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The Future of the EU Bioenergy Sector: Economic, Environmental, Social, and Legislative Challenges

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Abstract

The bioenergy sector is becoming of increasing interest: the European Union is not an exception. Indeed, it is in need of solutions to face one of the worst energy crises of the last century. The sector's growth faces numerous challenges. The main use of energy crops, as feedstock, generates stiff competition on the use of land for food and energy purposes. The production of bioenergy has relevant environmental implications in terms of greenhouse gas emissions. The social aspects related to the bioenergy sector are also potential obstacles to its development. These pressing issues for policymakers call for a better understanding on how national and international laws should regulate the growth of the bioenergy sector. Flying over the economic, environmental, social, and legislative aspects faced by the bioenergy sector, we conclude on threads, opportunities, and priorities that should be considered for its development and propose directions for future studies.

JEL classification

K32, Q18, Q42

Keywords

Bioenergy; European Union; impact; land use; law; sustainability

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1 Introduction

The COVID pandemic and the war in Ukraine have been two major shocks for the world economy, already threatened by the challenges imposed by the climate change, and the need to facilitate a transition toward a greener and more sustainable economy. A major impact of the two shocks has been the energy crisis which is severely impacting the European Union. This conjecture is calling for a structural modification of sources and logistic of energy across countries, and among sectors. While searching for short-term solutions to mitigate the immediate impacts on the society, policymakers, entrepreneurs, and scientists are redesigning the future. Within this context, the European Union (EU) bioenergy sector, the main portion of the EU renewable energy sector, is not only expected to be part of the game, but it is also called to play an important role.

The bioenergy, devoted to produce energy from biomass, accounts for a large share of the renewable energy sector. Apart from the conjectures mentioned above, the sector is experiencing a long-run tendency of increasing importance due to the shift of the economic paradigm from a liner model, based on inputs used for output production and waste discarded as by-product, to a circular model within which all inputs, intermediate, and final goods are loosely defined as they contribute multiple times to a production cycle based on reducing, recycling, and reusing inputs and waste. Within this new paradigm, using renewable energy, whose inputs and by-products are recyclable, fits in the long-run strategy of transitioning to a green and sustainable economy, a major goal for the EU, central in its policy, such as the European Green Deal (EC, 2019). If the direction is clear, the transitioning path is plenty of challenges.

We review the challenges by synthesizing the literature (rapidly increasing) on the EU bioenergy sectors from four perspectives: the *economic*, *environmental*, *social*, and *legislative* point of views.

The economic dimension refers to the economic convenience of producing energy from bioenergy crops, with respect to the existing alternative methods of production. Clearly, the use of bioenergy has the drawback of subtracting lands (a scarce resource) from other economic activities, mainly agriculture, as well as from carbon sequestration end-use (e.g., forests). As for the legislative aspects, which are complex, an ongoing debate refers to the green credentials of bioenergy crops and its impact on regulation as well as to the process itself of production of bioenergy. One of the main multidimensional issues is the land competition that the expansion of energy crops imposes on the land dedicated to food production (Muscat *et al.*, 2020).

The effects of competition are evident on market dynamics and on the environment: for instance, while the use of annual crops and perennial feedstocks (e.g., palm oil) may improve soil carbon balances, the depletion of forests tend to have impacts in terms of greenhouse gas (GHG) emissions that exceed the total potential annual savings due to the use of biofuels. The EU is one of the few countries that is actively devoting efforts to the amount of land devoted to forests: since the early nineties, the hectares of forests have increased by 10%, reaching about 160 million of hectares.

Since energy crops are currently the main feedstock used in biofuel production in relevant countries such as the EU, the United States (US), and Brazil, the environmental impacts related to their production are typically associated with large-scale agriculture production and involve cross-countries dynamics (de Andrade Junior *et al.*, 2019).

Other environmental aspects, such as the depletion of natural resources and of the biodiversity, call for a better trade-off between the environmental and the energy sustainability. The European Commission has warned that the increasing demand for bioenergy has to “come from better use of biomass wastes and residues and a sustainable cultivation of energy crops” (EC, 2020).

As for the socio-economic aspects connected to the use of bioenergy, the impacts on human health, employment and local development, gender and equal opportunities (especially in the developing countries, due to poor labor conditions on plantations, difficult access to land, disadvantaged position of women) are debated. The social dimension also includes aspects on social acceptability, one of the critical factors that is hampering the development of bioenergy projects.

Exactly because the bioenergy production and consumption imply, as aforementioned, both beneficial and detrimental economic, social, and environmental consequences, policymakers need to trade-off these aspects.

The EU is stimulating a circular economy approach with policy frameworks such as the Climate and Energy Package, the New Green Deal and the Next Generation EU: they are all inspired to the Sustainable Development Goals of the United Nations 2030 Agenda and, in particular, to the “Affordable and Clean Energy” and “Climate Action” agreements. More specifically, the EU bioenergy sector is regulated by the Renewable Energy Directive (RED), an evolving framework which put the bioenergy sector into the broader context of the fight to climate change risks, and regulates the implementation of advanced biomass, as they are not depleting the resources that may be devoted to food production. In order to assess the compliance with sustainability criteria, the EU relies on certification schemes which are managed by transnational actors: this represents an advanced form of multilevel governance, which of course needs to be taken in consideration.

Against this background and based on the authors’ expertise, we review the literature employing a holistic approach that integrate the different dimensions, to derive policy implications for decision-makers. Being comprehensive is far beyond the scope of this review, which is rather aimed at emphasizing key elements that need to be considered to deepen on the issues we present. Nonetheless, we conclude on the future of the EU bioenergy sector, and how it may be part of the solution to face one of the worst energy crises of the last decades.

2 The EU Bioenergy Sector: Qualitative and Quantitative Aspects

The term biofuel is often used as synonymous of bioenergy and indicates different energy carriers, such as solid, liquid, and gaseous fuels, for electricity or heat production, as well as for transport (Cadillo-Benalcazar *et al.*, 2021). The classifications of biofuels are numerous, due to the types of feedstocks, the historical order of appearance on the market and the level of technological maturity (Gasparatos *et al.*, 2013a; Liew *et al.*, 2014; Purcelli *et al.*, 2021; Tricase and Lombardi, 2008, 2009).

A generally adopted classification categorizes them in four generations.[1] The first generation, or conventional biofuels, relies on the production from food or animal feed crops (e.g., oil-based plants, sugar, starch crops); the other generations, referred to as *advanced biofuels*, are derived from nonfood crops, such as agricultural and forestry residues, as well as inorganic wastes, or (genetically modified) algae (Correa *et al.*, 2019; Lee and Lavoie, 2013; Sandesh and Ujwal, 2021). The advanced biofuels have been developed to overcome the environmental issues connected with the use of traditional biofuels, but they are still underproduced, due to an insufficient availability of biomass and the high production costs (Bawadi *et al.*, 2019): the market for advanced biofuels is still tiny.

The bioenergy, defined as the sector devoted to produce energy from biomass[2] accounts for a large share of the renewable energy sector: in the EU it accounts for 60%, and the production often relies on imports of raw materials from developing countries.

The importance of the EU bioenergy sector is also evident from the number of studies being produced over the last three decades (Figure 1), and from the surge in publications in the new millennium.

According to the official statistics released by Eurostat, the EU has reached a 22% share of gross final energy consumption from renewable sources in 2020, which is above the target. In addition, the share of energy from renewable sources that are feeding the transport industry has exceeded, in 2020, 10%. Marked differences characterize the EU Member States: Sweden ranks first in terms of share of renewables (about 60%), followed by Finland and Latvia (about 40%); the lowest proportions of renewables are currently observed in Malta, Luxembourg, and Belgium (about 10%).

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[1] Some authors have proposed five generations of biofuels (Mat Aron *et al.*, 2020). We prefer to present the (more) widely accepted categorization into four generations.

[2] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).

