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Moving Towards the Second Generation of Lignocellulosic Biorefineries in the EU: Drivers, Challenges, and Opportunities

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1 **Moving towards the second generation of lignocellulosic biorefineries in the EU:**
2 **drivers, challenges, and opportunities**

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24 **Abstract**

25 The EU aims to achieve a variety of ambitious climate change mitigation and sustainable
26 development goals by 2030. To deliver on this aim, the European Commission (EC) launched
27 the bioeconomy strategy in 2012. At the heart of this policy is the concept of the sustainable
28 Biorefinery, which is based centrally on a cost-effective conversion of lignocellulosic
29 biomass into bioenergy and bioproducts. The first generation of biorefineries was based on
30 utilization of edible food crops, which raised a “food vs. fuel” debate and questionable
31 sustainability issues. To overcome this, lignocellulosic feedstock options currently being
32 pursued range from non-food crops to agroforestry residues and wastes. Notwithstanding this,
33 advanced biorefining is still an emerging sector, with unanswered questions relating to the
34 choice of feedstocks, cost-effective lignocellulosic pretreatment, and identification of viable
35 end products that will lead to sustainable development of this industry. Therefore, this review
36 aims to provide a critical update on the possible future directions of this sector, with an
37 emphasis on its role in the future European bioeconomy, against a background of global
38 developments.

39

40 **Keywords:** Lignocellulose; biorefinery; bioenergy, biofuel, biochemicals, biomaterials.

41

42 **Acronyms:** EC, the European commission; UN, the United Nations; FAO, the Food and
43 Agriculture Organization; WHO, the World Health Organization; GHG, greenhouse gas
44 emissions; SDG, the sustainable development goals; SRWC, short rotation woody crops;
45 IBLC; integrated biomass logistics center.

46

47 **1. Introduction**

48 Unprecedented challenges now face the future development of Europe, spanning food
49 security, climate change, and an over-dependence on non-renewable resources.
50 Simultaneously, it must balance strategies that harness renewable resources to maintain
51 environmental sustainability, while maintaining economic growth. To achieve this, in 2012,
52 the European Commission (EC) launched the European bioeconomy strategy entitled
53 “Innovating for sustainable growth: a bioeconomy for Europe”. The interim fruits of this
54 initiative were assessed by the EU Commission in 2017 and indicated that the scope of the
55 current action plan was insufficient for the development needs of the biorefinery sector.
56 Within this strategy, the modern bioeconomy is defined centrally by the production of
57 biomass or the utilization of lignocellulosic wastes, with subsequent conversion into value-
58 added products, such as bio-energy, as well as novel bio-based innovation. At the EU level,
59 the current bioeconomy has an annual turnover of 2.3 trillion EURO, and generates a total
60 employment of 18.5 million people.

61 Biorefining is defined as the sustainable processing of biomass into a spectrum of marketable
62 products (food, feed, chemicals, and materials) and energy (fuels, power and/or heat) [1].
63 Representing a cornerstone of the bioeconomy, the goal of fully unlocking the value potential
64 of lignocellulosic plant biomass in a cost-effective way remains elusive. A ‘one-size-fits-all’
65 biorefinery concept, based on conversion of various lignocellulosic biomass feedstocks into
66 bioenergy and bioproducts, has not yet been achieved. Upstream aspects such as biomass
67 type, transport logistics and the downstream value proposition offered by conversion products
68 must be reconciled with the recalcitrance of the lignocellulosic structure: there is, as yet, no
69 fully scalable yet cost-effective extraction method to unlock valuable sugars and lignin from
70 this matrix, and this remains a key short-term research goal.

71

72 Lignocellulosic feedstock options for biorefinery use range from food/non-food crops to
73 primary residues/secondary wastes from agroforestry. The S2Biom project has estimated that
74 a total of 476 million tons of lignocellulosic biomass need to be secured to fulfil demand for
75 bio-based products by 2030 [2]. The market for bio-based products is expected to be worth 40
76 million EURO by 2020, increasing to about 50 billion EURO by 2030 (average annual
77 growth rate of 4%). Research in industry and academia has been galvanized to address the
78 twin challenge of lignocellulosic breakdown and conversion into viable products: between
79 130-150 patents are annually submitted in the lignocellulosic biofuel area, and this is
80 expected to reach 200 annual filings [3]. Additionally, a myriad of publications featuring
81 laboratory and pilot scale studies for pretreatment and conversion of lignocellulosic biomass
82 into bioenergy and bioproducts are published each year. Within the context of biofuel
83 production, 67 lignocellulosic biorefineries currently operate around the world (albeit only
84 about one-third operating at commercial scale), while additional advanced biorefineries are
85 under development [4]. Hence, this article aims to outline a possible roadmap of the future
86 biorefining industry in Europe by reconciling market drivers with current technical
87 challenges, and future opportunities; in addition to research and innovation in this area.

88 **2. The drivers for the development of biorefinery industry in the EU**

89 **2.1 Global environmental concerns**

90 Assuming that the current population growth rate of approximately 83 million people
91 continues each year, about 8.5 billion people will share the Earth by 2030 [5]. Thus, demands
92 for food, energy and economic development will continue to increase. The total energy
93 consumption in the world is expected to increase by 48% between 2012 to 2040, with
94 estimates of 664 and 860 quadrillion kilojoules (KJ) in 2020 and 2040, respectively [6].
95 Moreover, the Food and Agriculture Organization (FAO) has projected an annual growth rate
96 of total world consumption of all agricultural products to be 1.1 percent per year from 2005-

97 2050; this translates into a requirement for a 60% higher global production in 2050 than that
98 of 2005 [7]. Such increases in productivity must be achieved against a background of diverse
99 pressures on natural resources, such as land availability, water shortages and unpredictable
100 climate change impacts. The FAO has estimated that an additional 70 million ha of cultivated
101 land may be required by 2050, which will need significant investment. However, the
102 challenge is further exacerbated by the fact that most of the projected lands for expansion in
103 cultivation are in developing countries in Africa, which are often characterized by water
104 scarcity. Moreover, there is increasing competition for land use between urbanization and
105 agriculture. It has been reported that 1.8-2.4% of global cultivated land loss (equal to 3–4%
106 of worldwide crop production in 2000) may occur by 2030 due to urban expansion,
107 particularly in Africa [8]. Additionally, nature is suffering a further onslaught in the form of
108 climate change, worsened by increased population growth and associated economic activities:
109 increased global greenhouse gas emissions (GHG), environmental pollution, the ever-
110 increasing volume of solid wastes and over-exploitation of natural resources are all key
111 challenges that need to be tackled. Total GHG were measured at approximately 51.9
112 gigatonnes of equivalent carbon dioxide (GtCO₂e) per year in 2016, while the ambitious
113 global target is to reduce the GHG to 11 - 13.5 GtCO₂e by 2030 [9]. The World Health
114 Organization (WHO) reported that 3 million people are killed annually by outdoor air
115 pollution, and that only one-person-in-ten lives in a city that complies with the WHO air
116 quality standards [10]. The World Bank has estimated that cities around the world generate
117 about 1.3 billion tonnes of solid waste per year, costing \$205.4 billion in waste management,
118 and this volume is expected to increase to 2.2 billion tonnes by 2025, with concomitant
119 increases in waste management costs to \$375.5 billion [11]. Around the world, over 80% of
120 all wastewater is discharged into water bodies each year without treatment [12]. In addition,
121 the unsustainable use of natural resources by excessive fishing, hunting and forestry

