 °C above pre-industrial levels and pursue efforts to limit the temperature even further to 1.5 °C”* (‘The Paris Agreement | UNFCCC’ 2015). The severity of impacts differs at a 1.5°C and 2°C warming, but it is safe to say exceeding either is considered globally harmful. It is not the goal of this thesis to explore the differences and so the presumption we follow is that the motivation for GHG emission reduction is great for both scenarios²⁵.

Based on the IEA's World Energy Outlook (WEO) from November 2019 *“the world is currently not on track to meet the energy-related components of the Sustainable Development Goals (SDGs²⁶)”* (IEA – World Energy Model Analysis, 2020). This conclusion is based on the Stated Policies Scenario (STEPS) drawn up by EIA which takes into account “stated” policies. Regarding biofuels, the STEPS determines that oil security risks are still in place as dependence on Asia remains strong and despite market and policy changes, supply chokepoints persist. This offers an opportunity for biofuels as a stabilizing factor. It also poses several major warnings

²³ Based on the Intergovernmental Panel for Climate Change (IPCC) Second Assessment Report.

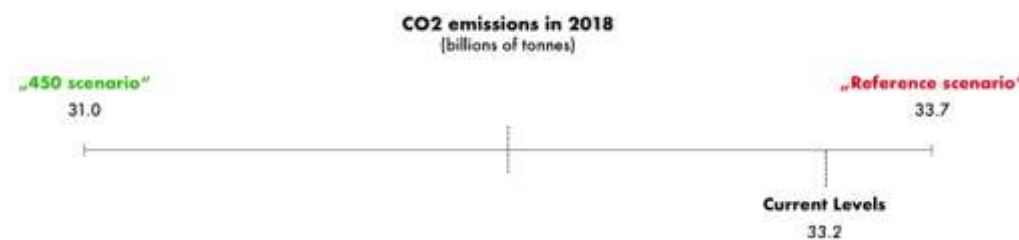
²⁴ 187 nations have reached a consensus on combating climate change along with adapting to its impacts.

²⁵ For more information on this see (Schleussner et al. 2016)

²⁶ United Nations SDGs most closely related to energy: to achieve universal access to energy (SDG 7), to reduce the severe health impacts of air pollution (part of SDG 3) and to tackle climate change (SDG 13).

regarding emissions. Most notably on the emissions and overall energy consumption. Out of the two scenarios from the 2008 WEO – “Reference” (no changes in existing policies) and “450” (offering ideal peak values for both emissions and consumption) – the current level of CO₂ emissions cling towards the worse off scenario (Fig. 5). Also, in 2018, the projected peak of 14 000 Mtoe in energy consumption was surpassed with no marks of slowing down. It is obvious that the forces of continuity (population growth, resp. energy consumption) have been stronger than those of change.

Fig. 5 – CO₂ emissions in 2018 in relation to IEA’s 2008 WEO scenarios



Source: Own processing based on (‘Sustainable Development Scenario – World Energy Model – Analysis’ 2020).

The IEA’s Sustainable Development Scenario (SDS) is fully aligned with the Paris agreement’s call for emissions to peak as soon as possible and decrease rapidly afterwards. It shows ways how to meet the above-mentioned SDG’s while staying sceptic to early-stage technology outcomes, as opposed to e.g. the IPCC’s scenarios. It states a 66% probability for temperature rise below 1.8% (without the reliance on global net-negative CO₂ emissions). This means a fall from 33 Gt CO₂ in 2018 to 10 Gt in 2050.

Even though institutions like IPCC or IEA, are not in the position to recommend specific levels of warming or greenhouse gas (GHG) concentrations, they provide essential information for science-based political decisions (Schleussner et al. 2016). We will be using the SDS as a benchmark for necessary improvements regarding emission reduction, resp. biofuel usage and promotion.