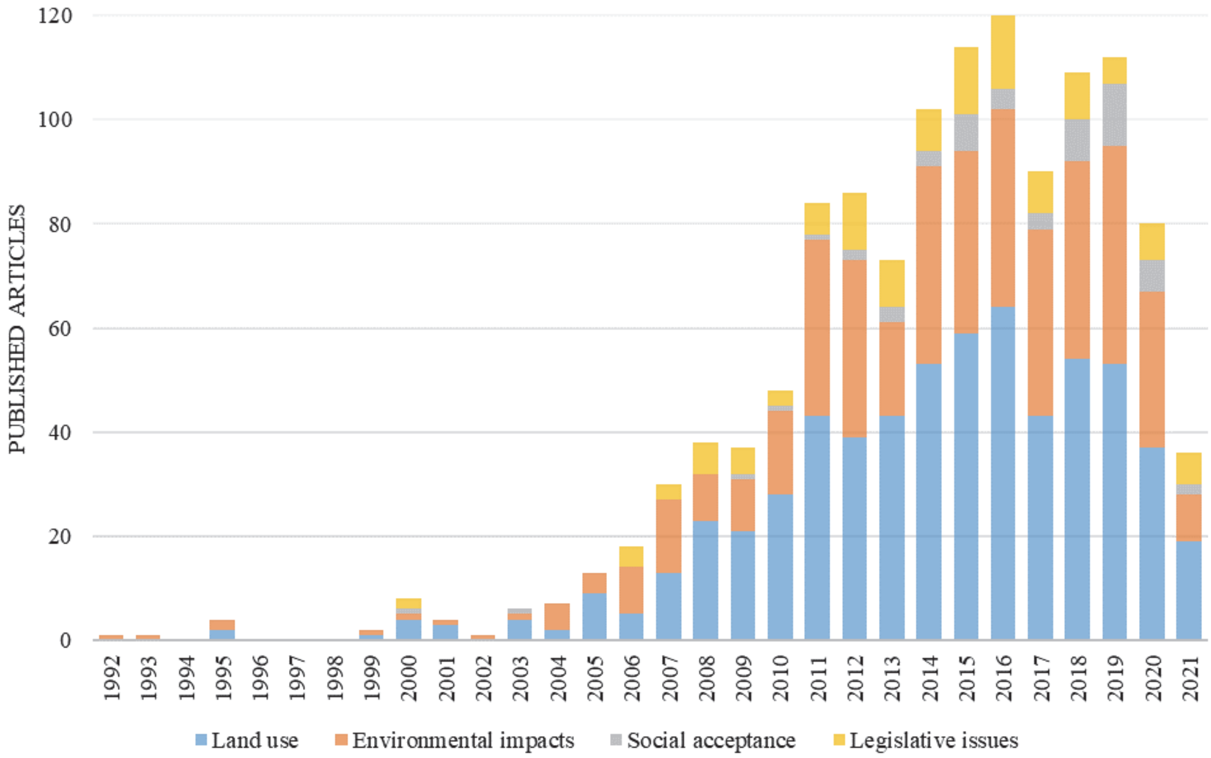

Figure 1: Published articles on the EU bioenergy sector by topic (data extracted in February 2021).

Source: Published articles are from the Scopus database.

The main sources (70%) of feedstock for biofuel production are the agricultural crops constituted the largest source, whereas 30% is generated by waste products and residues. The EU imports less than 5% of the bioenergy consumed, and trade flows are mainly between Member States. Nonetheless, we recognize that a large part of feedstock used in the biofuels (of first generation) industry are from extra-EU countries". On the contrary, the EU consumption of oil and petroleum products, solid fossil fuels and natural gas depends on imports for three quarters. The energy crisis, and the geopolitical changes are therefore pushing toward a greater centrality of the EU bioenergy sector.

3 Legislative Issues

The concept of bioenergy has firstly drawn attention for its renewability and eco-friendly nature. However, gradually, food security issues have been raised as food crops have been used for energy purpose, generating competition for agricultural land, water resources, and nutrient requirement.[3] Potential wildlife habitat destruction and increased dispersion of invasive plant species represent other reported weaknesses (Yadav *et al.*, 2019). With reference to biofuels, as stressed in Section 1, the scientific community has proposed new solutions based on the not-exclusive use of energy crops (Mat Aron *et al.*, 2020; Yadav *et al.*, 2019). The first generation of biofuels, from oil-based plants, sugar, and starch crops, and the second-generation biofuels, from nonfood crops, agricultural and forestry residues, have imposed negative effects on arable land and freshwater environments. The third and fourth generation biofuels, derived from (genetically modified) algae tend to have lower environmental impacts, but suffer of lack of biomass availability and of high production costs.

The evolution of energy crops is parallel to the development of the European legislative framework on biofuels, which represent an (low polluting) alternative to fossil fuels. As such, the biofuels express a mitigation strategy to reduce the GHG emissions. The debate on the green credentials of energy crops impacts on regulation, the implementation of the New Green Deal, and the goal of reducing GHG emissions to reach the climate neutrality are solid motivations to promote renewable energies (RE).[4] Increasing the share of RE is a sizeable shift in terms of energy provision that would allow the EU to reach its ambitious goals (Kingstone *et al.*, 2017). The use of biofuels seems to have great potential in terms of transportation, power-generation, and heating sectors.

A first legal definition of biofuel, "*liquid fuel for transport produced from biomass*", dates back to the 2003 Directive (Directive 2003/30/EC, 8 May 2003), which set targets for biofuels in transport in order to lower the CO_2 emissions, reduce the dependence on imported energy (security of energy supply), and facilitate a sustainable rural development. The Directive required the Member States to strive for the replacement of

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[3] The damage to the climate and the environment is comparable to, or even greater than, oil. The best-known research was carried out in 2005 by two well-known experts in the agri-food sector: Pimentel and Patzek (2005) and Patzek and Patzek (2007) where is stressed that "the continuing push into the tropics by ... biofuel producers will only accelerate a potential ecological catastrophe."

[4] For the energy strategy of the EU as an attempt to reconcile divergent goals see Ammanati (2018).

at least 5.75% of transport fossil fuels with biofuels by 2010, with an intermediate target of 2% by the end of 2005. The Biofuel Directive of 2003 was repealed by the RED-I (2009/28/EC), which has established a binding 10% target for renewables in transport for 2020 and has introduced the counting of renewable electricity and advanced biofuels (Cadillo-Benalcazar *et al.*, 2021). Although the 10% target was not restricted to biofuels and allowed the use of other sources of renewable energy, the EU Commission has put major emphasis on biofuels, claimed to be "*the only available large scale substitute for petrol and diesel in transport*" (Cadillo-Benalcazar *et al.*, 2021).

The Directive 2009/30/EC of the European Parliament, and the Council, on 23 April 2009, have amended the Directive 98/70/EC on the specification of petrol, diesel, and gas-oil, by introducing a mechanism to monitor and reduce GHG emissions. Furthermore, it has been amended the Council Directive 1999/32/EC on the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EE. Following these directives, the contribution from biofuels to the emissions cut targets has started to be central. As previously pointed out, the RED-I has mandated to use a minimum 10% share of renewable energy in the transport sector by 2020; the Fuel Quality Directive[5] has targeted a 6% GHG reduction for fuels used in the transport sector by 2020. In short, the directives have incentivized sustainability criteria to promote the production of biofuels and bioliquids, to reduce the negative environmental side-effects of bioenergy production.

Thus, the biofuels can be counted only if they meet the sustainability criteria set by the EU. When biofuels comply with these criteria, they are classified as "sustainable". The companies may demonstrate compliance by using the voluntary schemes recognized by the European Commission. The Biomass Biofuels Sustainability Voluntary Scheme and the International Sustainability and Carbon Certification are among the most popular schemes issuing certificates from EU RED-I.

The biofuels sustainability criteria aim to prevent the direct conversion of forests and wetlands, and areas with a high biodiversity value,

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[5] The Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amends the Directive 98/70/EC on the specification of petrol, diesel, and gas-oil, and introduce a mechanism to monitor and reduce greenhouse gas emissions. Furthermore, it amends the Council Directive 1999/32/EC on the specification of fuel, used by inland waterway vessels and repealing Directive 93/12/EEC.

for biofuel production and they require that biofuels must emit less GHGs than the fossil fuels they replace. However, there is no zero-risk that part of the additional demand for biofuels will be met through an increase in the amount of land devoted to agriculture worldwide, leading to an indirect increase in emissions through land conversion. Therefore, the Commission has focused on the impacts of iLUC (indirect Land-Use Change) on GHG emissions and reformulated the RED[6] legislative actions to minimize those impacts. The sustainability criteria were further detailed in the 2015 Biofuels Directive, which focus on the climate change risks posed by iLUC. In particular, the Directive (EU) 2015/513 of the European Parliament and of the Council of 9 September 2015 amends the Directive 98/70/EC on the quality of petrol and diesel fuels and the Directive 2009/28/EC on the promotion of the use of energy from renewable sources. The new legislative framework stresses the importance of sustainability certification of biofuels and of course of European and national certification bodies, to verify the compliance to the criteria.