122 represents an alarming threat to global biodiversity. Global wildlife populations have
123 declined on average by 58% since 1970, and this may reduce further to 67% by 2020 [13]. To
124 overcome these unprecedented environmental challenges, in 2015, the 193-member states of
125 the United Nations came to an agreement on 17 sustainable development goals (SDG) for
126 2030 [14]. The SDG included ensuring sustainable consumption and production patterns,
127 promotion of socially responsible industrialization and fostering of an innovation culture,
128 ensuring access to affordable and clean energy for all, and taking urgent action to combat
129 climate change. Additionally, the UN countries adopted the international climate mitigation
130 agreement in 2015 at the Paris climate conference which aims to limit global warming to
131 below 2°C on a national level. In this context, fostering the global bioeconomy ethos as the
132 pathway for achieving SDGs and climate change mitigation is vital.

133 **2.1 The EU environmental challenges and the future bio-based economy**

134 Viewed through the lens of environmental sustainability, many of the global concerns are
135 also relevant to the situation of the EU, and span over-dependence on fossil fuels, intensive
136 agriculture, over-fishing, non-sustainable forest and water resources management, pollution,
137 and poor land use. The EU possesses a high ecological footprint of 4.7 global hectares per
138 person, which is equal to twice the size of its biocapacity [15]. Worryingly, environmental
139 concerns in other regions of the world also affect the EU directly, through the impact of
140 global GHG, or via socio-economic pressures emanating from the global loss of biodiversity
141 or over-exploitation of natural resources. Driven by such challenges, the EU launched the
142 bioeconomy strategy in 2012 and established tangible action plans to actively shape the
143 targeted circular economy in Europe by 2030, thus enabling it to assume leadership in this
144 field. As a direct consequence, the industrial revolution in the 21st century is likely to be
145 based on renewable biological resources, with a paradigm shift in evidence after the historical
146 reliance on oil and other fossil fuels which came to dominance over the past three hundred

147 years. In this context, biorefining represents a bridge to a sustainable bio-based industry by
148 conversion of biomass into valuable products. However, when compared to fossil-based
149 refineries, biorefineries are an embryonic industry, with a variety of different biomass
150 feedstocks, a need for efficient conversion technologies and a portfolio of products which
151 may have varying market receptivity.

152 **3. The Challenges in the biorefining value chain**

153 **3.1 Feedstocks**

154 Integral to the biorefinery concept is accessing suitable feedstocks which are amenable to
155 cost-effective processing. Biorefining is a capital-intensive industry with large capital
156 expenditure (CAPEX) and requires knowledge of the feedstock resource base that is
157 sustainably available at low cost to support a facility.

158 **3.1.1 First generation (food crops)**

159 The first generation of feedstocks depended on easily accessible and edible fractions of food
160 crops, with the main product being biofuel. Bioethanol may be produced from sugar (e.g.
161 sugarcane, sugarbeet, and sweet sorghum) and starch (e.g. corn, and cassava) crops, while
162 biodiesel is produced from oil seed crops (e.g. soybean, oil palm, rapeseed, and sunflower)
163 [16]. However, in recent years, serious criticisms have been raised about competition in land
164 use that has arisen as a direct consequence of incentivizing energy and oil crops at the
165 expense of food crops.

166 **3.1.2 Second generation (Non-food crops and lignocellulosic wastes)**

167 The growing controversy of ‘food versus fuel’, along with associated production economics,
168 biofuel policies and sustainability trends, promoted the rise of a second generation of
169 feedstocks based on lignocellulosic biomass. The latter include non-food, short rotation
170 grasses that have high yield and suitability to marginal lands or poor soils (e.g. poplar,

171 willow, eucalyptus, alfalfa, and grasses such as switch, reed canary, Napier and Bermuda),
172 agricultural residues (e.g. forest thinning, sawdust, sugarcane bagasse, rice husk, rice bran,
173 corn stover, wheat straw, and wheat bran), and agroindustrial wastes (e.g. potato and , orange
174 peel, spent coffee grounds, apple pomace, ground nut oil and soybean oil cake) [17–19].
175 Critically, the latter are so-called negative cost waste materials from other industries, and so
176 theoretically the value proposition has heightened appeal. However, such materials are also
177 the most refractory to extraction of sugars (Figure 1).

178 3.1.2.1 Non-food terrestrial biomass

179 Non-food energy crops have received much attention as an alternative to food crops during
180 the first phase of transition toward the second generation biorefinery, and these may be
181 categorized mainly into woody and herbaceous crops.

182 3.1.2.1.1 Woody crops (short rotation woody crops)

183 Examples of short rotation woody crops (SRWC) are cottonwood, silver maple, black locust,
184 willow, poplar, and eucalyptus. Generally, SRWC are hardwood trees that are traditionally
185 used in paper and pulp industries [20]. Wood is an age-old source of energy for man and
186 sustainable systems for its conservation are well established. Furthermore, SRWC has
187 significant advantages over many other lignocellulosic biomass types in terms of widespread
188 availability in most regions of the world, high energy density and existence of well-
189 established handling technologies arising from the pulp and paper industries. However,
190 utilizing the global forests for biorefining as a sole feedstock will have significant effects on
191 forest management, wood processing, and the pulp and paper sectors; such aspects need to be
192 explored fully. Long production cycles (up to 12 years from plantation) are complicated by
193 aspects such as weed control and sustainability of supply. Additionally, the issue of
194 competition with land for other uses (especially food) also remains. The best potential for
195 utilizing woody crops as a biorefinery feedstock lies in integration with wood-based

196 industries, particularly the pulp and paper sectors, as these players currently only extract
197 about 47% of value from lignocellulosic materials [21].

198 3.1.2.1.2 Grassy crops (herbaceous perennials)

199 Challenges in exploiting woody crops have led to active investigation of herbaceous
200 perennials as a potential energy crop, as these can grow on marginal lands. These species
201 include herbaceous energy crops such as miscanthus, energy cane and sorghum. Early
202 pioneering work in 1991 by the U.S. Department of Energy in North America focused on
203 Switch grass as a model high energy crop. It was subsequently introduced into Europe and
204 other parts of the world due to its high genetic diversity, good productivity and adaptability
205 [22,23]. In addition, Miscanthus was first introduced from Japan to Europe and then to North
206 America, and has become a leading contender as an energy crop due to its adaptability over a
207 range of European and North American climatic conditions, as reported by the 2012 EU
208 project OPTIMISC (Optimizing Miscanthus Biomass Production) [24]. Energy cane,
209 sorghum, alfalfa, bluestem, and grass varieties such as elephant, wheat, reed canary, Napier
210 and Bermuda are examples of other herbaceous plants which are being investigated as energy
211 crops. Grassy crops have a number of advantages over food crops as an energy feedstock.
212 They are perennial (no need for annual plantation), possess a high harvest index (all parts of
213 plant are used), demonstrate reasonable productivity, and have relatively low water
214 requirements and nutrient inputs. On the down-side, likely future competition with food crops
215 for land use (and indirect land use change), combined with production issues (e.g. weed
216 control) and required production inputs (e.g. nitrogen fertilizers) are all aspects that must be
217 considered.