The SDS requires an investment increase of 25 % (‘Sustainable Development Scenario – World Energy Model – Analysis’ 2020) over the 2020 to 2050 period compared to STEPS. The much needed improvements in transport relate to the fact that, e.g. in the EU, the transport sector is the 2nd largest CO₂ emitter, but is the only one failing to maintain a downward trend from the 1990 values (19.2 % higher in 2017. (‘Europe 2020 Indicators - Climate Change and Energy - Statistics Explained’ 2020)

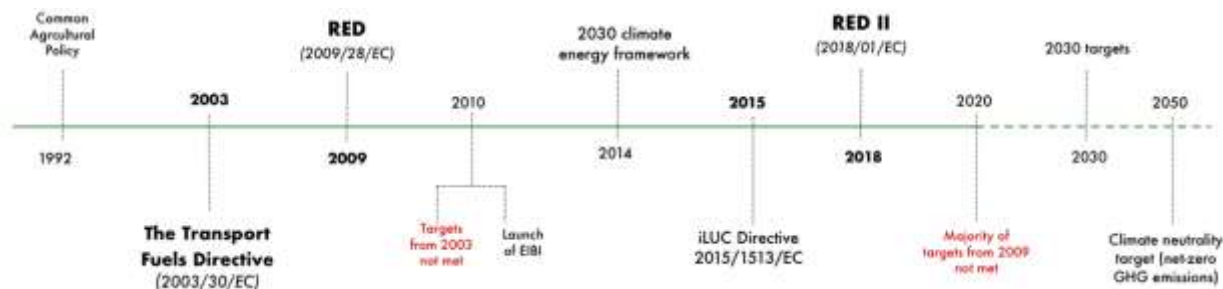
5.2 Policies in major countries

The U.S., Brazil and EU are globally on the forefront of biofuel production and consumption. In order to illustrate biofuel related policies, we will use these three government bodies. All three are original signatories to the Paris agreement, however, for the U.S. this changed in 2019 when President Trump could finally carry out his previously stated intention to leave.

5.2.1 The European Union

The EU's first major directive concerning biofuels was passed in May 2003. This marks the commencing of largescale biofuel production. The targets – 2 % by 2005 and 5.75 % by 2010 – were not met as the 2006 consumption levels were equal to 1.06 % and 3.9 % in 2010. With only Germany (3.86 %) and Sweden (2.11 %) exceeding the target, 22 out of 27 states failed to reach them. The targets were not binding, if the member states gave valid reasons, which was probably the cause. (Wessler and Drabik 2016)

Fig. 6 – EU's policy timeline



Source: Own processing based on: (Bacovsky et al. 2016), (Pelkmans 2019), (Janda, Kristoufek, and Zilberman 2012), (Nguyen et al. 2017)

In 2009, The Renewable Energy Directive (RED) established an European framework for renewable energy promotion²⁷. It set three major targets²⁸, including consumption of energy from renewables, where a sub-target of a 10 % in transport was set. Multiplication factors applied for certain types of renewable energy. The policy also contained GHG emission reduction targets (from 1990 levels). Notable are the sustainability criteria, which set GHG emission savings requirements and defined materials, land types, etc. prohibited for biofuel production²⁹.

²⁷ Sometimes referred to as the “20-20-20” policy (Janda, Kristoufek, and Zilberman 2012)

²⁸ See: https://ec.europa.eu/clima/policies/strategies/2020_en#tab-0-0

²⁹ For details, see Article 17 of the Directive.

These were crucial for effective implementation and also binding, irrespective of whether the raw materials were cultivated inside or outside the territory of the Community (if the fuels were to be declared renewable) (‘EUR-Lex - 32009L0028 - EN - EUR-Lex’ 2020). In cooperation with the Fuel Quality Directive (2009/30/EC), these two directives became the core of transport biofuel regulation in the EU (Wesseler and Drabik 2016).

The 2030 climate and energy package which builds on the 2020 package sets targets for 2030. However, in contrast to the RED, it contains no specific sub-targets for given sectors nor binding targets for each member state (Bacovsky et al. 2016).