A more recent action has been the adoption of the “Clean Energy for all” or “Winter Package”. The package, adopted in 2019, has modified (through a complete revision of the Third Energy Package with new legislative acts such as Energy Performance of Buildings, Directive 2018/844), the RED-II (EU) 2018/2001, the Energy Efficiency Directive (EU) 2018/2002, the Governance of the Energy Union and Climate Action (EU) Regulation 2018/1999. The new regulations represent an innovative asset of rules for the energy sector. By coordinating these changes at EU level, the legislation has also underlined the EU leadership in tackling the global warming and has provided an important contribution to the EU’s long-term strategy of achieving carbon neutrality by 2050. Specifically the European New Green Deal, announced in the communication (COM(2019)640) of 11 December 2019, sets out a detailed vision to make Europe the first climate-neutral continent by 2050, safeguard biodiversity, establish a circular economy and eliminate pollution, while boosting the competitiveness of European industry and ensuring a just transition for the regions and workers affected.

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[6] The dLUC (direct Land-Use Change) occurs when a land type use is converted in the biomass feedstock production, while the iLUC occurs when the changes in land-use across the globe due to an increased biofuels production are taken into account (Garcia and You, 2018).

In 2020 the Commission adopted the communication 'Stepping up Europe's 2030 climate ambition — Investing in a climate-neutral future for the benefit of our people' (commonly known as the 2030 EU Climate target plan). It includes an updated 2030 emissions reduction target of net 55% compared to 1990 levels, from the previous 40% emissions reduction target.

The transition to renewable energy implies a new approach: the new RED (in force by July 2021) establishes the binding target and provides new rules to be implemented, reaching a compromise between instruments steering the market and (bottom-up) decentralized initiatives. Specifically, the 2018 recast of RED-II of the European Commission offers a new definition of biofuels, which differs from advanced biofuels. The article 2 states that biofuels '*means liquid fuel for transport produced from biomass*' and advanced biofuels '*are produced from the feedstock listed in Part A of Annex IX*'.

The Red-II Directive enhances the sustainability perspective, retaining, since its recitals, the sustainability criteria and focusing on advanced biofuels, establishing it is appropriate to limit the number of biofuels and bioliquids produced from cereal and other star-rich crops, sugars, and oil crops. The Directive underlines that the sustainability criteria are effective only if they lead to changes in behaviors of market actors and that those changes would occur only if biofuels meeting those criteria command a price premium compared to those that do not. Those criteria are set out irrespective on the used raw materials that are cultivated within the Member States, and all Member States should apply a similar methodology to verify the compliance with the sustainability criteria for biofuels.

The RED-II Directive preserves the double-accounting system already proposed in RED-I. The contribution of biofuels made from biomass not competing with food and not generating detrimental land-use changes is double-counted in relation to the calculation of the mandatory share of renewable energy in the transport sector. Moreover, the production food-based biofuels (therefore, the first-generation biofuels) becomes less convenient, even if it is not yet phased out. The Directive contains specific provisions for low iLUC projects, considering "improved agricultural practices" or "the cultivation of crops on areas which were previously not used for cultivation of crops, and which were produced in accordance with the sustainability criteria for biofuels".

As mentioned in the precedent sections, a delegated act adopted by the Commission in May 2019 (as prescribed by Art. 16 of the Directive), supplementing the RED-II, sets out the criteria for certification of low iLUC-risk biofuels, bioliquids, and biomass fuels and for determining the high iLUC-risk feedstock for which a significant expansion of the production area into land with high-carbon stock is observed. With this act, palm oil diesel is considered 'high iLUC risk'. By 1 September 2023, the Commission shall review the criteria laid down in the delegated act and therefore, there is an ongoing debate on the criteria for identifying low iLUC biofuels.

The Commission is invested with the new role of monitoring the origin of biofuels, the impact of their production, including the impact as a result of displacement, on land-use in the EU and in the main third countries of supply. The role of regulation is crucial to identify the legal, fiscal, and organised tools necessary to achieve the goals of the GHG reduction through biofuels. Those goals need to be clearly stated and defined and this calls for the troubled relationship between science and law. Science, which plays a central role in environmental issues as well as in public health, is not offering just "the right solution". Therefore, policymakers should make the choice. The regulator must choose which predictions and whose risk perceptions do carry in formulating the provision or the final decision, balancing technical, and policy priorities.

The political choices must consider that the modernisation of the economy needs to ensure security and resilience of energy supply. The Multiannual Financial Framework and Next Generation EU, worth EUR 750 billion, provide opportunities to transition and grow the economy simultaneously. Specifically, according to the Green Deal policy, the RR Facility aims to make economies and societies more inclusive and better prepared for the green and digital transitions.

The facility, which is the centrepiece of NextGenerationEU, will provide large-scale financial support to Member States of up to EUR 672.5 billion in grants and loans to finance reforms and investments, which need to be spent by 2026. The Recovery and Resilience (RR) plans are strictly connected with the Green Deal policy. In point of fact, RR plans propose investments and reforms that reflect the country-specific challenges and circumstances in each Member State, but they are all expected to substantially contribute to the six pillars foreseen in the Regulation: green transition; digital transformation; smart, sustainable and inclusive growth, productivity and competitiveness; social and territorial cohesion; health, economic, social, and institutional resilience; and policies for the next generation, children and the youth.

Overall, the different plans contain a significant share of climate-related and digital expenditure, as well as measures contributing to social and territorial cohesion and resilience. There must be at least 37% of expenditure for climate investments and reforms.

Furthermore, the facility stresses on a new principle, which was just introduced by the so-called taxonomy regulation on private investments (Regulation (EU) 2020/852 (Taxonomy) on the establishment of a framework to facilitate sustainable investment): the principle of do no significant harm (DNSH). This means that there must be no significant impact on six environmental objectives covered by the taxonomy regulation: climate change mitigation and adaptation, sustainable use and protection of water and marine resources, circular economy, pollution prevention and control, and protection and restoration of biodiversity and ecosystems. To meet the EU's climate and energy targets for 2030 and 2050 and reach the objectives of the European Green Deal, it is vital that not only public, but even private investments are directed to toward sustainable projects and activities.

In that context, the 'Fit for 55' package contains legislative proposals to revise the entire EU 2030 climate and energy framework, including the legislation on effort sharing, land-use and forestry, renewable energy, energy efficiency, emission standards for new cars and vans, and the Energy Taxation Directive. The commission aims to strengthen the emissions trading system (ETS), extend it to the maritime sector, and reduce over time the free allowances allocated to airlines. A proposed new ETS for road transport and buildings should start in 2025, complemented by a new social climate fund.

As European Green Deal includes a target to reduce transport-related greenhouse gas emissions by 90% by 2050, the Commission intends to adopt a comprehensive Smart and Sustainable Mobility Strategy to ensure that the EU transport sector is fit for a clean, digital and modern economy, increasing the uptake of zero-emission vehicles. This proves very difficult for air sector mobility. In this line, the Fit for 55-package includes the RefuelEU Aviation initiative. The initiative proposes the creation of a European-level mandate on the supply and use of Sustainable Aviation Fuels at all major EU airports. The ReFuelEU

Aviation initiative proposes EU-wide harmonized rules for sustainable aviation fuels (SAF) that will apply to all operators and therefore create a level-playing field. The proposal contains an obligation on airlines to uplift SAF-blended aviation fuel when departing from EU airports and introduces an obligation on fuel suppliers to include increasing shares of SAF into jet fuel from 2025 to 2050. This proposal, therefore, specifically promotes the use of first and foremost advanced biofuels, together with synthetic fuels, produced from green electricity.

The Russia's invasion of Ukraine in the end of February 2022 and the consequent global energy market disruption, asked for a new recent intervention by the European Union. The Commission presented the REPowerEU Plan, to make Europe independent from Russian fossil fuels well before 2030.

In this complex scenario biofuels production and use will play a significant role.

The amendments show a growing recognition of the need for alignment of bioenergy policies with the cascading principle of biomass use, with a view to ensuring fair access to the biomass raw material market for the development of innovative, high value-added bio-based solutions and a sustainable circular bioeconomy.

The rich and evolving legislative set of regulations is only one the scheme drawing the complex framework within which is inserted the EU bioenergy sector. In the subsequent sections we will focus on more specific aspects: the land-use competition, the environmental impacts, and the social acceptance.