218 3.1.2.2 Agroforestry residues & processing wastes

219 Separation of plant biomass intended for the biorefinery from that which may be used in the
220 food/feed-chain is a key aspect of future sustainability. Hence, lignocellulosic materials from

221 wood processing, pulp and paper industries, agricultural residues and agro-industrial wastes
222 hold the most potential for use as feedstocks; they are also low cost, abundantly available and
223 generally comply with environment sustainability goals. However, the transport and handling
224 logistics of this feedstock type, combined with a dearth of cost-effective lignocellulosic pre-
225 treatment operations, are major drawbacks that are delaying progress in their utilization for
226 this purpose. In response to such issues, the EU has funded the SUCELLOG project as an
227 example of an integrated biomass logistics center (IBLC) in four EU countries (Spain,
228 France, Italy, and Austria). The aim of this work is to overcome aspects such as the
229 seasonable availability of feedstock and supply logistics via improved handling, pretreatment
230 and storage of lignocellulosic biomass in a logistic center, with shipment directly to local
231 biorefineries or transported to be sold to the global market [25].

232 3.1.2.2.1 Primary agroforestry residues (agricultural & forestry residues)

233 Agricultural and forestry residues are generated during cultivation activities of crops and
234 trees (e.g. harvesting and shaping) and have a low economic value for primary producers.
235 While both are lignocellulosic in nature, agricultural residues contain a lower level of lignin
236 as compared with forestry residues. It was estimated that the realistic potential of agricultural
237 crop residues is 74.89 Mt/year in the EU, while the realistic potential of forestry residues is
238 43.5 Mt/year in the EU, Ukraine and Belarus [26]. The realistic potential is calculated from
239 the technical-sustainable potential, while the latter is derived from the theoretical potential.
240 Examples of agricultural residues are non-edible components of cash crops such as straw
241 (stalks, leaves) from cereals and legumes, as well as stalk, stubble and leaves from sugar,
242 tuber, oil, and vegetable crops. Furthermore, examples of forestry residues are stumps,
243 branches, treetops, needles and leaves after harvesting, weeding, trimming and pruning.

244 3.1.2.2.2 Secondary agroforestry wastes (food industry & wood processing wastes)
245 Food industry byproducts encompasses wastes from various industries such as sugarcane
246 bagasse (from sugar milling), pomace (pressing of tomato), apple and grapes (juice), olives
247 (for oil), brewer's spent grain (BSG - from beer-brewing), spent coffee grounds (coffee
248 preparation), as well as citrus and potato peels. The global production of some of these
249 humble wastes are significant. For example, potato peels generate between 70 and 140
250 thousand tons worldwide every year [27]; this compares with 5-9 million metric tonnes of
251 grape pomace and 3-4.2 million metric tonnes from apple pomace per annum [28]. BSG
252 generated from beer-brewing has been estimated at 3.4 million tonnes annually in the EU
253 alone, and over 4.5 million tons in USA as the largest craft beer producer [29]. Wood
254 processing industries include wastes such as cuttings, shavings, veneer, sawdust and sludge
255 from the production of panels, furniture, cardboard, pulp and paper.

256 In the EU, around 11 million tonnes of solid waste were generated from paper and pulp
257 industries per annum in 2005 [30]. Significantly, an increase in agricultural residues and
258 wastes is expected to result from a required population-led increase in food production.
259 Following on from this, an increase in forestry residues and wastes is also expected.

260 **3.1.3 Third generation (Non-food marine biomass)**

261 Algae have been proposed as a potential non-food marine biomass, spanning macroalgae
262 (seaweed) and microalgae. However, the majority of algal species share some of the
263 disadvantages of other second-generation feedstocks: variable efficacy of conversion
264 technologies, and in some cases, high production cost and technical challenges in the scale-up
265 of cultivation operations.

266 3.1.3.1 Macroalgae (Seaweeds)

267 Seaweeds include green, red and brown macroalgal species such as *Ulva lactuca*, *Gracilaria*
268 *vermiculophylla* and *Saccharina latissimi*. Classification of seaweeds is based on the
269 composition of their photosynthetic pigments and diverse cellular structures. Seaweeds are
270 currently used in production of food, feed and nutritional supplements. They demonstrate a
271 rapid growth rate, high photosynthetic efficiency and do not require either arable land or
272 fresh water resources to grow [31]. Seaweeds (particularly green algae) have seen noticeable
273 investigation for production of biofuels [32]; the ash content in red and brown algae can
274 reach up to 60 %, while the cellulose content is generally low in all seaweeds [33].

275 3.1.3.2 Microalgae

276 Examples of microalgae include *Schiochytrium sp.*, *Botryococcus braunii*, *Nitzschia*,
277 *Hantzschia*, and *Neochloris oleoabundans*. Microalgae are generally richer in lipid content
278 compared with carbohydrate, and therefore attention has focused on their use for biodiesel
279 production. However, biodiesel production from microalgae demonstrates a relatively low
280 production capacity and higher production cost compared with the use of lignocellulosic
281 biomass: about 90% of biodiesel production costs are represented by microalgae production
282 [34].

283 3.2 Valorisation of second generation feedstock processes

284 Scale-up and industrialization of the first generation of biofuels was achieved smoothly. A
285 key enabling factor in their development was the relative ease of extraction of fermentable
286 sugars and oils from the plant biomass. Processes based on extraction of sucrose from the
287 stem of sugarcane to produce bioethanol, or the transesterification of oils from oil palm,
288 soybean or sunflower to produce biodiesel, could all take advantage of pre-existing large-
289 scale extraction technology. However, lignocellulosic biomass from second generation

290 feedstocks are complex structures which contain variable levels of cellulose, in association
291 with tough substrates such as hemicellulose and lignin, as well as other composites.
292 Lignocellulosic structure has been a major impediment to the development of efficient,
293 flexible and scalable pretreatment/conversion technologies: releasing fermentable sugars
294 from this complex structure represents the major hurdle for full valorisation. Figure 2 shows
295 various drivers, challenges, and opportunities exists for second generation lignocellulosic
296 biorefineries in the EU. During the last two decades, and particularly the last ten years, there
297 has been a tangible growing interest in biorefining (total 4,098 publications), with the
298 majority of studies focusing on the development of cost-effective processing methods for
299 biorefinery operations [35].

300 3.2.1 Pretreatment of lignocellulosic biomass

301 A disruption of the complex lignin-carbohydrate structure in lignocellulosic material is an
302 essential first step in making carbohydrates more available for fermentative processes
303 [36,37]. A variety of approaches have been investigated over the last few decades, spanning
304 physical (e.g. steam explosion and liquid hot water), chemical (e.g. concentrated acid
305 hydrolysis and dilute acid), biological (e.g. bacteria, fungi), physiochemical (e.g. steam
306 explosion and ammonia fiber expansion) or other combinations of methods (e.g. fungal and
307 physicochemical) [38–42]. However, conventional pretreatments have significant drawbacks.
308 The latter include high energy consumption (cost), environmental concerns and the formation
309 of inhibitors that may limit subsequent fermentation processes [43]. Additionally, the
310 efficiency of thermochemical conversion of lignin may be compromised (e.g. lignin loss or
311 unaltered lignin). Therefore, the development of flexible and scalable technology will be
312 essential for full commercial valorisation of the lignocellulosic biorefinery [44–46].

