2. Dittrich, P.S. and Manz, A. (2006) Lab-on-a-chip: microfluidics in drug discovery. *Nat. Rev. Drug Discov.* 5, 210–218
3. Sackmann, E.K. *et al.* (2014) The present and future role of microfluidics in biomedical research. *Nature* 507, 181–189
4. Chin, C.D. *et al.* (2012) Commercialization of microfluidic point-of-care diagnostic devices. *Lab Chip* 12, 2118–2134
5. Volpatti, L.R. and Yetisen, A.K. (2014) Commercialization of microfluidic devices. *Trends Biotechnol.* 32, 347–350
6. Ramsey, J.M. (1999) The burgeoning power of the shrinking laboratory. *Nat. Biotechnol.* 17, 1061–1062
7. Whitesides, G.M. (2006) The origins and the future of microfluidics. *Nature* 442, 368–373
8. Blow, N. (2007) Microfluidics: in search of a killer application. *Nat. Methods* 4, 665–670
9. Bhatia, S.N. and Ingber, D.E. (2014) Microfluidic organs-on-chips. *Nat. Biotechnol.* 32, 760–772
10. Huh, D. *et al.* (2013) Microfabrication of human organs-on-chips. *Nat. Protoc.* 8, 2135–2157
11. Yum, K. *et al.* (2014) Physiologically relevant organs on chips. *Biotechnol. J.* 9, 16–27
12. van der Meer, A.D. and van den Berg, A. (2012) Organs-on-chips: breaking the *in vitro* impasse. *Integr. Biol. (Camb.)* 4, 461–470

Science & Society

The Fall of Oil Prices and the Effects on Biofuels

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This analysis is focused on the effect of the abrupt decline of oil prices on biofuels, particularly second-generation ethanol. The efforts to decrease the production costs of biofuels, especially cellulosic ethanol (CE), will be greatly threatened if current oil prices remain low, especially since production is not slowing. Only huge state subsidies could alleviate this threat, but the challenge is to persuade citizens that this sacrifice is worthwhile.

The Viability of CE

Ethanol is a strategically important transportation fuel that has been adopted worldwide (Table 1). Brazil's ethanol relies almost exclusively on sugarcane whereas the USA has a long tradition of ethanol production from corn kernel. By contrast, in Europe the most commonly used feedstocks in ethanol production are wheat, maize, and sugar beet, which represent approximately 90% of raw materials used [1] beyond the use of barley, rye, and triticale. The role of wastes and residues in current production is irrelevant, although the approval in April 2015 of the 'iLUC Directive' by the European Parliament put great emphasis on the production of advanced biofuels from waste feedstocks while establishing a cap of 7% on the contribution of biofuels produced from crops, to meet the target of 10% for renewables in transport fuels by 2020.

Table 1. The World's Main Ethanol Producers (in Billion Liters), 2013 Data

	Production Capacity	Production	Consumption	Imports	Exports
USA	56	51	50	1.6	2.9
Brazil	40.7	23.5	20.9	0.3	3.6
EU	8.8	6.7	7.9	1.2	0.1

Data from [1].

If all of the wastes and residues that are sustainably available in the EU were converted into advanced biofuels, this could supply 16% of road transport fuel in 2030, thus reducing the carbon intensity of transport fuels without significant impacts on food commodity markets or land resources (http://europeanclimate.org/wp-content/uploads/2014/02/WASTED-final.pdf). Estimates suggest that by 2030 approximately 220 million tonnes (Mt) of residues from agriculture (139 Mt), forestry (40 Mt), and municipalities (44 Mt) will be available for ethanol production, creating up to 300 000 jobs in Europe (http://europeanclimate.org/wp-content/uploads/2014/02/WASTED-final.pdf) and thus optimizing resource efficiency and boosting the rural economy beyond the greenhouse gas (GHG) savings and the reduction of EU oil imports. Additionally, dedicated biofuel crops grown on marginal land fallow, such as herbaceous switchgrass (*Panicum virgatum* L.) and *Miscanthus* spp., can be converted into CE. Both practices (use of residues and/or biofuel crops) are important to implement the Renewable Energy Directive and the EU climate and energy targets for 2020, known as the 20%–20%–20% targets.