4 Economical Issues

The growing demand in the market of energy crops, driven by renewable energy policies, is contributing to expand the agricultural sector at a global level (Chen and Önal, 2016; Gohin and Chantret, 2010). According to the OECD-FAO (2019), energy crops are the main source of first-generation biofuels, biodiesel, bioethanol, and biogas, and in fact they may be inputs to produce different types of energy products (Koçar and Civaş, 2013). Oil crops, such as rapeseed, sunflower, palm, and solid energy crops, such as sorghum and cardoon, are used both as resources to produce heating and electricity fuels as well as automotive ones. Similarly, cereals, such as corn, barley, wheat, starch and sugar crops, such as sugar beet and potato, may be used for ethanol production (Sims *et al.*, 2006). The costs of producing energy crops are not negligible, and very variable. An early study estimated costs ranging from 20 to more than 100 US dollars per tons and tight margins along the supply chain (Walsh, 1998): energy crop marginal prices are estimated to be 29, 46 and 55 US dollars, respectively at farmgate, wholesale, and delivery points. Also, for the EU the costs are very heterogenous: the JRC estimates a range between 3 and 30 euro per GJ (Ruiz *et al.*, 2015), with higher costs associated with less efficient crops, or for inputs that require costly pre-treatments (e.g., urban waste). The end-use price is further affected by the cost of logistic, which account for about 10–15% (Walsh, 1998). It is evident that the sector has not reached its economic maturity and efficiency. However, despite the costs of producing energy from energy crops are still relatively high, the contribution of these plants to the energy production is expected to be, in the next two decades, comparable with the contribution of oil and above (by far) of coal (gas) (Winchester and Reilly, 2015). The use of food crops for energy purpose has strengthened the linkages among them, putting pressure on the prices of the agricultural commodities (e.g., oil crops, cereals) and of the processed products, such as the vegetable oils (Santeramo and Searle, 2019, 2020), and also impacting their supplies (Santeramo *et al.*, 2021a). Recent studies have shown that the substitution and the displacement dynamics among energy crops, due to price movements, may induce the producers to modify planting decisions and land allocations (Kim and Moschini, 2018). Moreover, the agricultural land may be converted to the production of energy crops in order to accommodate the increasing demand of the energy industry (Peri and Baldi, 2013).

Apart from these dynamics, the changes in the production use of agricultural land may also have direct and indirect effects in terms of GHG emissions (Edwards *et al.*, 2017; Santeramo *et al.*, 2020): the direct emissions are mainly due to the agricultural practices implemented to produce the energy crops (Delta, 2011; Humalisto, 2015), whereas the iLUC emissions are mostly associated with the extension of agricultural land into noncrop land (e.g., grassland, forest) or with the conversion of the existing cropland, previously adopted for other agricultural uses (e.g., food or feed production) (Haile *et al.*, 2016; Searchinger *et al.*, 2008).

The extension of the agricultural lands into noncrop lands to produce energy crops contributes to increase the level of the GHG releases, with potential detrimental impacts on climate change (Santeramo *et al.*, 2021b; Santeramo and Searle, 2019). Differently, the conversion of existing cropland to produce energy crops may aggravate the pressure on land supply and exacerbate the competition between crops intended to energy production and those intended for food and feed consumption (Tomei and Helliwell, 2016). While converting forests for crop production may have severe impacts in terms of GHG emissions that would go beyond the potential annual savings from energy crops, the use of annual crops or perennial feedstocks (e.g., soybean, palm oil) may improve soil carbon balances (Santeramo and Searle, 2019). However, the net LUC emissions depend on the type of energy crop whose production is expanding (Malins *et al.*, 2014). More precisely, rapeseed, palm, and soy are associated with relevant emission savings, with sunflower being the most GHG emission saving (Edwards *et al.*, 2017). On the other hand, the production of palm (and palm oil), not produced in the EU, is associated with high level of deforestation (European Commission, 2019b) and with the highest LUC emissions, due to the oxidation of carbon-rich peat soils (Miettinen *et al.*, 2012; Valin *et al.*, 2016): these aspects, only sketched here and deepened in subsequent sections, put further (social) pressure on the sustainability of bioenergy from palm. In general, and differently from other energy crops, palm is not produced in developed countries, while imported from tropical countries, which are the most severely impacted in terms of LUC (Danielsen *et al.*, 2009b).

Another aspect that should be taken into consideration in the debate on land-use competition is the yield increase. This latter, and the thoughtful use of inputs, are important to alleviate the pressing competition on land-use among food and energy crops. The challenge should be solved through an efficient use of land, as indicated by the emissions from input and output uses, and from the productivity of the land (Searchinger *et al.*, 2018). For instance, the specific pedo-climatic conditions of a certain land may favor the production of an annual food crop (i.e., a more efficient land-use) rather than a perennial energy crop. These considerations should be taken into account when the land is allocated for different uses. As suggested by several scholars (e.g., Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Tilman *et al.*, 2006), a potential solution to reduce the land-use competition for food and energy crops, and the related environmental impacts, may be the use of marginal agricultural land such as abandoned farmland, degraded land, and wasteland (Khanna *et al.*, 2021). Restoring abandoned land previously used for agriculture or pasture or land with a low productivity susceptible to degradation may be socio-economic (e.g., new income and employment, improvement of rural areas and social welfare) and environmental (e.g., less emissions from land extension and/or conversion) sustainable, without affecting land allocated to the production of feedstock intended for both human and animal consumption (Cai *et al.*, 2010; Elbehri *et al.*, 2013), exactly because the biomass produced on marginal lands causes little or no competition with land for food crops (Mehmood *et al.*, 2017).

Last but not least, another solution to limit the negative economic impacts of bioenergy crops may be the adoption of policies limiting or disincentivizing the production of biofuel from food crops. Similar strategies are already implemented in the US, where the Energy Independence and Security Act of 2007 provides a limited list of crops to produce renewable fuel and the limits for land used to produce bioenergy crops (Shrestha *et al.*, 2019). On the contrary, a nonsupportive strategy is adopted in the EU, where the CAP has historically not provided direct support for perennial plantations producing feedstock for energy purposes (Englund *et al.*, 2020).

5 Environmental Issues

To tackle the climate change and ensure affordable and clean energy, as established by the UN 2030 Agenda, the bioenergy production and use may represent one way to meet these goals. However, after two decades from the integration of the bioenergy in the current energy systems, some concerns on its effective environmental sustainability persist, especially on the first-generation biofuels, defined as "conventional", as stressed in the introduction section (Tricase and Lombardi, 2012a,b). The most widely adopted types are liquid and tend to be used in the transport sector (e.g., bioethanol, biodiesel, and hydrotreated vegetable oil] (European Commission, 2018). Their use has been fostered as a mitigation strategy to climate change for reducing the GHG emissions in transportation (fuels for road, shipping, and aviation use), which represents the third economic sector responsible for the global GHG releases (16.2%), especially as compared to the total energy-related CO_2 emissions (24%) (Crippa *et al.*, 2020; IEA, 2019; Ritchie, 2020). Furthermore, transport biofuels are used to improve the urban air quality, since they can decrease atmospheric pollutants, such as sulfur dioxide, particular matter, hydrocarbons, and volatile organic compounds (Demirbas, 2009; Hess *et al.*, 2009; Wagstrom and Hill, 2012). These substances tend to be harmful for the human health and ecosystems, through acid rains, the depletion of ozone layer, the formation of tropospheric ozone, and through changes in regional weather patterns that exacerbate the effects of the climate change (Correa *et al.*, 2019; Scovronick and Wilkinson, 2014).

Several concerns have to be considered before promoting the use of biofuels. The issues are mostly related to their expansion, especially under intensive agricultural production systems, which are associated with negative impacts on biodiversity, with low water availability, depletion of water quality, soil degradation, negative carbon and energy balance, and higher GHGs due to uncontrolled dLUC and iLUC (Campbell and Doswald, 2009; Correa *et al.*, 2019; Creutzig *et al.*, 2015; FAO, 2013; Jeswani *et al.*, 2020; Rana *et al.*, 2016).

In light of these premises, the assessment of the environmental sustainability of the first-generation biofuels becomes crucial to clarify the benefits for the climate and in terms of energy security, considering both the increasing demand for bioenergy, that is expected to be observed primarily in developing countries,[7] and the time required for adopting the most sustainable *advanced biofuels* (European Commission, 2020; OECD/FAO, 2020). Being aware of the risks associated to their production and use will allow stakeholders to adopt them in sustainable way. It seems necessary to rely on valid tools to evaluate the risks associated with the certification of biofuel options, and to provide environmental benefits compared to fossil energy use (Collotta *et al.*, 2019).