313 3.2.2 Lignocellulose conversion technologies

314 Two principal conversion technologies are generally used for valorisation of lignocellulose in
315 the biorefining industry and may be classified as biochemical and thermochemical.
316 Biochemical conversion of lignocellulose involves the hydrolysis of carbohydrates to soluble
317 sugars, followed by microbial fermentation, or by direct anaerobic digestion with/without
318 fermentation [47], while the thermochemical route involves direct combustion, pyrolysis,
319 gasification or torrefaction [48].

320 Fermentation is the process of converting sugars to alcohol or acids by microorganisms in the
321 absence of oxygen, while anaerobic digestion is the process by which biomass is broken
322 down by microorganisms in the absence of oxygen to form biogas [49]. In terms of
323 optimizing the biochemical conversion of lignocellulose, the priority mainly lies in
324 development of efficient pretreatment technologies, along with cost-effective hydrolytic
325 enzymes and improved strains of microorganisms [50].

326 Combustion is a highly exothermic process which features the complete oxidation of
327 biomass, compared with gasification which is the partial oxidation of biomass in the presence
328 of reduced oxidant level. Pyrolysis is the thermo-chemical decomposition of biomass at
329 elevated temperatures (approximately between 500°C and 800°C) in the absence of air, and
330 torrefaction is a milder form of pyrolysis conducted at lower temperatures, typically between
331 200 and 320 °C [51]. Efficient thermochemical conversion processes will also require
332 improving and standardising the lignocellulose properties of the feedstock by the
333 optimization of lignin content (via plant breeding and environmental stimuli) and heating
334 value levels, and the reduction of minerals, elemental ions, ash and moisture content, as well
335 as the reduction of pollution associated with conversion processes [52].

336 As a possible solution to these challenges, hybrid approaches based on combined
337 thermochemical–biochemical methods are actively under investigation [53]. However,
338 toxicity of the crude pyrolytic substrates, the formation of growth inhibitors from raw syngas
339 contaminants, and mass-transfer limitations in syngas fermentation are critical challenges
340 which limit the efforts to commercialize hybrid processing. Despite this, combined
341 biochemical and thermochemical conversion technologies represent the greatest hope for
342 exploitation of biomass to produce a broad range of value-added products.

343 **3.3 The opportunities: Bioenergy and Bioproducts**

344 Biorefining is analogous to petroleum refineries and have so far been conceptualized around
345 production of energy and biofuels [54]. Furthermore, integrated biorefining to produce a
346 wider range of bio-based products (spanning food, feed, chemicals and biofuels) is the
347 preferred valorisation approach in future bioeconomic models [55]. The global biorefinery
348 products market reached almost US\$438 billion in 2014, and is expected to reach US\$1128
349 billion by 2022 [56]. While over 64 countries and sub-national governments in the world
350 demonstrate strong support for bio-products, and particularly biofuels, the United States and
351 Brazil are the major players in these sectors. The EU also has ambitious national plans in this
352 area (particularly Germany), with an emphasis on biodiesel and biogas. Outside the EU and
353 US, in Canada, 190 establishments were identified to be engaged in the production or
354 development of industrial bio-products in 2015 (including biofuels, bioenergy, organic
355 chemicals and intermediates, materials and composites). The latter featured estimated total
356 lignocellulosic biomass purchases of \$2.3 billion: purchases representing 12.3 million metric
357 tonnes of forestry biomass and 8.8 million metric tonnes of agricultural biomass [57].

358 3.3.1 Energy

359 The current EU policy for renewable energy includes the “20/20/20” mandatory goals for
360 2020: a 20% reduction in CO₂ emissions compared to 1990 levels, a 20% share the energy
361 market for renewables (at least 10% blending target for transport biofuels) and a 20%
362 increase in energy efficiency. In energy-driven biorefineries, biomass is utilized for the
363 production of liquid (biodiesel or bioethanol) and/or gaseous (biomethane) road
364 transportation biofuels [58].

365 3.3.1.1 Liquid Biofuel

366 The EU shows an over-reliance on diesel as a transport fuel: the latter is divided into 71%
367 diesel and 29% petrol [59]. In fact, 70% of world sales of diesel cars and vans are represented
368 by Europe [60]. The boom in diesel vehicles that started at the end of the 1990s in the EU
369 was supported by fuel taxation policies and vehicle emission regulations [61]. However, a
370 recent re-evaluation of the polluting capacity of diesel fuel may mean that its EU market
371 share could fall significantly in future years [62]. Contrasting with this, biodiesel engines
372 have a demonstrably lower polluting capacity [63], and are a promising alternative to diesel
373 fuel derived from petroleum sources.

374 The dominant liquid biofuel in the EU market is biodiesel (81%), with bioethanol
375 representing 19% of the market place [59]. However, bioethanol is the dominant biofuel in
376 the global market (80% market share compared with 20% for biodiesel; [64]). Table 1
377 represent the key figures on biofuel production in the United States, Brazil and Europe
378 [65,66].

379 Biodiesel can be used alone, or it can be blended with petro-diesel to be used in standard
380 diesel engines; it can also be used as a low-carbon alternative to heating oil. It has many
381 advantages over petroleum diesel in having a relatively low environmental impact, and in

382 being biodegradable, while maintaining similar combustion properties to petroleum diesel
383 [67]. A total of 34.08 million tonnes of biodiesel were produced globally in 2016;
384 approximately 37 % of this figure from the EU-28, with a total biodiesel production of
385 12,610 million tonnes [68]. The key feedstock for production of biodiesel in the EU is
386 rapeseed. However production of biodiesel can also be achieved by esterification of oils and
387 fats from edible oil crops (e.g. palm, sunflower, soybean and rapeseed), non-edible oil crops
388 (e.g. *Calophyllum inophyllum*, *Nicotiana tabacum*, *Jatropha curcas*, *Hevea brasiliensis*),
389 waste oil (e.g. cooking oil, soapstocks, spent bleaching earth oil), microalgae (e.g.
390 *Botryococcus braunii*, *Phaeodactylum tricornutum*, *Neochloris oleoabundans*), cyanobacteria
391 (e.g. *Cyanobacterium aponinum*, *Phormidium sp.*, *Synechococcus sp.*), or even yeasts
392 (*Rhodotorula sp.*, *Cryptococcus sp.*, *Lipomyces sp.*, *Candida sp.*) [69].