In this context, both the USA and Europe are now entering a new phase to bring CE into the promising future of renewable energy. The US Renewable Fuel Standard (RFS) program requires renewable fuel to be blended into transportation fuel in increasing amounts each year, reaching 36 billion gallons (b.g.) by 2022. In 2014, US fuel ethanol production reached a maximum of 14.3 b.g. of ethanol mainly derived from corn (http://www.eia.gov/todayinenergy/detail.cfm?id=21212), a value close the plateau of 15 b.g. defined by the RFS. Thus, the challenge for the ethanol industry is to meet the 16 b.g target for CE in 2022, maintaining the quota of 15 b.g. of corn ethanol. The European Commission agrees that ethanol is the most cost-effective and readily available means of substantially decarbonizing Europe's transport sector [1] responsible for over a quarter of the EU total GHG emissions.

CE production is expensive due to both capital and operational costs, with biomass pretreatment the most expensive processing operation due to so-called 'biomass recalcitrance' [2]; that is, the natural resistance of plant cell walls to microbial and enzymatic deconstruction.

Estimates put the production cost of CE at US$3.4 per gallon (in 2012, NREL and its industry partners claimed to produce CE

at a minimum selling price of $2.15 per gallon through thermochemical and biochemical process modeling; http://www.nrel.gov/docs/fy14osti/60663.pdf), compared with US corn and Brazilian sugarcane ethanol production costs, which are in the range US$1.14–1.51 per gallon [3]. Thus, CE is far from competitive for blending purposes and is threatened by current oil prices; predictions for 2015 average prices were: US$2.23 per gallon for wholesale ethanol versus US$2.39 per gallon for motor gasoline [4].

Although positive blending margins were more common (when ethanol prices are below the price of wholesale gasoline) and 1.0 was accepted as the breakeven ethanol/gasoline price ratio [5], occasionally negative blending margins may occur. If that happens, the expected response would be higher Renewable Identification Numbers (RINs), a tradable commodity created by US Environmental Protection Agency (EPA) to enforce biofuel mandates.

The benefits of CE (reduction of oil imports and carbon footprint, among others) lead some authors to claim for strong public investment in R&D, subsidies, and other support policy decisions [2,3]. Ethanol producers are also encouraged to switch from corn kernel to dedicated cultures or agroforestry wastes. Nevertheless, it must be emphasized that considerable variations in GHG emissions and the production costs of CE were observed, depending on the feedstock and location, mostly due to soil proprieties and differences in yield [6]. Compared with gasoline, the GHG savings from *Miscanthus*-based ethanol ranged between 130% and 156% and from switchgrass between 97% and 135%, whereas those from corn stover were 57–95% [6].

Despite a strong belief that the ethanol market is already saturated, the ability to absorb more ethanol in the future depends on the raising of the blend wall. E10 has become the maximum feasible blend adopted for all car models and years in the USA and Europe, although in 2012 the US EPA approved E15 for use in vehicles from the 2001 model year to date [7]. If CE production is unable to advance rapidly enough to meet the RFS mandate (36 b.g. by 2022), other unexpected biofuels sources may be forced to step in and fill the void [7].

The Viability of CE in the Face of Low Oil Prices

The abrupt decline of oil prices in the world market (from approximately US$100 per barrel in August 2014 to near US$50 in January 2015, a price that still remains in November this year) will have consequences at various levels, especially in the implementation and success of ethanol production from renewable sources. The US Energy Information Administration forecasts that Brent crude oil prices will average US$54 per barrel in 2015 and US $59 per barrel in 2016 [8], suggesting that the price of crude oil will remain relatively low. Regarding ethanol, high oil prices per barrel favor its competitiveness, as claimed by Tyner [9] ('If oil stays above $100 per barrel, corn ethanol under normal conditions will be viable simply because of the energy demand for it as a substitute for gasoline'), who also claimed that government subsidies and mandates could be abolished. This threshold was also assumed by other scholars [10,11] or may fall within the