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[7] The biofuels industry has been strongly impacted by the Covid crisis. Global transport biofuel production in 2020 is anticipated to decline by 12% from 2019s record. This is the first reduction in annual production in two decades, driven by both lower transport fuel demand and lower fossil fuel prices diminishing the economic attractiveness of biofuels. The biggest year-on-year drops in output are for US and Brazilian ethanol and European biodiesel.

In this context, as already stressed in the legislative section, the EU has encouraged a sustainable development of biofuels by issuing the RED-I, in 2009, establishing several specific sustainability criteria and recognizing different certification system — at both national and international level — that use voluntary and mandatory approaches (Lombardi *et al.*, 2014). Specifically, the Article 17 has defined five criteria that the biofuel production systems should consider: (i) reduction of greenhouse gas emissions by at least 35% (up to 50% in 2017) in comparison with fossil fuels; (ii) protection of biodiversity; (iii) protection of land with high carbon stock; (iv) protection of un-drained soil; and (v) guarantee of good agricultural and environmental conditions. The economic operators may benefit from market incentives for biofuel production on condition that they provide evidence of compliance with these criteria (European Commission, 2009).

In 2018 the EU has reinforced its sustainability framework for bioenergy, publishing the RED-II that tried to ensure more and more the GHG emission savings and to minimize unintended environmental impacts (European Commission, 2019c). To this end, the EU has provided guidelines to measure the climate change impacts of the biofuel production systems by accounting for all GHG emissions (particularly carbon dioxide — CO_2, methane — CH_4, and nitrous oxide — N_2O) released from the whole supply chain, from the resource supply to the final energy products (Rana *et al.*, 2016).

5.1 Life Cycle Assessment

These recommendations are based on the Life-Cycle Assessment (LCA) methodology; indeed, the European Commission adopted this approach for systematically estimating the climate-change mitigation potential of biofuels from various feedstocks (Brandao *et al.*, 2021), so representing the main assessment perspective. According to ISO 14040:2006, the *LCA is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle* (ISO, 2006), and it is therefore often implemented at scientific and corporate levels to investigate the environmental impacts of services (Ingrao *et al.*, 2015). The analysis of each step of the process informs on strategies that may be implemented to reduce the environmental impacts (i.e., GHG emissions, acidification, eutrophication, photochemical smog, human toxicity, and ecotoxicity) (ISO, 2006; IEA, 2011; Kazamia and Smith, 2014). Nevertheless, this methodology does not investigate the economic and the social aspects of sustainability that are strongly interlinked with the environmental ones. Collotta *et al.* (2019) stressed the importance of the Life-Cycle Sustainability Assessment (LCSA), an approach that can evaluate the overall sustainability of a biofuel production system, including environmental (LCA), economic (life-cycle costing (LCC)), and social impacts (social life-cycle assessment (S-LCA)). This approach allows to conduct a more comprehensive impact evaluations of the biofuel sector. Also, Meyer and Leckert (2018) underlined that the Ecosystem Services (ESS) approach could be more appropriate than the Environmental Assessment (EA) carried out by the LCA to get a more complete sustainability assessment of biofuels, in that it covers the entire social–ecological dimensions of biofuel production. It can be argued that ESS studies may support policymaking, bridging existing gaps such as the underrepresentation of social assessments in the EU RED.

Only few LCAs include additional criteria, such as water use or impacts on soils (FAO, 2013) and the findings are frequently diverging across the supply chains or the system boundaries that have been considered in the study, as well as due to data variation or the type of software that has been adopted (Hoefnagels *et al.*, 2010; Jeswani *et al.*, 2020).

As for the GHG emissions, the principal aim of using biofuels in transportation is to decrease the GHG emissions derived from the fossil fuels. On average, the biofuels have lower GHG emissions but it is not always true that they fulfil the typical GHG emission saving target established by the EU directives (i.e., 70% for bioethanol from sugarcane and 56% from corn; 40% for biodiesel from soybean and 36% from palm oil — see Annex V). This is highlighted by the large amount of LCA studies that, also considering the same biofuel feedstock, have shown conflicting results. This variation is partially due to the differences in the assumptions, data sources and allocation[8] methods the research used. When the dLUC or iLUC are considered into the environmental evaluation, the results indicate that there is an increase in GHG emissions, as compared with gasoline and diesel (Fargione *et al.*,

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[8] To allocate means to distribute the environmental impacts between the biofuel and its co-products mainly according to their energy content (ISO, 2006).

2008; Gomiero, 2018; Searchinger *et al.*, 2008). Thus, the land-use changes are important as they influence the global warming potential (Carneiro *et al.*, 2017).

As already mentioned, the dLUC are due to the conversion of biomass in feedstock production, whereas the iLUC are due to an increase in biofuels production. Thus, the measurements of these changes are very different: the direct changes rely more on natural science, whereas the indirect ones are due to the reactions of the markets to the increasing demand for biofuels (Ahlgren and Di Lucia, 2014). Thus, the iLUC is the indirect market-mediated effects that can result in emissions of GHGs, outside the system boundaries, still largely debated by the environmental impact assessment community (Rana *et al.*, 2016). As already stressed in the legislative section, the RED-II has introduced a new approach to address the emissions from iLUC, adopting criteria to determine the high iLUC-risk feedstock, for which a significant expansion of the production area into land with high carbon stock is observed, and to certify low iLUC-risk biofuels (European Commission, 2019a; European Union, 2018).

The bioethanol from sugarcane in Brazil has led to a continuous expansion of land used for the sugarcane cultivation, involving the deforestation of tropical rainforest. Their GHG emissions have been evaluated 60% higher than those produced by the gasoline. The same results have been found for the biodiesel derived from soya bean and from palm oil, cultivated, respectively, in the peat and forestlands of Central and South America and in Malaysia and Indonesia. The use of areas with high carbon stock value for the biofuel feedstock production have caused both dLUC and iLUC which have turned up to 40 times higher GHG emissions than diesel (Danielsen *et al.*, 2009a; Jeswani *et al.*, 2020; Jusys, 2017; Searle and Giuntoli, 2018). For this reason, the RED-II has classified palm oil-based biodiesel under a high iLUC risk category (European Union, 2018) and, therefore, consumption of this biodiesel is expected to decline in the EU by 2030 (OECD/FAO, 2020).

As for the energy balance, the first-generation biofuels show another critical controversy. Scientists and economists have already proved that, in the energy production processes, the quantity of energy delivered (energy output) by renewable sources is often less than (or equal) to the energy consumed in capturing and delivering it to the customers (energy input) (Rana *et al.*, 2020). Thus, the role of biofuels on the energy security depends on their energy efficiency, i.e., a trade-off between the energy content and the fossil energy consumed for their production (energy required in the agricultural phase, in production process, in transport and distribution) (FAO, 2013).

The energy efficiency of the biofuels can be measured though several methodologies and indices. We focus on the Energy Return Ratio (ERR) and, specifically, on the Energy Returned On Investment (EROI). This is the ratio of the total energy supplied by biofuel combustion to the total energy used during biofuel production. Values of EROI greater than 1 imply net-energy gains (Gasparatos *et al.*, 2013a; Weißbach *et al.*, 2013).