393 Bioethanol can be used in the production of oxygenated fuel additives (ethanol-petrol blends)
394 to improve petrol fuel properties and to decrease GHG in gasoline vehicles. More than
395 119.3 million m³ of bioethanol were produced globally in 2016, while approximately 73% of
396 the global production came from the United States and Brazil, with a total bioethanol
397 production of 58.5 and 28.4 million m³, respectively [68]. The key feedstock for the global
398 production of bioethanol is maize. However, production of bioethanol can be achieved by
399 fermentation of sugars or starch (after a hydrolysis step) from grain (e.g. maize, wheat) or
400 sugar crops (e.g. sugar cane, sugarbeet) as in the first generation of biofuels, or from
401 saccharification and subsequent fermentation of lignocellulosic feedstock, as in second
402 generation biofuels [70].

403 3.3.1.2 Biogas

404 Biogas can be used for a diverse range of purposes, including producing heat, steam and
405 electricity, or it can be upgraded to biomethane and used as an equivalent of natural gas as a

406 fuel [71]. In the EU, biogas is mainly used for production of electricity and/or heat. Germany
407 is the leader in biogas production from the fermentation of agricultural crops and residues,
408 accounting for 64 percent of total EU production in 2015. The United Kingdom, along with
409 Estonia, Greece, Ireland, Portugal, and Spain, rely on waste management processes of
410 anaerobic digestion of landfill and sewage sludge for over 80 percent of their biogas [72].
411 According to the European Biogas Association (EBA), a total of 17,662 biogas plants and
412 503 biomethane plants were in operation in Europe in 2016 [73]. The EBA further reported
413 that 67% (+7,699 units) of the total increase in biogas plants in the EU from 2009 to 2016
414 (from 6,227 to 17,662 units) was due to an increase of biogas plants utilizing agricultural
415 substrates. Moreover, in France for example, 48.5 % of the biomethane production in 2016
416 (199 GWh production share from the total annual production of 410 GWh) was from
417 facilities that utilize agricultural biomass.

418 Although the energy-driven model remains dominant in the biorefinery industry, there is a
419 lack of energy balance studies in the published literature to justify the commercial feasibility
420 of available technologies for biorefining of lignocellulose. Table 2 represents examples of
421 literature data on the energy balances of lignocellulosic biorefinery scenarios.

422 3.3.2 Bioproducts

423 There are only a limited number of product-driven biorefineries in commercial operation
424 today in the EU [74]. However, according to a 2016 survey conducted by the European
425 Commission's Joint Research Centre on EU bio-based industry, 284 products have been
426 developed in total by 50 companies which are either currently or expected to be produced as
427 bio-based products [75].

428 3.3.2.1 Bio-based food and feed ingredients

429 Food and feed ingredients that can be produced by biorefining of lignocellulose include
430 xylitol (used as sweetener in chewing gum manufacture; [76]), xanthan gum (used as a
431 thickening and stabilizing agent in both food and medicine; [77]) and animal feed co-
432 products generated from biorefining of lignocellulose [74].

433 3.3.2.2 Biochemicals

434 The Bio-based consortium in the EU aims to replace 30% of overall chemical production
435 with biomass-derived biochemicals by 2030 [78]. According to the National Renewable
436 Energy Laboratory in USA, the latter can be finished products or intermediates that then
437 become a feedstock for further processing [79]. Biochemicals produced from the biorefining
438 of lignocellulose include organic acids (e.g. citric, acetic, benzoic, lactic and succinic),
439 microbial enzymes (e.g. amylase, cellulase, pectinase, xylanase, mannanase), and building
440 blocks for bio-based polymers (e.g. phenylpropanoids, polyhydroxyalkanoates) [80–82]. The
441 projected production of some lignocellulosic-based chemicals and materials in Europe (in
442 2020 and 2030) is summarized in Figure 3 [83].

443 3.3.2.3 Bio-Polymers

444 Novel materials that can be produced from biorefining include biosurfactants, biolubricants,
445 and bioplastics (from bio-based polymers e.g. polyesters, polyamides, and polyimides)
446 [74,80]. Global output of bio-based polymer production is forecast to increase from 6.6
447 million tonnes in 2016 to 8.5 million tonnes in 2021, with Europe's share projected to grow
448 from 27.1% to 26.0% [84]. Of special note, bioplastics are receiving significant global
449 attention as a replacement for non-degradable plastics that are currently produced in large
450 quantities. On a world-wide basis, 335 million tonnes of plastic materials were produced in
451 2016, with 17.9 % of this being produced in the EU [85]. However, Europe's position in
452 producing bio-based polymers is somewhat limited, due mainly to the current preference for

453 starch blends, arising from an unfavorable political framework and a tendency to import
454 biopolymers (e.g. Polybutylene adipate-co-terephthalate and Polylactic acid from Asia; [86]).

455

456 **4. Research impact and development trends**

457 The EU movement towards a “knowledgeable-based economy”, that prioritized research and
458 innovation, started in earnest in 2000 when the Lisbon Strategy set out the development
459 action plan for the EU for the first decade of the new century. The Horizon 2020 framework
460 is the current Pan-European research funding programme that will last until 2020, having
461 started in 2014. Under this scheme, seven grand challenges have been identified by the EU
462 where targeted investment in research and innovation may bring the largest impact on
463 society. In this context, Horizon 2020 aims to support European industry through stimulating
464 heightened research and innovation activities. Of special note is the signaling of the
465 importance of biorefining as a pivotal element of the engine of the new bioeconomy. Such
466 innovation represents an important part of the solution for societal challenges relating to
467 food Security and sustainable agriculture, marine, and inland water research, Energy security-
468 efficiency, climate change and integrated transport solution.

469

470 The EU established the Bio-based Industries Joint Undertaking (BBI JU) in 2014 (due to run
471 until 2024) as a €3.7 billion Public-Private Partnership between the EU and the Bio-based
472 Industries Consortium. The BBI JU aims to develop new biorefining technologies to
473 sustainably convert renewable biomass into biofuels, bioproducts, and biomaterials. Over the
474 first two years, the BBI JU funded 65 projects (with a total investment of 414.29 EUR
475 million) to support the biorefining sector [89]. The majority of BBI JU funding (Figure 4) is
476 directed at developing lignocellulose-based biorefineries. Examples of current EU-funded
477 projects in lignocellulose biorefining are shown in Table 3[90]. The ongoing development

478 trends to support biorefining in the EU is focused on three pillars: policies, biomass
479 availability, and value chain modelling (feedstock logistics, processing, and marketing of
480 value-added products) [91].

481

482 4.1 Policies

483 The biorefining industry and research within this field has benefited greatly by many EU
484 policy initiatives. The latter include the European bioeconomy strategy for 2020 and beyond
485 (2012), the climate and energy framework for 2030 (2014), and recently the circular economy
486 package for 2030 (2018) [92]. Through such measures, bioeconomy action plans have been
487 developed for sectors such as environment, forestry, agriculture, industry, and energy [93].

488

489 However, arguably most of the current policies tend to focus on the bioeconomy in rather
490 general terms. Terms such as ‘bioeconomy’ and ‘bio-based economy’ are not equivalent. The
491 term “bioeconomy” is usually associated with conversion processes while “biobased
492 economy” is usually employed in the context of a raw material focus (an instead of non-
493 renewables, such as fossil-based raw material, which here represent the total economy) [94].