Since the 2008 and 2011 commodity price booms calls for reform resonated in the EU. As a result, the ILUC³⁰ Directive (2015/1513/EC) set a 5 % cap on 1G biofuels and multipliers for advanced biofuels to limit the contribution of 1G feedstock externalities (land use change and overall GHG emissions). (Wesseler and Drabik 2016)

The most recent piece of major EU biofuels legislation is the revised RED (known as “RED II”), entering into force in December 2018. It raised the share of renewables in transport from 10 % to 14%. For the first time a sub-target of 3.5 % for advanced biofuels (2G & 3G) appeared (see Tab. 8). Also, to boost the stagnating progress of advanced biofuels in shipping and aviation, advanced fuels can contribute with a 1.2 multiplication value. Moreover, the counting of biofuels identified by the ILUC Directive will be frozen at 2019 levels and gradually phased out from 2023 towards 2030. In addition, sustainability criteria were reformulated (see Tab. 9). (Pelkmans 2019)

Tab. 8 – RED II mandates, caps and limits

RED II Mandates	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Cap on Conventional Biofuels	7.0%									
Minimum for Advanced ^a	-	0.2%	-							3.5%
Maximum for Advanced ^b	1.7%									

^a from feedstocks in Part A of Annex IX of the 2018/2001/EU Directive

^b from feedstocks like waste fats, oils, etc. Part B Annex IX of the 2018/2001/EU Directive

Source: (Phillips et al. 2018)

Tab. 9 – GHG savings thresholds in RED II

³⁰ ILUC - Indirect Land Use Change.

Plant operation start date	Transport fuels	Transport renewable fuels of non-biological origin
Before October 2015	50%	-
After October 2015	60%	-
After January 2021	65%	70%
After January 2026	65%	70%

Source: (Phillips et al. 2019)

Several successive Framework Programmes (FPs) for research and technological development (R&D), covering all the production chain phases, were used to boost cost cutting research. Between 1998 and 2002 only 8 projects (out of 100) were clearly transport related. FP6 (2002-2006) supported 7 projects with a fully 2G biofuel focus (out of 10,082 ('CORDIS - EU research projects under FP6', 2006)). During this period the Biofuels Technology platform was launched, becoming the core of the EU biofuel community. During FP7 period (2007-2013) numbers of projects on biofuels grow quickly as a result of high oil prices during the period. Twenty projects were supported with around EUR 70 million. (Pelkmans 2019) Currently (2014-2020) all funding goes through the Horizon 2020, the largest R&D programme to date with EUR 80 billion available over 7 years. Under the "Secure, Clean and Efficient Energy" part of Horizon 2020, EUR 640 million and EUR 670 million, in 2014 and 2015 respectively, will be spent just on bioenergy. Along with all the private investment this move could attract. (Pelkmans 2019)

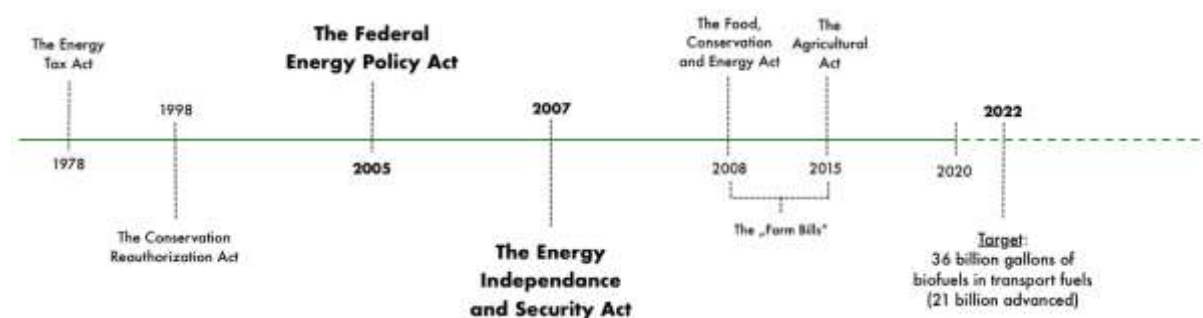
Another worthy institution launched in 2010, the EIBI, focuses on innovative bioenergy value chains, not yet commercially available, which could bring significant contribution to the bioenergy markets by largescale development (Pelkmans 2019). Through a merge in 2016, EIBI became the European Technology and Innovation Platform Bioenergy (ETIP Bioenergy) aiming to implement the Strategic Energy Technology (SET) Plan coming from the European Commission. In particular, it's key action No.8, "Renewable Fuels and Bioenergy" ('ETIP-B-SABS 2' 2020).

