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# Navigating bioenergy horizons: a critical examination of Europe's potential, with Belgium as a case study

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## Abstract

Estimates of the energy potential of the different energy sources are essential for modelling energy systems. However, the potential of biomass is debatable due to the numerous dimensions and assumptions embedded. It is thus important to investigate further the final potential to understand their implications. Therefore, this study analyses European studies assessing biomass potential and proposes a critical discussion on the different results to converge to a realistic range of potentials for 2030. Biomass is divided into four categories: forestry products, agricultural residues, energy crops and other waste, each with sub-categories. Belgium is used as a case study to highlight the convergences and divergences of the studies. Having a national case study allows for more precise analyses through in-depth comparisons with national data and reports. The potential estimates are compared with the current production for each category in order to have a better view of the gap to be bridged. From these national perspectives, the European potential can be better apprehended. The results show that the realistic potentials for 2030 for Belgium and Europe are somewhat in the lower range of the estimates of the different studies: from 30 to 41 TWh and from 2000 to 2500 TWh, respectively. The forestry biomass is already well exploited with a slight potential increase, while the agricultural residues present the most significant potential increase. The realistic potential for energy crops in Belgium turned out to be close to the minimum estimates. Indeed, the implications of those crops are considerable regarding the agricultural structure and logistics. This article emphasises that no energy potential is neutral, as it involves a specific system in terms of agriculture, forestry or waste management, with broader social, economic or environmental implications. Consequently, using one estimate rather than another is not a trivial matter; it has an impact on the system being modelled from the outset.

**Keywords** Biomass, Potential, Forestry products, Agricultural residues, Energy crops, Waste

## Introduction

Biomass is a significant energy source in the current global energy mix, but its further development is also crucial for the energy transition to renewable fuels (IEA, 2023). In this context, it is necessary to evaluate the potential of this resource more precisely. Indeed, the potentials are key data used in energy system models, which are essential tools to pave the way towards a low carbon future. Moreover, as biomass is a versatile but limited resource, it is crucial to understand its availability and the related constraints in order to optimise its uses within whole energy systems. However, due to the large

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number of dimensions to be considered (e.g. social, economic, agricultural, diet and biodiversity) (López-Bellido et al., 2014), it is impossible to define its potential unambiguously, and a multitude of debatable potential assessments can be found in the literature, with various degrees of agreement from the scientific community (Strapasson et al., 2017).

Biomass potential studies aim to evaluate the quantity of biomass available for energy production considering various constraints. The scope of such studies varies from assessing the theoretical potential with very few constraints to assessing the implementation potential that considers technical, economic and sustainability constraints (Batidzirai et al., 2012). Biomass is usually analysed by category: forestry, agriculture and waste (Imperial College London, 2050). Each category requires a specific methodology to define its potential for bioenergy. Various disciplines must be considered (agriculture, forestry, waste management), all coupled with economic, social and ecological considerations (e.g. jobs, infrastructure, competing uses). As these unavoidably correlate to preconceptions of society, economics and nature, biomass potential assessments always remain debatable.

Many studies evaluating the biomass potential have been published with various results, scopes and resolutions as mentioned in these two reviews (Batidzirai et al., 2012; Berndes et al., 2003). When some studies present similar overall estimates, they can diverge in terms of detailed results per categories or sub-categories of feedstock, which translates to totally different realities. A careful consideration of the underlying methodologies and assumptions is therefore required to compare the available results and draw conclusions on reasonable estimates. Most of the time in the literature, the potential estimates are taken as simple exogenous data for energy system modelling (Limpens et al., 2020; Rixhon et al., 2022), with no further discussion on the systemic implications.

Additionally, evaluating the feasibility of mobilising this potential is complex compared to the current situation. Indeed, the current statistics and data on biomass used for bioenergy are disparate and incomplete, making it hard to have a complete view of the production and its potential development. However, comparing the current situation with the potential would be of great help to the decision-makers or the users of energy models to assess the possible increase and the related changes required.

Therefore, we propose to compare and discuss different biomass potentials with their assumptions. We decided to work at a national scale from European studies. Indeed, the national scale allows to have a more precise view, with more available data related to one coherent geographical entity. As biomass potential is related to

forestry, agriculture and waste management that vary in every country or even region, it makes more sense to work in detail on the bioenergy potential of one coherent political entity as the country. Moreover, in this paper, current productions of biomass by sub-category are assessed by cross-referencing different databases in order to enrich the biomass potential analysis. Estimating the current production per sub-category is more accessible at a national scale due to data gaps and inconsistency at a larger scale. Afterwards, the 2030 potentials from different estimates and methodologies are critically discussed in order to converge to a pragmatic potential for biomass in Belgium. Finally, the Belgian case study provides a framework for assessing the European estimates more precisely, their convergences and divergences, and their strengths and weaknesses.