494

495 Recently, the FAO assessed the classification of sectors such as biorefineries as a pillar of
496 bioeconomic strategy in different countries and regions, including the EU [95]. Results
497 showed that countries such as USA, Australia, Malaysia, and South Africa are actively
498 cultivating biorefining as a component of their bioeconomic strategies. However, while
499 supporting the biofuel-bioenergy sectors, the EU (with the noted exception of Germany) is
500 not taking such an inclusive approach to biorefining.

501

502 Over-exploitation of natural resources and food insecurity are among the potential risks from
503 unsustainable practices in primary production [96], and may be partly addressed by novel
504 biorefining approaches. Recently, the commission expert group on bio-based products in the
505 EU reported that progress in the development of a renewables-based economy is at risk of
506 being slower than the rest of the world in achieving the targeted shift to a renewables-based
507 economy [97]. As a result, the expert group recommended the revision of the EU
508 bioeconomic strategy and to extend the BBI JU for a second term.

509

510 European Commission initiatives, such as Projects-for-Policy (P4P), aims to use results from
511 research and innovation projects to shape policy making. In this context, P4P (2018)
512 published reports have recommended policy measures to unlock the unexploited potential of
513 industrial waste streams, and to enhance circular utilisation of resources [98]. Moreover,
514 independent alliances, such as the European Bioeconomy Alliance, have requested revision
515 of the bioeconomy strategy to ensure that biorefineries and related technologies become an
516 integral part of EU level policies [99].

517

518 4.2 Biomass availability

519 The supply of lignocellulosic biomass in the EU varies with respect to source, quantity,
520 composition and cost. A number of studies have produced varying data regarding the
521 availability of (sustainable) lignocellulosic biomass in the EU (and beyond) [100]; part of this
522 challenge relates to varying estimates of available land area and agricultural productivity in
523 the future. The perspective is also complicated by additional factors, such as climate change.

524

525 The project “Biomass Futures” (2010-2012) estimated the future availability of
526 lignocellulosic biomass based on review of previous studies (EUBIONET, RENEW,

527 REFUEL, BEE, Elobio,4FCROPS) and attempted to model the biomass supply chain to
528 provide data for decision makers and other stakeholders [101]. The project identified
529 agricultural wastes as the largest reservoir of cost-effective feedstocks while forestry residues
530 represented the most expensive.

531

532 The S2Biom project (2013-2016) investigated the sustainable potential of about fifty
533 feedstock types available across the EU (in addition to Western Balkans, Moldova, Turkey
534 and Ukraine) [2]. However, S2Biom recommended further research work on improving yield,
535 cropping technologies, biomass composition, and competition for resources (e.g. land and
536 water).

537

538 The BioTrade2020plus project (2014-2016) studied the potential sustainability of sourcing
539 lignocellulosic biomass (wood chips, pellets, torrefied biomass and pyrolysis oil) from the
540 main geographic regions outside the EU (Canada, US, Russia, Ukraine, Latin America, Asia
541 and Sub-Saharan Africa) [102]. The project raised concerns about the cost efficiency of
542 importing lignocellulosic biomass from forest residues, and considered agricultural residues
543 as “the cheapest option”. Furthermore, in the case of strong global climate policy, such
544 regions will probably retain a greater percentage of biomass for domestic use. Therefore,
545 future biomass supply to Europe may be jeopardized.

546

547 Recently, the AGRIFORVALOR Project (2018) studied the potential of lignocellulosic
548 biomass residues and wastes for a sustainable biobased economy in the EU [103]. The project
549 estimated the availability and type of lignocellulosic residues and wastes through conducting
550 literature reviews and interviews with farmers, foresters and industry. The project developed
551 three potential investment opportunity scenarios based on Spain (biorefinery of olive
552 biomass), Ireland (biorefinery of grass) and Hungary (biorefinery of whey and straw).

553

554 The primary focus of most biomass availability studies recently conducted has been on the
555 production of biofuels and bioenergy. More studies are required on cost efficiency of
556 multiproduct biorefining, combined with an examination of greenhouse gas emissions
557 associated with multiproduct biorefining of different biomass feedstock.

558

559 4.2 Biomass value chain modelling

560 Feedstock supply, processing and product markets are the main components of the targeted
561 value chain. Regardless of lignocellulosic biomass type, in most cases feedstock is collected
562 at a certain location near the source(s) and then transported (by methods such as road and
563 rail) to biorefineries at different locations. Therefore, managing the feedstock supply chain
564 can effectively reduce the cost of feedstock supply, and therefore the cost of the final product,
565 as well as ensuring sustainable supply of feedstock [104]. However, lignocellulosic biomass
566 varies in nature, and the structure of the supply chain is different, so no standard model can
567 be applied directly for supply of any biomass. Therefore, studies have attempted to optimize
568 the feedstock supply chain, taking into account supply and demand uncertainties [105].

569

570 Additionally, value chain models have developed to allow for flexible conversion scenarios
571 [106], and this has encouraged additional study of the impact of conversion technology
572 choice and targeting of final products for value chain optimization. Lignin and sugar
573 valorisation is a noteworthy focus in such work, as well as the production of biochemical,
574 biopolymers and bioethanol. Such an integrated biorefining model, along with the use of
575 efficient conversion technologies, is expected to provide the best chance for more widespread
576 commercialization of lignocellulosic biorefineries, an aspect which thus far has been difficult
577 to achieve [107-109]. However, given multi-faceted nature and fast-changing character of

578 this sector, predictions for the future of the biorefinery sector will carry a degree of
579 uncertainty [110].

580

581 **Conclusion**

582 Driven by global environmental challenges, the EU is attempting to take a large step towards
583 a modern bioeconomy. At the heart of this strategy is a new biorefinery concept based on
584 replacement of first generation feedstocks derived from edible crops with second generation
585 lignocellulosic materials and wastes. Valorisation of technologies is still a formidable hurdle
586 facing the development of this nascent industry, and productive integration of individual
587 biorefinery operations remains at a relatively early stage. Although biorefining aimed at
588 energy production remains the most dominant model in this industry, product-driven
589 biorefining is a promising business with a growing market share. The current ongoing
590 research in the area of biorefineries is therefore focused on developing an advanced model
591 which can utilize a wide range of feedstocks, have integrated conversion processes, and
592 produce a greater variety of higher value end products.

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596

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Tables

863 Table 1. Key figures on biofuel production in the Unites States, Brazil and Europe

Country/Region	Bioethanol Production (Billion liters)	Biodiesel Production (Billion liters)
The United States	^a 59.8	^b 5.5
Brazil	^a 26.7	^b 3.8
Europe	^a 5.4	^b 6.1

864 * Where: ^a: figures of 2017, and ^b: figures of 2016.

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869 Table 2. Literature data on energy balance of lignocellulosic biorefinery (Ethanol production).

Biomass	[87] Corn stover	[88] Switchgrass	[88] Woody energy crops	[88] Forest harvest residues
Biomass Yield	5,212	8,360	10000	8000
Energy Inputs	3.04	5.389	5.675	5.526
Net Energy	7.46	1.764	1.478	1.627

870 * Where Biomass Yield unit is kg/ha/year, and Energy unit is MJ/kg biomass.

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883 Table 3. The BBI JU funded projects to support lignocellulose biorefining industry in the EU.