5.2.2 The United States

The United States first began exploring biofuel policies during the 1970s when introducing The Energy Tax Act which set tax exemptions and subsidies for ethanol blended gasoline. Biodiesel followed suit in The Conservation Reauthorization Act in 1998. This early concern was caused by a series of oil crises between 1967 and 1979 – most notably the 1973 embargo imposed by Arab oil producers (Macalister 2011). Furthermore, oil imports, therefore

dependence, quintupled during the 1970s ('U.S. Imports of Crude Oil (Thousand Barrels per Day)' 2020) and efforts to lower GHG emissions and boost demand for domestic farm products also played their role. In this way, the U.S. and Brazil share similar motivation. Generally, U.S. fiscal incentives and mandates vary across states but are in line with the federal legislation level (Janda, Kristoufek, and Zilberman 2012). However, in November 2019 President Trump could finally begin his previously announced withdrawal from the Paris agreements making the U.S. the only major economy to have not signed and ratified the Agreement³¹ (*BBC News* 2019).

Fig. 7 – U.S. policy timeline



Source: Own processing based on: (Bacovsky et al. 2016), (Drennan and Spaeth 2019), (Janda, Kristoufek, and Zilberman 2012), (Nguyen et al. 2017)

The Federal Energy Policy Act (EPACT) was a ground-breaking policy in the U.S. In effect since 2005, not only did it initiate mandates on biofuels consumption – an objective to purchase 4 billion gallons in 2006 and 7.5 billion in 2012 – but mainly since it gave life to the Renewable Fuel Standard (RFS) program. The RFS is the statute that currently regulates biofuel production and consumption through setting annual targets (mandates in volumetric terms). (Nguyen et al. 2017), (Bacovsky et al. 2016)

In 2007 the RFS was amended by The Energy Independence and Security Act (EISA). A biodiesel mandate was added and total mandated quantity of renewable fuel to be blended into transport fuels was expanded. In addition, a long-term target was set, 36 billion gallons, of which 21 billion shall be advanced (2G and higher) biofuels. Also, conventional biofuels were capped at 15 billion gallons starting 2015. The 2022 mandate for biodiesel is 1 billion gallons.

A series of so-called Farm Bills established (2008) and then reauthorized and expanded (2014) several programs (e.g. The Biomass Crop Assistance Program, BCAP) to provide

³¹ For full list of countries see United Nations Treaty Collection.

financial assistance to all parts of the production chain. Together they distributed over USD 880 million. (Nguyen et al. 2017), (Bacovsky et al. 2016)

To achieve the EISA and RFS goals, the Environmental Protection Agency (EPA) sets out annual targets (Nguyen et al. 2017). Compliance is tracked using the Renewable Identification Number (RIN) system which assigns a RIN to each gallon of renewable fuel (defined by legislation). Obligated parties may then fulfil their Renewable Volume Obligations (RVOs) by either selling required volumes of biofuels or purchasing RINs from parties that exceeded their RVO ('Alternative Fuels Data Center: Renewable Fuel Standard' 2020). EPA can also offer Small Refinery Exemptions (SRE) to producers based on their application. In the recent years, heated debates surround the SREs (*Reuters* 2019).