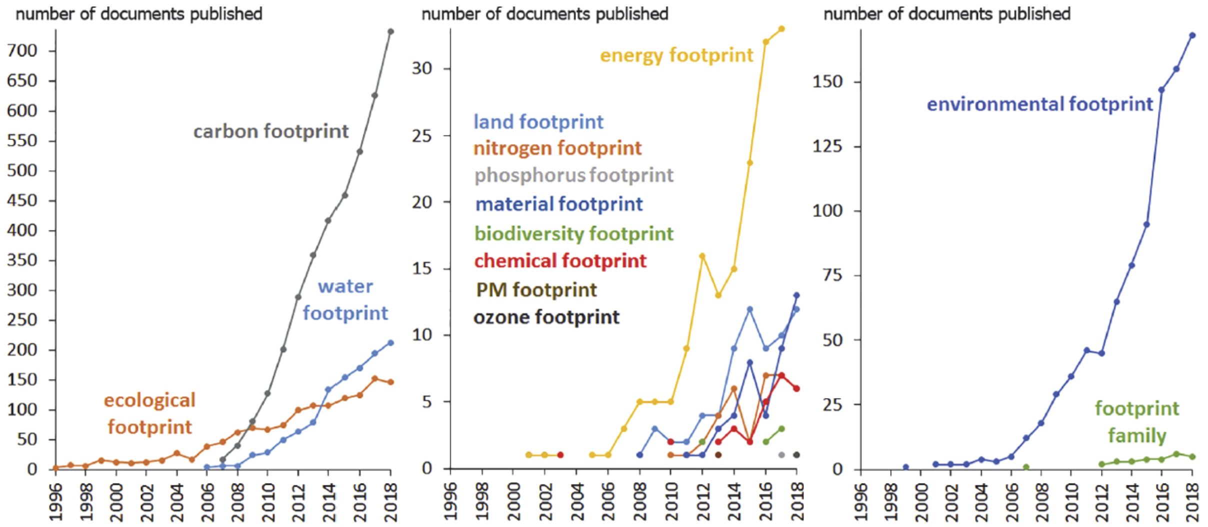
Several parameters affect the energy efficiency: the variety of biomass feedstock, the different energy extraction and the conversion methods, and the way the biomass is produced and collected. It is therefore challenging to compare biofuels EROEI results (Rana *et al.*, 2020). Nevertheless, the LCA studies have shown high EROI for sugarcane bioethanol, with value higher than 3.0, as well as, for rapeseed and palm biodiesel, with an EROI value around 2.4–2.6. Sugar beet and cassava bioethanol, rapeseed and soybean biodiesel have the highest EROI, while corn and wheat bioethanol exhibit relatively low EROI (Carneiro *et al.*, 2017; Gasparatos *et al.*, 2013a). These values are lower than those of the equivalent fossil fuels (15–20) (Hall *et al.*, 2014; Murphy *et al.*, 2010): so, the first-generation of biofuels is still more expensive and less efficient than the gasoline and the diesel, especially due to their lower density, higher moisture content, and hydrophilic nature, which cause their heating value to decrease, making it difficult to use biomass for large-scale productions. Moreover, they also over rely on fossil fuel — intensive commodities such as fertilizers and agrochemicals and so, with these characteristics, they can be possible energy options only in the short-to-medium term (Gasparatos *et al.*, 2013b). It is important to overcome these issues in improving the energy efficiency in order to allow them to play a real important role in future energy models (Rana *et al.*, 2020).

As for the water use and pollution, the LCA does not assess the water use of biofuel production; even several researches have analyzed this aspect. Of course, the first-generation biofuels require high water amount, mainly in the cultivation of some specific energy crops (Fingerman *et al.*, 2011; Jeswani *et al.*, 2020).

5.2 Environmental Footprint Assessment

In order to integrate the LCA studies in assessing the environmental sustainability of biofuel, it is also important to introduce the Environmental Footprint Assessment (EFA), which includes the Footprint Family indicators. They are based upon life cycle thinking, as LCA, but they diverge in aim and approach; indeed, they are resource use and emissions oriented (pressure human activities place on ecosystems), while LCA is impact oriented (potential consequences due to such pressure) (Vanham *et al.*, 2019). Specifically, they represent a tool for providing a comprehensive picture of the quantified pressure along the entire investigated supply chain, and they can be used for products at any stage of the supply chain, for companies or economic sectors. Thus, their application allows helping the decisionmakers to develop environmental mitigation strategies and interventions (Chen *et al.*, 2021). There are different indicators, such as energy, nitrogen, water, carbon footprints, etc. All of them derive from the ecological footprint, defined and applied in 1995 as a comprehensive environmental measure (Wackernagel and Rees, 1995), and used since 2006 as complementary measure of the ecological footprint (Figure 2).

Among these, surely the water footprint (WF) plays an important role in assessing the environmental concerns linked to the bioenergy



(a) (b) (c)

Figure 2: Trend of published studies about footprint family indicators.
Source: Vanham *et al.* (2019).

production. This indicator, compared to the other ones, measures not only the pressure on the environment [resource use and emissions] but also the relative impacts. According to Hoekstra *et al.* (2011), the WF is "an indicator of freshwater use that looks not only at direct water use of a consumer or producer, but also at the indirect water use", this latter called "virtual or embedded water"; it can be expressed as m^3 per ton of production, per hectare of cropland, per unit of currency and in other functional units. Additionally, "it is a multidimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total WF are specified geographically and temporally" (Hoekstra *et al.*, 2011). The WF considers three components: green, blue and grey WF.[9]

A few researches have been carried out on biofuel WF in Europe and the differences among the WFs of biomasses are large, depending on the type of biomass, the agricultural system applied and climatic conditions (FAO, 2013). For instance, Berger *et al.* (2015) who revealed average WF values for the first-generation biofuels, produced in European countries. Specifically, they observed a consumption of $1.9\,m^3$ of blue water per GJ of biodiesel, produced in 12 countries, and of $3.3\,m^3$ for bioethanol, produced in 23 countries. This represents an increase by a factor of 60 and 40 compared to fossil diesel and gasoline (Correa *et al.*, 2017; Gerbens-Leenes, 2017).

According to Gerbens-Leenes *et al.* (2012), in 2030, the global blue biofuel WF might have grown to 5.5% of the totally available blue water for humans, causing extra pressure on freshwater resources. This turns into the need to consider this factor in the environmental assessment in order to satisfy future transport energy demand. Galan-del-Castillo and Velazquez (2010) stressed the strong nexus between water and energy in biofuel production, assessing the virtual water content and the WF from the biofuel raw material in Spain. They

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[9] Hoekstra *et al.* (2011) stated that "The blue water footprint refers to consumption of blue water resources (surface and groundwater) along the supply chain of a product. 'Consumption' refers to loss of water from the available ground-surface water body in a catchment area. Losses occur when water evaporates, returns to another catchment area or the sea or is incorporated into a product. The green water footprint refers to consumption of green water resources (rainwater insofar as it does not become run-off). The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards".

revealed that it is critical to estimate these indicators as promoting biofuel production causes negative concomitant effects on water and other resources. Yang *et al.* (2009) investigated the associated water demand for biofuel production in China, according to the government plans for 2010 and 2020. They revealed a requirement of 32–72 km^3 of water per year, equivalent to the annual discharge of the Yellow River, posing important impacts on China's food supply and trade. Thus, to decrease the WF of biofuels, the best energy crops would be drought-tolerant, high-yield plants grown on little irrigation water. Conversely, the water requirements to produce an equivalent amount of energy from biofuels are comparatively big and more consumptive (Dominguez-Faus *et al.*, 2009).

Finally, also water quality is affected by the bioenergy production due to the runoff fertilizers and agro-chemicals used intensively. Some parts of these nutirents are lost during the agricultural production of biofuel feedstock. They reach the surface waters making them toxic to close communities and leading to eutrophication, with potentially devastating effects to aquatic ecosystems and the human populations (Dominguez-Faus *et al.*, 2009; Hein and Leemans, 2012). Increased eutrophication is a key characteristic of biofuels from energy crops when compared with fossil fuels (Czyrnek-Delêtre *et al.*, 2017).

5.3 Ecosystem Services

Another important aspect to consider, as environmental concern for bioenergy production, is the impact of biodiversity, defined as the abundance of species (plants, animals, and microorganisms) in a habitat, essential for the performance of an eco-system (FAO, 2013). LUC, climate change, pollution, and destruction of native ecosystems are, indeed, responsible for the biodiversity loss, reducing so the ecosystem resilience. Biofuels have the potential to contribute to the loss of biodiversity, depending on the feedstock used and scale of production, high-input managed biomass crops (fertilizers and pesticides) and LUC. This is particularly true when the natural habitats, such as tropical rainforests, are cleared to increase the biofuel production (Campbell and Doswald, 2009; FAO, 2013; Jeswani *et al.*, 2020; Sala *et al.*, 2009). According to Elshout *et al.* (2019), the first-generation biofuel production enhances the potential global species loss, in comparison with the fossil fuel use in transport, specifically when the feedstock assumed are solely mono-cropped (Correa *et al.*, 2017).

The EU Commission has recognized concerns in terms of protecting the biodiversity of ecosystems and carbon stocks, as stressed by the RED-II that has defined the no-go areas (principally land with high carbon stock or high biodiversity) as those that cannot be the source of the raw material used for producing biofuels (Art. 29) (European Union, 2018).

Nevertheless, the most used LCA approaches in RED-II do not consider the accumulation of environmental impacts on local and regional scales (i.e., on multiple scales) and the related cumulative effects on different ecosystem services. As discussed previously, LCA can investigate the energy provision and emissions, but not meaningfully other important impacts related to biodiversity loss, food security and socio-economic issues (Gissi *et al.*, 2016). For this reason, an alternative, or complementary approach to it, is the ESS — the benefits that people get directly and indirectly from ecosystems (Burkhard *et al.*, 2012). Specifically, biofuel production can provide a range of ecosystem services (benefits) such as feedstock for fuel and climate regulation, and it can affect other ecosystem services such as food and water services in positive or negative ways.