Project/Website	Start date	End date	BBI JU contribution (€)	Aim
BIOFOREVER https://www.bioforever.org	Sep. 2016	Aug. 2019	9,937,998.02	Demonstrate the commercial viability of lignocellulosic biorefining (from woody biomass) for the chemical industry.
BIOSKOH http://bioskoh.eu	June 2016	May 2021	21.568.195	Demonstrate the first of a series of new second generation bio-refineries for Europe.
EUCALIVA http://eucaliva.eu	Sep. 2017	Feb. 2021	1,795,009.88	Create a whole value chain from lignin, using Eucalyptus waste as its source.
GRACE http://www.grace-bbi.eu	June 2017	May 2022	12,324,632.86	Explore the potential of the non-food industrial crops as a source of biomass for the bio-economy.
GREENSOLRES http://www.greensolres.eu	Sep. 2016	Aug. 2021	7,451,945.63	Demonstrate the commercial viability of converting lignocellulosic biomass to levulinic acid.
HYPERBIOCOAT http://www.hyperbiocoat.eu	Sep. 2016	Aug. 2019	4,617,423.75	Develop biodegradable polymers derived from food processing by-products.
IFERMENTER	May 2018	April 2022	3,997,825	Conversion of forestry sugar residual streams to antimicrobial proteins by intelligent fermentation.
LIBRE http://www.libre2020.eu	Nov. 2016	Oct. 2020	4,566,560	Lignin based carbon fibres for composites
LIGNIOX http://www.ligniox.eu/	May 2017	April 2021	4,338,374.88	Lignin oxidation technology for versatile lignin dispersants
LIGNOFLAG http://www.lignoflag-project.eu	June 2017	May 2022	24.738.840	bio-ethanol production involving a bio-based value chain built on lignocellulosic feedstock.
PEPERENCE	Sep. 2017	Aug. 2022	24,999,610.00	Producing FDCA (furan dicarboxylic acid), a bio-based building block to produce high value products.
SSUCHY https://www.ssuchy.eu/	Sep. 2017	Aug. 2021	4,457,194.75	Sustainable structural and multifunctional bio-composites from hybrid natural fibres and bio-based polymers
SWEETWOODS	June 2018	May 2022	20,959,745	Production and deploying of high purity lignin and affordable platform chemicals through wood-based sugars
UNRAVEL	June 2018	May 2022	3,603,545	Develop advanced pre-treatment, separation and conversion technologies for complex lignocellulosic biomass.
US4GREENCHEM http://www.us4greenchem.eu/	July 2015	June 2019	3.457.602,50	Combined Ultrasonic and Enzyme treatment of Lignocellulosic Feedstock as Substrate for Sugar Based Biotechnological Applications
VALCHEM http://www.valchem.eu	July 2015	June 2018	13.125.941	Value added chemical building blocks and lignin from wood
WOODZYMES	June 2018	May 2021	3,253,874	Extremozymes for wood based building blocks: From pulp mill to board and insulation products
ZELCOR http://www.zelcor.eu	Oct. 2016	Sep. 2020	5,256,993.00	Zero Waste Lingo-Cellulosic Biorefineries by Integrated Lignin Valorisation.

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Figures

888 Figure 1

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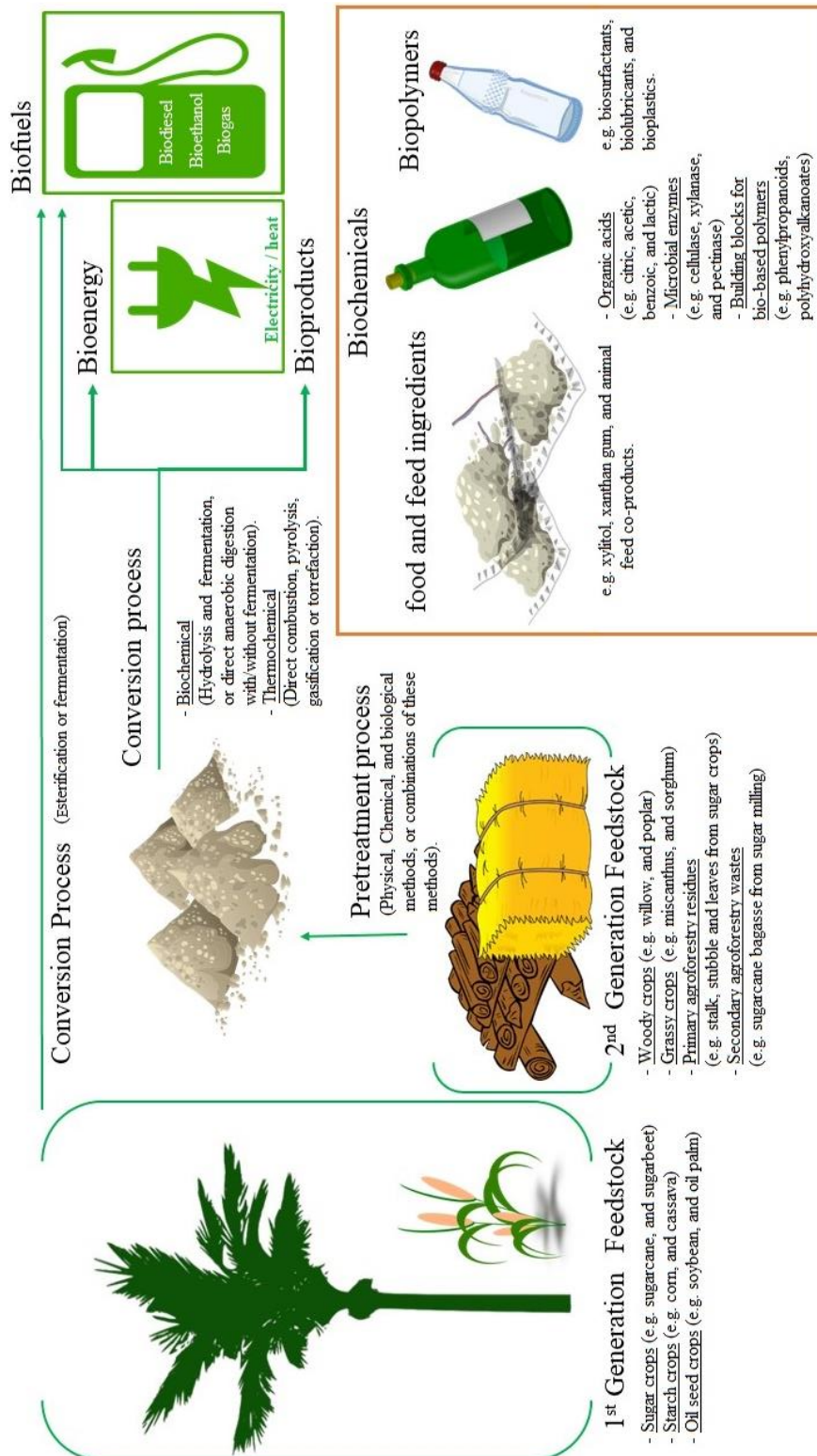
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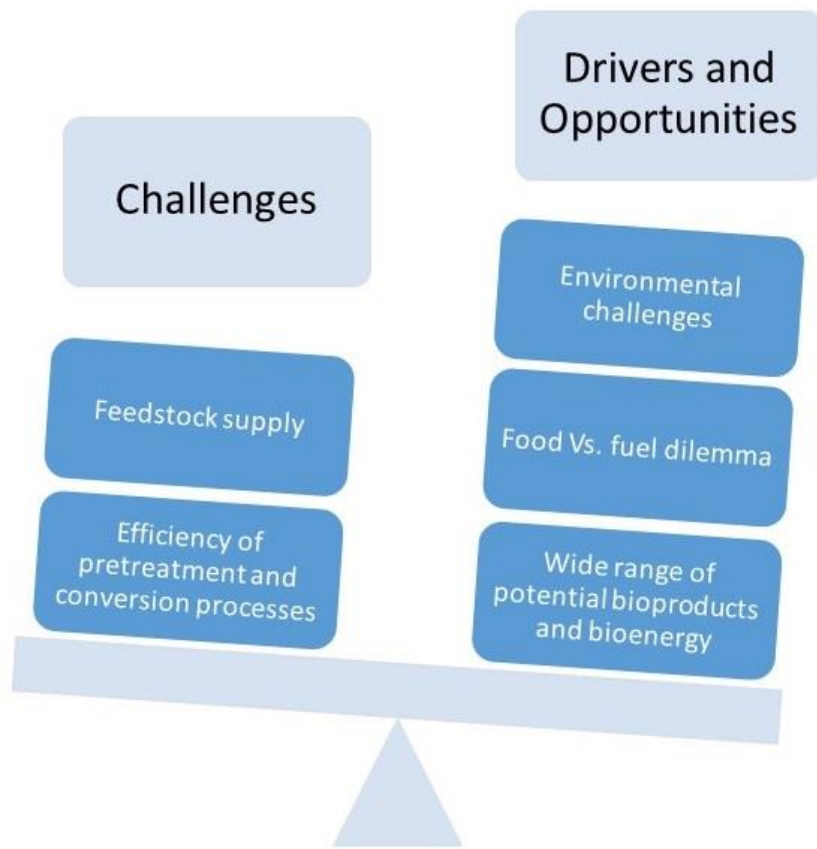
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910 Figure 1. Schematic diagram shows differences between lignocellulosic feedstocks from the