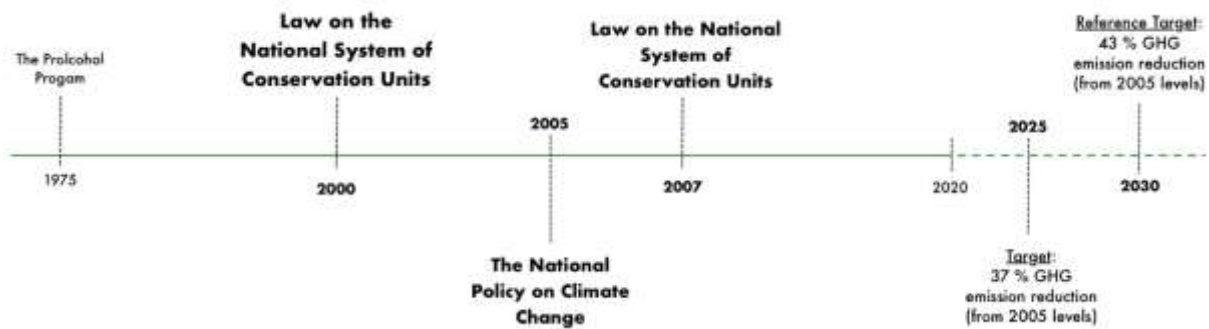
Subsidies and R&D support goes through various federal and state institutions. For example, in 2014 The Department of Energy (DOE) issued a USD 4 billion loan guarantee solicitation for innovative renewable energy and energy efficiency projects that avoid, reduce, etc. GHG. In 2015 another USD 500 million were added. The DOE also supports through the State Energy Program (SEP). In 2014 Farm Bill also authorized USD 3 million for biomass R&D grants. The recently released Federal Activities Report³² on the Bioeconomy provides an overview of wide-ranging, federally funded, currently helping to bolster the bioeconomy through bioenergy production (incl. biofuels) and research (Bacovsky et al. 2016).

5.2.3 Brazil

Brazil's path towards biofuel related legislation began as a reaction towards the petroleum shortage caused by the 1973 oil crisis (Janda, Kristoufek, and Zilberman 2012). Today, even though Brazil is considered a developing country with further social and development challenges its efforts in emissions reduction represents one of the largest undertakings by a single country to date. Between 2005 and 2015 it managed to reduce emissions by 43.9 % (GWP-100 measurement used for quantification). In addition, while also reducing deforestation by 82 % (2004-2014) and having a 43 % share of renewables in its energy mix, this currently qualifies Brazil as a low carbon economy. (Ferreira 2019)

Fig. 8 – Brazil's policy timeline

³² Available at: http://www.biomassboard.gov/pdfs/farb_2_18_16.pdf



Source: Own processing based on: (Bacovsky et al. 2016), (Ferreira 2019), (Janda, Kristoufek, and Zilberman 2012), (Nguyen et al. 2017)

Commencing in 1975 the Pró-Alcool program framework was designed to support demand and supply of ethanol, trying to increase the domestically produced share. This program terminated in the 1990s. However, full liberalization came between 1996 and 2000 resulting in the Law on the National System of Conservation Units (Janda, Kristoufek, and Zilberman 2012). Under this Law, all policy measures and actions to implement Brazil's INDC (see below) are carried out. The National Policy on Climate Change (2009) and the Law on the Protection of Native Forests (2012) were passed to broaden the framework of Brazil's climate change and bioenergy policies established in 2000. (Bacovsky et al. 2016)

In 2008 Brazil introduced a biodiesel blending target of 2 % and increased this to 5 % in 2013. In 2012 the blending obligation for ethanol was 18–25 %³³ for gasoline (Janda, Kristoufek, and Zilberman 2012). This mandate along with the success of flex-fuel vehicles made it possible for ethanol fuel to replace 50 % of gasoline consumption in transport. In March 2015 the ethanol blend of gasoline mandate was increased from 25 % to 27 % (Nguyen et al. 2017). These levels remain in 2019, with biodiesel blending mandates set at 10 %. The Common External Tariff of Mercosur³⁴, in place since 1995, also protects Brazil's domestic biofuels production with duties and tariffs on import and export. Some of these were reduced in the Mercosur-EU 2019 deal.

The official document driving the renewable energy policies is Brazil's intended nationally determined contribution (INDC or just NDC) towards achieving the Paris agreement GHG emission mitigation objective. It provides guidance for energy planning documents like the PDE (Ten Year's Energy Plan) which is elaborated by the Energy Research Agency (EPE) and published annually by the Ministry of Mines and Energy. Currently, Brazil's targets in GHG

³³ This mandate concerns itself only with conventional gasoline blending. Hydrous ethanol (85-100 %) for flex-fuel vehicles isn't included.