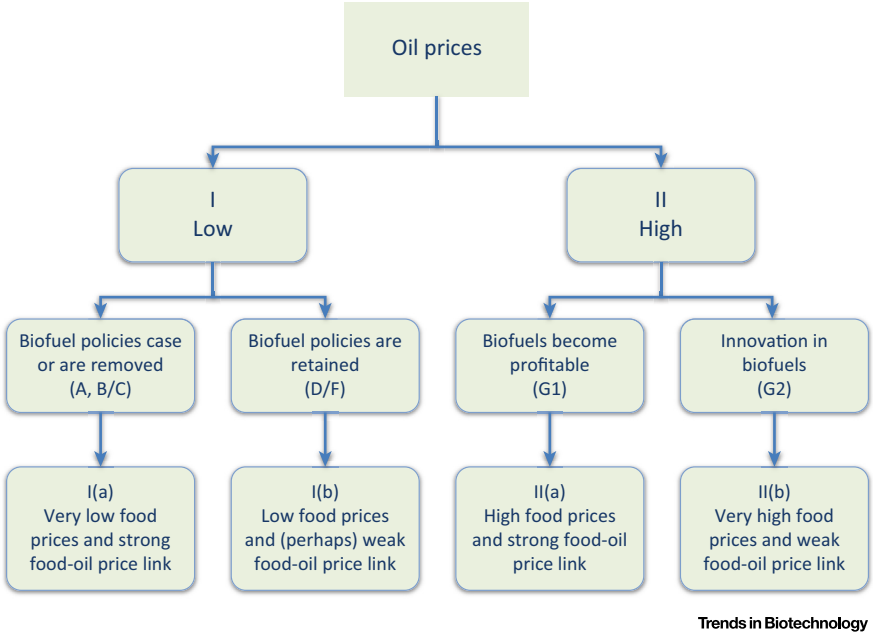

Figure 1. Food Prices Under Low and High Oil Prices. Reproduced from [10] with permission of Elsevier.

range US$80–120 per barrel [12], although the precise figure is uncertain.

It is well recognized that high energy prices increase the costs of production and the price of agricultural commodities as well as their volatility and induce policies (RFS mandates, subsidies to ethanol blenders, and import tariffs) that divert food crops to biofuel production [10]. An interesting evaluation analysis was conducted by Baffes [10] showing in a schematic diagram the relationship among, oil prices, biofuel policies, and food prices and how they can interact (Figure 1).

de Gorter and Just [13] calculated that the costs of the tax credits in 2008 to fulfill the mandated production derived from the RFS were worth over US$6.5 billion, increasing to US$21 billion in 2022 (the tax credit for corn ethanol is US$0.45 per gallon, for CE US$1.01 per gallon, and for biodiesel US$1.00 per gallon). However, these costs could be lowered by the price of carbon and estimated CO_2 emissions from ethanol. In 2012 the EU-28 spent €38.3 billion in subsidies to expand renewable energy, biomass being responsible for €8.3 billion (http://europa.eu/rapid/press-release_IP-14-1131_en.htm).

Critics claim that these practices distort investment markets by creating unfair competition within the energy market and taxpayer costs of biofuels are very high *vis-à-vis* the benefits [13].

It seems reasonable that countries seek independence from nonrenewable fuels, for climate and economic reasons. One may argue that climate change needs clean fuels, even if they are as expensive as fossil fuels. CE produces at least 60% less GHG than petrol, although when indirect land-use change is considered plus the direct emissions, some biofuels, such as biodiesel from palm oil, soya bean, rapeseed, or sunflower, produce more carbon emissions than fossil fuel [14].

The gradual move away from oil was a consequence of oil's escalating price. Meanwhile, car engines are able to run with 10% ethanol in the blend (E10) (Figure 2). Let us imagine for a moment that all vehicles are flexible fuel and that E85 is implemented: this will be the worst nightmare for major oil-producing countries, especially those heavily dependent on oil exports. In this context, the more expensive the oil price, the more rapid the reversion of the paradigm will be. Thus, cheap oil can function like a brake on investments in CE production, unless climate change agenda maintain the purpose of GHG mitigation using biofuels, a strategy questioned by various experts and even the Intergovernmental Panel on Climate Change (IPCC): 'However, land conversion and forest management that lead to a large loss of carbon stocks and iLUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts' [15].

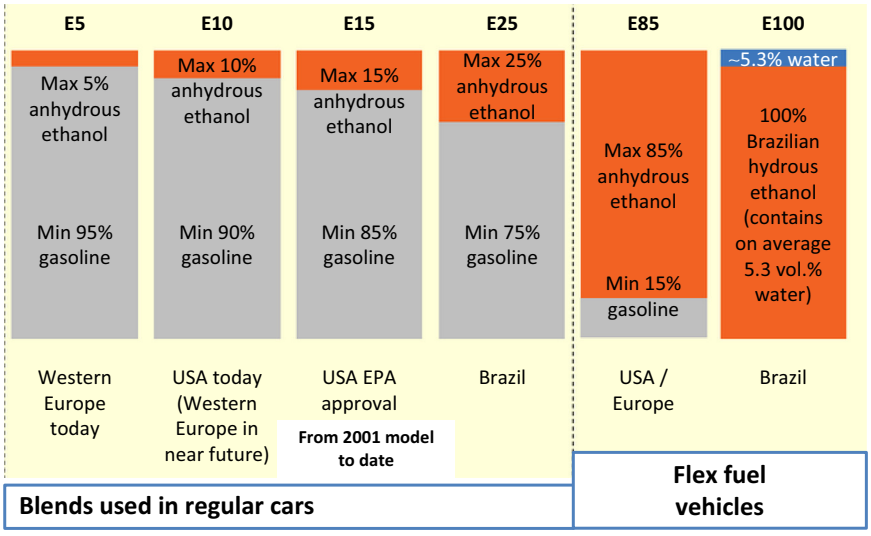

Figure 2. Main Ethanol Blends Used Around the World (http://en.wikipedia.org/wiki/Common_ethanol_fuel_mixtures)..