911 first and second generation: sources, valorisation processes, and end products.

912 Figure 2



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915 Figure 2. Drivers, challenges, and opportunities exists for second generation lignocellulosic

916 biorefineries in the EU.

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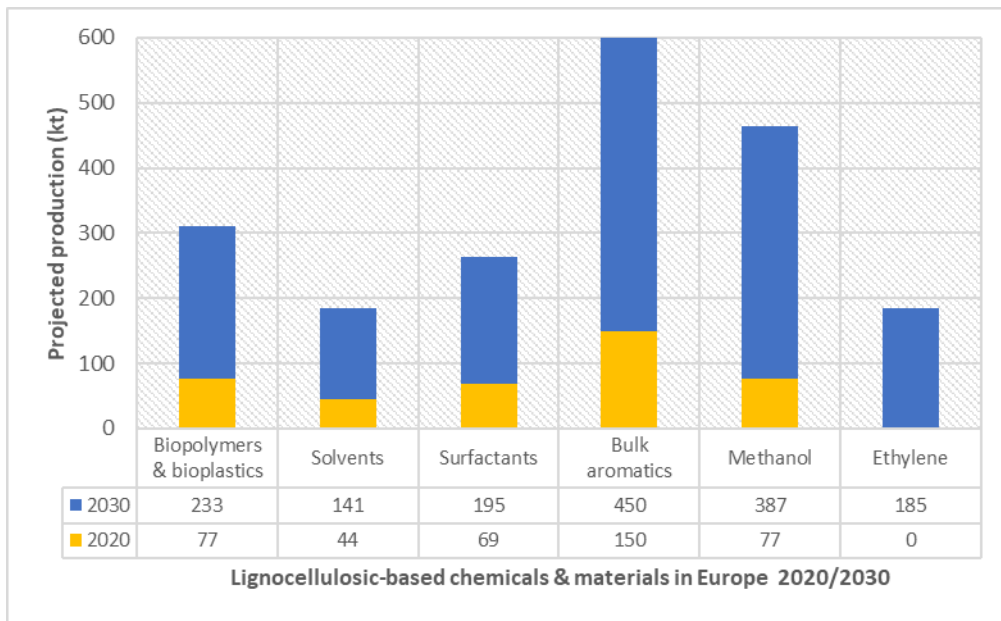
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926 Figure 3



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928 Figure 3. Projected production of biobased chemicals and materials in Europe 2020/2030

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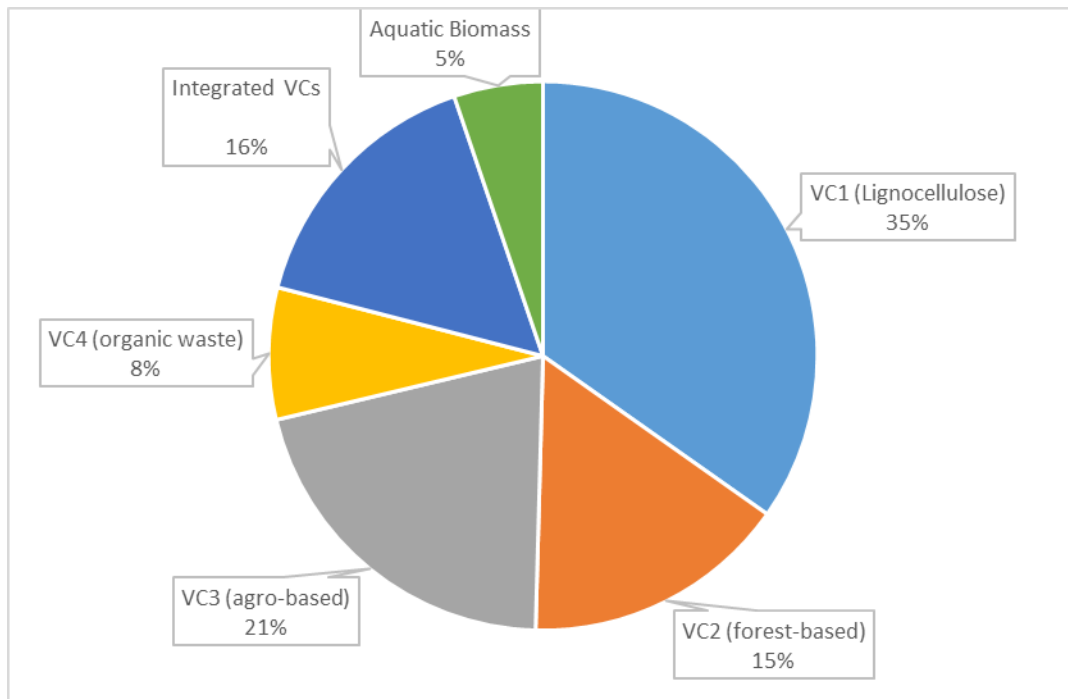
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940 Figure 4



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942 Figure 4. BBI JU funding share per value chain (VC) in the EU (2014-2016).

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