Hence, this different perspective helps to deeper analysis of issues at the landscape level, and it assesses the impacts on all aspects of human well-being (Correa *et al.*, 2019), expanding to bundles of impact categories (social–ecological dimensions of biofuel and bioenergy production) (Gasparatos *et al.*, 2018), and thus integrating the environmental assessment studies dominated by LCAs (Baker *et al.*, 2013; Meyer and Leckert, 2018). In this way, ESS studies provide a holistic view of the cause-effect relationships of biofuel and bioenergy production.

However, only some empirical studies have adopted an ecosystem services perspective to assess biofuel impacts in the EU, such as Gissi *et al.* (2016) and Milner *et al.* (2016), which presented the first assessment of the impact of LUC to second-generation bioenergy crops on ecosystem services. Surely, the ESs approach can offer a greater flexibility to choose the most appropriate combination of impact assessment methods from the environmental and social sciences (Meyer and Leckert, 2018).

5.4 Other Approaches and Final Consideration

Actually, there are other methods that can be used for assessing the environmental issues concerning the biofuel production. Summarizing some other examples, it is worthing to remind the Integrated Environmental Assessment (IEA) recognized as an important technique for managing the environmental impacts of human actions. Specifically, it is defined as "interdisciplinary process of identification, analysis and appraisal of all relevant natural and human processes and their interactions which determine both the current and future state of environmental quality, and resources, on appropriate spatial and temporal scales, thus facilitating the framing and implementation of policies and strategies" (Anderson *et al.*, 1996). Feehan and Petersen (2003) were the first environmental analysts of the EEA (European Environment Agency) who proposed the application of this approach for the biofuel production. Furthermore, some scholars have combined different methodologies for their larger space and time scale characteristics. For instance, Cavalett and Ortega (2010) have assessed the environmental impact of biodiesel production from soybean in Brazil, using the Emergy Accounting (EA), Embodied Energy Analysis (EEA), and Material Flow Accounting (MFA). Each of them has a specific features: MFA evaluates the environmental disturbance linked to the extraction or change of material flows of resources from their natural ecosystem pathways; EEA evaluates the gross energy demand of the analyzed system; while the EA investigates the environmental performance of the system on the global scale, considering all the free environmental inputs, as well as the indirect environmental support embodied in human labor and services, not usually included in EEA. The results showed that for one liter of biodiesel 8.8 kg of topsoil are lost in erosion, besides the cost of 0.2 kg of fertilizers, about 5.2 m^2 of crop area, 7.33 kg of abiotic meaterials, 9.0 tons of water, and 0.66 kg of air and about 0.86 kg of CO_2 were released. Finally, OFID (2019) proposed the FAO/IIASA Agro-ecological Zone model and the IIASA global food system model. This approach encompasses climate scenarios, agro-ecological zoning information, demo-graphic and socio-economic drivers, as well as production, consumption and world food trade dynamics.

Some final considerations can be remarked after having discussed on the different frameworks/perspectives used for the assessing the environmental sustainability of conventional biofuels: they are not always easily measurable and comparable, due to the complexity and the variety of indicators used for their evaluation: some are global (GHG, energy efficiency), others local or regional (water management, soil and resource depletion, local pollution, etc.).

The first-generation biofuels may not represent the final solution to the energy and climate change issues. They will help to expand energy supply and to promote the spread of local energy systems, but they need the support of global changes in energy policies. According to Smeets *et al.* (2014), it is important to consider the bound effect for which "the use of biofuels has economic implications that affect the consumption and price of oil and that, as a result, an increase in biofuel use is not by definition followed by an equal decrease in oil consumption (on energy basis)". In short, it is not so evident their contribution to GHG emission saving effects. Policymakers should take into consideration this evidence in order to redefine their policies and strategies, and to foster the large-scale replacement of fossil fuels with bioenergy in the energy system.

6 Social Issues

The energy transition has potential to bring considerable benefits also from a socio-economic point of view, but it entails high costs that will require, on the one hand, ambitious policies to effectively mitigate these consequences (OECD, 2019) and, on the other hand, tailored instruments to further support its implementation (Ladu and Blind, 2017; Leonhardt *et al.*, 2022; Yakubiv *et al.*, 2019). However, for enhancing supporting tools (e.g., financial, legislative), together with environmental targets (see Section 5) also social targets must be met. Indeed, this will enable to foster both public and private commitment. As underlined by the UN, the socio-economic aspects will require a greater effort for achieving SDGs, particularly in relation to the gender equality, lower unemployment and poverty rates, and limited inequality. Reaching these goals has become a greater challenge after the COVID-19 pandemic (UN, 2020) and the actual energetic crisis. Additionally, it should be noted that this obviously holds even more true for sectors such as bioenergy where sustainability is supposed to be a core component.

Against this background, two main interconnected issues, related to the social dimension, are placed at the heart of our review: the socio-economic effects and the social acceptance of biofuels production and consumption processes.

The first deals with the positive and negative impacts (Brinkman *et al.*, 2019; Rutz, 2014) that can affect in different ways company, region, and state levels and to various degrees a number of actors involved in different stages of supply chain (Macombe *et al.*, 2013). Accordingly, as set out in the environmental impacts section, it would always be preferable to adopt a life cycle approach to gain an overall picture of the socio-economic impacts associated with these stages and associated stakeholders, complementing the environmental analysis and thereby covering in a complete manner the sustainability analysis. Despite being a rather neglected area within the literature related to bio-based products in general, the social dimension has gained importance over the last years, and the S-LCA method has been increasingly employed (Falcone and Imbert, 2018; Imbert and Falcone, 2020). Several S-LCA studies related to bioenergy have been indeed published so far (e.g., Ekener *et al.*, 2018; Manik *et al.*, 2013; Mattioda *et al.*, 2020; Petersen *et al.*, 2014). Although employing different system boundaries, as for instance some of them did not consider the consumption phase, several main socio-economic issues have emerged, encompassing, among others, short- and long-term effects on human health, labor and gender issues, property rights, access to land, food security, wealth and well-being creation. Overall, these topics have been investigated by a great number of studies whether being or not a S-LCA case study.

With specific reference to adverse socio-economic impacts related to bioenergy, emphasis has been placed on challenges faced by smallholders (particularly women) involved with the production of energy crops in developing countries (Beall, 2012; Florin *et al.*, 2014; Rossi and Lambrou, 2009; Sakai *et al.*, 2020). Particular attention has thereby been placed on the early stages of the supply chain, i.e., extraction and processing of raw materials. Poor working conditions, food security, land-use and land grabbing indeed were at the heart of the debate of both the literature (see among others Bioenergy IEA, 2010; Constantin *et al.*, 2017; Maltsoglou and Khwaja, 2010; Popp *et al.*, 2014) and European institutions. These aspects have encouraged the implementation of the revised RED-II and a growing number of studies particularly focused on opportunities, but also critical implications and challenges associated with feedstocks alternative to first generation, as mentioned in the previous sections (e.g., Ayodele *et al.*, 2020; Holland *et al.*, 2015; Kuchler, 2014; Panoutsou *et al.*, 2021; Ripa *et al.*, 2021; Schrama *et al.*, 2016; Zabaniotou, 2018).

The literature on social aspect of the bioenergy sectors have emphasized that the economic opportunities, in terms of greater competitiveness, economic growth, and regional development (Busu, 2019; D'Adamo *et al.*, 2020a; Ronzon *et al.*, 2020; Omri and Belaïd, 2021), may be coupled with the emergence of new income opportunities (additional local revenue streams) and the creation of additional new jobs (Cambero and Sowlati, 2016; Domac *et al.*, 2005; Lehtonen and Okkonen, 2016; Zahraee *et al.*, 2020). Moreover, a broad range of other interlinked socio-economic topics have gained attention, i.e., the rehabilitation of degraded or marginal lands (Panoutsou and Chiaramonti, 2020), the provision of training and skills development (Diaz-Chavez *et al.*, 2015), the synergic and pro-innovation role of networks of stakeholders (Lopolito *et al.*, 2022; Pitkänen *et al.*, 2016; Sanz-Hernández *et al.*, 2019), and the positive spillovers generated by the end of life cycle (D'Adamo *et al.*, 2020b).

The RED-II itself (EU, 2018, p. 1) sets out the role that the energy from renewable sources can play allowing for "social and health benefits as well as major opportunities for employment and regional development, especially in rural and isolated areas, in regions or territories with low population density or undergoing partial deindustrialisation". Interestingly, several large-scale bioenergy plants result from the conversion of former conventional plants affected by the economic crisis (see Falcone *et al.*, 2021).