Over the long term, if oil prices are within the ranges predicted by the US Energy Information Administration [8] and by the World ank in January 2015 (https://www.worldbank.org/content/dam/Worldbank/GEP/GEPcommodities/GEP2015a_commodity_Jan2015), investments in CE could fall. Only huge investments (public or public/private partnerships) could promote a large reduction in the cost of CE leading to its consolidation in the renewable context. How to persuade taxpayers from countries with anemic economies, such as those in Europe, to divert large amounts of money to renewable energies is a challenge for policymakers that will not always be understood by the audience in general.

Concluding Remarks

Cheap oil can be a brake on the development of and investment in biofuel technologies, particularly regarding second-generation ethanol, unless a massive public/state subsidy flow is implemented. However, this could be socially unacceptable.

Also, the production of shale oil in the USA and bitumen in Canada and projects involving drilling in deep water are not competitive *vis-à-vis* current oil prices unless subsidized. Large-scale CE plants operated by Poet-DSM, DuPont, and Abengoa, which became operational in early 2014, were planned when oil was above US$100 per barrel, the threshold above which biofuels can

be profitable even without government interventions.

Acknowledgments

The authors are grateful to anonymous reviewers for their constructive and helpful comments.

Disclaimer statement

The opinions expressed and arguments used herein are those of the authors.

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http://dx.doi.org/10.1016/j.tibtech.2015.10.002

References

1. European Renewable Ethanol (2014) *Renewable Ethanol: Driving Jobs, Growth and Innovation throughout Europe. State of the Industry Report 2014, Brussels*. www.epure.org/sites/default/files/publication/140612-222-State-of-the-Industry-Report-2014.pdf
2. Wyman, C.E. (2007) What is (and is not) vital to advancing cellulosic ethanol. *Trends Biotechnol.* 25, 153–157
3. Stephen, J.D. *et al.* (2012) Will second-generation ethanol be able to compete with first-generation ethanol? Opportunities for cost reduction. *Biofuels Bioprod. Biorefin.* 6, 159–176
4. EIA (2015) *Annual Energy Outlook 2015 With Projections to 2040,* US Energy Information Administration
5. Irwin, S. and Good, D. (2014) Do falling gasoline prices threaten the competitiveness of ethanol? *Farmdoc Daily* 4, 219
6. Dwivedi, P. *et al.* (2015) Cost of abating greenhouse gas emissions with cellulosic ethanol. *Environ. Sci. Technol.* 49, 2512–2522
7. Schnepf, R. and Yacobucci, B.D. (2013) *Renewable Fuel Standard (RFS): Overview and Issues,* CRS Report for Congress, Congressional Research Service
8. EIA (2015) *Short-Term Energy and Winter Fuels Outlook October 2015,* US Energy Information Administration
9. Tyner, W.E. (2008) The US ethanol and biofuels boom: its origins, current status, and future prospects. *Bioscience* 58, 646–653
10. Baffes, J. (2013) A framework for analyzing the interplay among food, fuels and biofuels. *Glob. Food Sec.* 2, 110–116
11. Searchinger, T. and Heimlich, R. (2015) *Avoiding Bioenergy Competition for Food Crops and Land. Working Paper, Installment 9 of Creating a Sustainable Food Future,* World Resources Institute
12. U.S. Government Accountability Office. In *Biofuels: Potential Effects and Challenges of Required Increases in Production and Use Report, GAO-09-446*. U.S Government Accountability Office
13. de Gorter, H. and Just, D.R. (2010) The social costs and benefits of biofuels: the intersection of environmental, energy and agricultural policy. *AEPP* 32, 4–32
14. Van Noorden, R. (2013) EU debates U-turn biofuels policy. *Nature* 499, 13–14
15. Edenhofer, O. *et al.*, eds (2012) *Renewable Energy Sources and Climate Change Mitigation. Summary for Policymakers and Technical Summary. Special Report of the Intergovernmental Panel on Climate Change (IPCC)*, IPCC