³⁴ An economic and political agreement between Argentina, Brazil, Paraguay and Uruguay.

emissions reduction are 37 % by 2025 (from 2005 levels) and a reference target of 43 % in 2030 (from 2005 levels). (Ferreira 2019)

Brazilian R&D currently focus on 2G ethanol (E2G). In synergy with conventional ethanol from the sugarcane the E2G is aiming to expand 2G ethanol production without needs for area cultivation increases. This and use of other feedstock such as sugarcane straw, bagasse or others like wood chips should increase competitiveness of this fuel. This process continues under the RenovaBio Program in which both private and public parties are engaged (Ferreira 2019). RenovaBio is based on three main instruments:

- annual carbon intensity reduction targets (gCO₂/MJ) for a minimum period of ten years,
- certification of biofuels by efficiency in reducing GHG emissions, and
- Decarbonization Credits (CBIO). (Flake and Barros 2019)

The aim of the CBIOs is to formally recognize environmental benefits behind biofuel usage and also remunerate the sector for its role in GHG emission reduction.

6. Conclusions

The industry of biofuels is one that has experienced rapid growth over the past two decades. After initial overall enthusiasm, it has become clear that food based, conventional (1G) biofuels are not correct way forward. Nevertheless, even though the academic debate regarding their many vices has been around since the late 2000s, e.g. the influential paper by Searchinger et al. (2008) on land use change, the political lock-in on these fuels and running government support allowed to, at least goal-wise, leave them behind in late 2010s (e.g. the 2015 iLUC Directive in the EU).

The substitutes, advanced biofuels (2G and 3G), have initially been developing in the shade of their older brother and waiting for a chance to prove themselves. Once in the spotlight, they have proven to be a more ecological and socially less harmful alternative, on the other hand, they have also shown their reverse side in the form of technological and therefore cost handicaps and challenges. As we have shown in the technological overview and the costs analysis chapter, some of these traps still stand till today and raise uncertainty, whether or not the sector will be able to ever, cost-effectively, overcome them. At the same time, with 3G generation (algae) biofuels pushing forward in their evolution, they are hopefully soon to become a commercialized industry. In their first stages of commercialization they will probably serve as complements, however over time, if their use proves economically and socially valid, they will likely overcome the prime agricultural

land requiring fuels of previous generations. So, a question may be raised, whether or not it is currently prudent to still focus on 2G biofuels, or rather somewhat skip the generation as whole. The biggest argument being the fact that 3G fuels demand only about 0.3–2.7 % (Ullah et al. 2014) of global non-arable land, whereas e.g. using soybeans (1G) land share needed would be 73 % (with 2G fuels being somewhere in between, closer towards the 1G figure). The answer to that would probably have to be refusing the argument for the following reasons. Some types of 2nd generation fuels have already reached commercial stages (e.g. biodiesel, bioethanol, biogas) and most of the rest have potential to follow suite. Also, the transport sector truly needs to accelerate its reduction of GHGs and push away from traditional fossil fuels and with electric cars also facing several problems, the use of different fuels in today's engines seems to be the only remaining way how to do this in wholesale measures. Also, in comparison to 3G fuels, 2G conversion processes can be integrated into current 1G biorefineries (while costs rise minimally) offering a solution in the short-term.

All that being said, in order to truly make a difference, the biofuel industry must maintain and gradually develop certain characteristics. Firstly, it is vital that the whole production process from feedstock to use is able to reduce emissions, at least to a lower level than fossil and 1G fuels. Obviously, ideally even further. Secondly, also a crucial attribute, they must minimize negative externalities, both social and environmental. And thirdly, the hardest challenge of all, they must do all the above while staying cost competitive. Using current 1G biofuel, fossil fuel prices and their respective feedstock prices, we have set a benchmark level 2G fuels must achieve to become widely used. Also, several ways how to further cut costs have been displayed, especially in the feedstock cultivation and pre-treatment phase. Furthermore, the role of financial markets will also play its role, since biofuel producers face intense initial capital requirements. To attract investors willing to dedicate capital on a long-term basis, these companies must be capable of stabilized growth and also offer profit.

In conclusion, apart from technological obstacles preventing 2G fuels from being as cost-effective as 1G or fossil fuels and political lock-in (in the form of subsidies, etc.) still hovering over the 1st generation, there are currently no major barriers for 2nd biofuels to fully penetrate the global market and we can expect them to play a significantly more important role than they have so far.

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