The second main issue concerning the social dimension deals with the social acceptance,[10] which is particularly important during the implementation phase of bioenergy projects (McCormick and Kåberger, 2007; Prosperi *et al.*, 2019) and affecting various levels, i.e., macro, intercommunity, and intracommunity (Ruggiero *et al.*, 2014). As outlined by Leibensperger *et al.* (2021) each category of stakeholders, including among others, governmental actors, nongovernmental organizations

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[10] Social acceptance falls within the socio-economic impacts, and it is often considered as an impact subcategory of the S-LCA although, due to its relevance as a key factor for bioenergy plants/projects implementation, we decided within this review to analyze it as a single topic.

(NGOs), suppliers, bio-refineries, cooperatives and local communities has its own value in terms of costs and benefits related to a specific bioenergy project. Particularly, it has been stressed the role played by environmental NGOs arguing about the unsustainability of projects that rely on the employment of first-generation feedstock from developing countries, and that might also create other adverse environmental impacts (as reported in the previous section), as well as their skepticism about new emerging technologies such as bioenergy with carbon capture and storage (BECCS) (Fridahl and Lehtveer, 2018). Moreover, in addition to socio-political acceptance, hence referring to how innovation is viewed at the broader level there are other two strongly intertwined social acceptance dimensions that should be considered, i.e., community and market acceptance (Wüstenhagen *et al.*, 2007). Regarding local community, the literature has reported on diffused opposition from local actors concerned about potential risks to health, visual appearance, odor and waste, water pollution and competition, increase of traffic and other issues affecting the quality of life of local communities living near bioenergy plants (McCormick, 2010; Upreti, 2004).

This critical issue affects especially large-scale bioenergy projects that, despite their greater potential in achieving significant environmental goals (e.g., in terms of GHG emissions savings), face yet, in many cases, great opposition. Notably, the literature outlines that the scale of a project per se represents an important variable and that often large-scale bioenergy plants face more challenges in terms of social acceptance (Devine-Wright, 2007). First of all, it should be stressed that several adverse environmental and socio-economic impacts, especially health-related, resulted from traditional industrial plants such as the conventional refineries (i.e., linear and fossil based), have generated growing distrust, especially in local communities (Falcone *et al.*, 2021). Consequently, this longstanding mistrust is rather difficult to reverse also when green alternatives are proposed. Moreover, besides the health risks, a number of studies draw attention to the above-mentioned specific aspects such as odor issues, traffic congestion, aesthetic degradation and decreased property values (Upreti and van der Horst, 2004; Vlachokostas *et al.*, 2020). To tackle these barriers, various research argued that before locating a facility, such as a bio-refinery, systematic analysis to evaluate social acceptance is needed (Lee *et al.*, 2017). Specifically, an increased public interest, gained for instance by connecting new technologies with countries' national narratives (Malone *et al.*, 2017) and likewise greater communication, involvement and engagement among the different stakeholders involved consistently raise projects success rate (Leibensperger *et al.*, 2021; Ludovico *et al.*, 2020) as well as stimulate an increased use of more sustainable regional embedded feedstock (Morone and Imbert, 2020; Pehlken *et al.*, 2016, 2020). In this respect, a multicriteria decision analysis approach that include socio-economic aspects, represents a valuable tool to better orient plants siting decisions (Martinkus *et al.*, 2019; Vlachokostas *et al.*, 2020).

Notwithstanding the importance of large-scale projects, especially when revitalizing abandoned industrial sites that besides environmental impacts have caused significant damage to people's health, jobs, and well-being, there are local decentralized small-scale systems which show strong potential toward socio-economic sustainability. Small-scale systems require less biomass for final energy production and can be entirely powered with local feedstocks (including agricultural residues, agro-industrial wastes), creating new jobs and income by closing the loop (Situmorang *et al.*, 2020; Zabaniotou *et al.*, 2015). Specifically, they may create fewer side effects and obtain more easily support from local communities whether an efficient stakeholder involvement strategy is put into place that means favoring the democracy of the energy policy processes (Prosperi *et al.*, 2019).

Finally, with reference to the third dimension of social acceptance, i.e., market acceptance, consumers, investors, and other market actors are directly involved (Fytili and Zabaniotou, 2017; Wüstenhagen *et al.*, 2007). Several aspects dealing with bioenergy such as confusion about efficiency and performance of products, higher price and willingness-to-pay (WTP), lack of information and knowledge on the environmental impacts and risk of greenwashing emerged as key barriers concerning bioenergy. In this regard, it has been stressed the importance of certifications and labels in stimulating consumers green premium in terms of WTP (Magar *et al.*, 2011; Schubert and Blasch, 2010), even though this positive correlation should be not given for granted since there is still need to provide more clear information on the environmental and social benefits, related, for example, to advanced biofuels, otherwise it will not be possible to reach aware and better informed consumers (Lanzini *et al.*, 2016). Moreover, to reduce greenwashing perceptions a possible way could be stronger communication of involved companies through enhanced social corporate communication, proving that their interests are perfectly compatible with social and environmental outcomes (Taufik and Dagevos, 2021). Likewise, also clear information about properties and performance of bioenergy should be communicated since consumers expect comparable, if not better, performance (Das and Schiff, 2020). Lastly, it should be noted that the EU Taxonomy, aimed at increasing private investors' role toward sustainable projects and activities through a clear definition for which economic activities can be considered environmentally sustainable, is aiming at including in a more comprehensive manner the social dimension.

7 Conclusive Remarks

The EU bioenergy sector has increased in prominence and has been considered for years a major source of clean energy that may help reducing the pressure on other traditional (and impactful) sources of energy. Despite some appealing features, the bioenergy production is tricked by several challenges: high production costs, affected also by competition for land; conspicuous direct and indirect effects on the environment; undesired social implications, including socio-economic challenges and social acceptance; legislative needs which require coordination and coherence across different domains.

By reviewing the debate along the four perspectives (economic, environmental, social, and legislative) we conclude on threads, opportunities and priorities that should be considered when designing a more sustainable development of this sector.

The rich and rapidly evolving legislative set of regulations is central to understand the evolution of the sector. Indeed, we have discussed on the need to foster the transition to renewable energy through a new approach, which has been initiated by several directives, such as the new Renewable Energy Directive, and the 'Fit for 55' package. The evolution of the legislative framework has to go hand-by-hand with the development of the sector and has to be ready to future changes and challenges.

As for the economic aspects, a central issue is the economic convenience of producing energy from crops, as compared to alternative sources of energy, especially because the energy price must be affordable for the final consumers. These costs are kept relatively high by the production processes, which need to be improved, as well as by the costly dependence from a scarce resource: land. The competition for land has driven the economic concerns for decades, and to be surpassed switching to new modes of production, based on the use of marginal lands and by-products. This direction, which seems to be particularly promising for the EU, has great potential and should be encouraged as it would benefit from the synergy induced by the transition to a circular economy.

The environmental issues are also numerous: the most important are the negative balance in terms of GHG emissions, the potential loss of biodiversity, and the depletion of natural resources (e.g., water). As for these aspects we distinguish a long-run agenda, which should focus on the limiting the GHG and preserving the biodiversity, from a short-run agenda, dictated by the necessity to reduce the use of scarce resources to ensure food and water security.

As for the social aspects, we have emphasized the importance of retrieving degraded and marginal lands, the opportunities triggered by the networks of stakeholders, and the potential benefits of the end-of-life cycle. We have also spent words of caution on social acceptance, which is possibly a major obstacle for the (further) development of the sector toward its maturity. Research and planning efforts should proceed in this direction.

Finally, a few words of prudence are needed. This manuscript has faced the challenge to review the existing scientific knowledge on major issues related to the EU bioenergy sector. While we believe that combining the points of view of different disciplines has added value to this piece, we acknowledge that the sector is in a very rapid evolution, interested by a frenetic search for new and greener technologies, and perturbed by giant and frequent shocks. For instance, a major change we are observing in the EU, and that we have not addressed in this review, is the tendency toward the electrification of transports which is expected to increase (by far) the demand for energy. The impacts of this tendency should be investigated in detail.

The rapidly evolving global economy, and the role of the EU in the world economy, will imply other dynamics that may elevate the importance of the bioenergy sector, or leading it to an end. We are still far from this, but if the final goal for the EU is to produce energy in an efficient and sustainable ways, no solutions should be avoided *a priori*, and the research for improvements should remain eager.

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