## Materials and methods

To analyse and discuss biomass potential, we first identified and selected studies that held relevance in the context of biomass potentials at the European scale with detailed approaches and results at the national level. Four central studies are considered to discuss the resource potentials: CONCAWE (Imperial College London, 2021), ENSPRESO (Ruiz et al., 2015), OUTLOOK (Elbersen et al., 2016) and S2BIOM (Dees et al., 2017). The considered studies assess the technical potentials under specific sustainability and/or economic constraints for some categories. They start from the theoretical potential, before applying technical constraints. This potential is then further investigated according to different scenarios based on various sustainability and economic constraints. Their main characteristics are given in Table 1. The four different studies rely on EU models for prospecting the dynamics and evolution of the different sectors. The European Forest Information SCENario Model (EFISCEN) (Verkerk et al., 2016) is used to evaluate the states of forests, except in CONCAWE (Imperial College London, 2021), where the authors developed their own methodology. This EFISCEN model is used to evaluate forest development for up to 60 years, and it is based on national forest inventory data. This model can create different scenarios based on management and policies, but also climate change. The Common Agricultural Policy Regional Impact Analysis model (CAPRI) (Britz & Witzke, 2014) is used to simulate the agricultural dynamics and prospects in all studies, together with the MITERRA (Oenema et al., 2009) model for evaluating livestock evolution and related residues. The CAPRI model simulates the evolution of the agricultural landscape in Europe based on the policies and market evolution. This model is used as a basis in the different studies compared in this work to set up the initial land allocation in their reference

**Table 1** General presentation of the four central studies estimating biomass potentials used in this work

| Studies                                 | Biomass categories covered | Number of sub-categories | Geographical focus and details                              | Years of study      | Scenarios                                                    | Year of the publication |
|-----------------------------------------|----------------------------|--------------------------|-------------------------------------------------------------|---------------------|--------------------------------------------------------------|-------------------------|
| ENSPRESO (Ruiz et al., 2015, 2019)      | All                        | 17                       | EU with national details                                    | 2020–2030–2040–2050 | 3: Low–medium–high                                           | 2019                    |
| CONCAWE (Imperial College London, 2021) | All                        | 15                       | EU with national details                                    | 2030–2050           | 3: Low–medium–high                                           | 2021                    |
| S2BIOM (Dees et al., 2017)              | Lignocellulosic biomass    | 49                       | EU with national details                                    | 2012–2020–2030      | 11: Technical–Reference–high and eight alternative scenarios | 2017                    |
| OUTLOOK (Elbersen et al., 2016)         | All                        | 25                       | EU with national details and ten specific national analyses | 2010–2020–2030      | 3: Low–medium–high                                           | 2016                    |

scenarios, but also for some agricultural assumptions such as the yield of different crops, the available land, or the evolution of livestock. For the waste category, the studies rely on historical data and general statistical trends.

The studies CONCAWE, ENSPRESO and OUTLOOK all present three main scenarios with relatively similar narratives: (i) a low potential scenario where bioenergy is not a priority while competing uses and sustainability criteria are enhanced; (ii) a reference potential scenario considers sustainability criteria and medium competing use similar to current practices and (iii) a high potential scenario increasing the production of bioenergy with reduced competing uses and limited sustainability criteria (high mobilisation). S2BIOM (Dees et al., 2017) project focuses on lignocellulosic biomass. However, it presents an extensive range of data across Europe, adding a level of discretisation that is very informative for comparison and discussion. Indeed, the study details 49 biomass categories (including, for example, post-consumer wood, cereal straw or logging residues), including historical data. Additionally, S2BIOM considers numerous scenarios with variations in terms of end-uses and competing practical uses which are helpful for informing the discussion. In this work, the reference scenario (i.e. considering the current sustainability practices) will be used for general comparison with other EU studies. The other S2BIOM scenarios will enrich the discussion for some specific aspects (e.g. forestry products).

The databases related to the four studies presented in Table 1 are explored and compared comprehensively. The different categories, the related structuring assumptions and methodologies were analysed. The temporal dimension of this research is anchored in the year 2030 (due to the data availability of the different studies), which serves as the baseline for our discussions and analyses. However, when relevant, the estimates and projections

for the year 2050 are used for comparison to add depth and nuance to the discussions. The biomass potential is divided into four distinct categories: the three usual ones, i.e. forestry products, agricultural products and waste, and the fourth category, energy crops. Agricultural products gather mostly residues, while energy crops gather the plants grown for energy as the first purpose (usually contained in the agricultural products). This fourth category is added because energy crops cover a large part of the potential in most studies, while their implementation is based on specific and essential assumptions, mainly the allocation of land, which is one of the critical assumptions in bioenergy studies (Batidzirai et al., 2012). Therefore, it is helpful to distinguish the potential related to new lands available for energy crops from the potential related to other agricultural practices in terms of impacts on land management and systems.

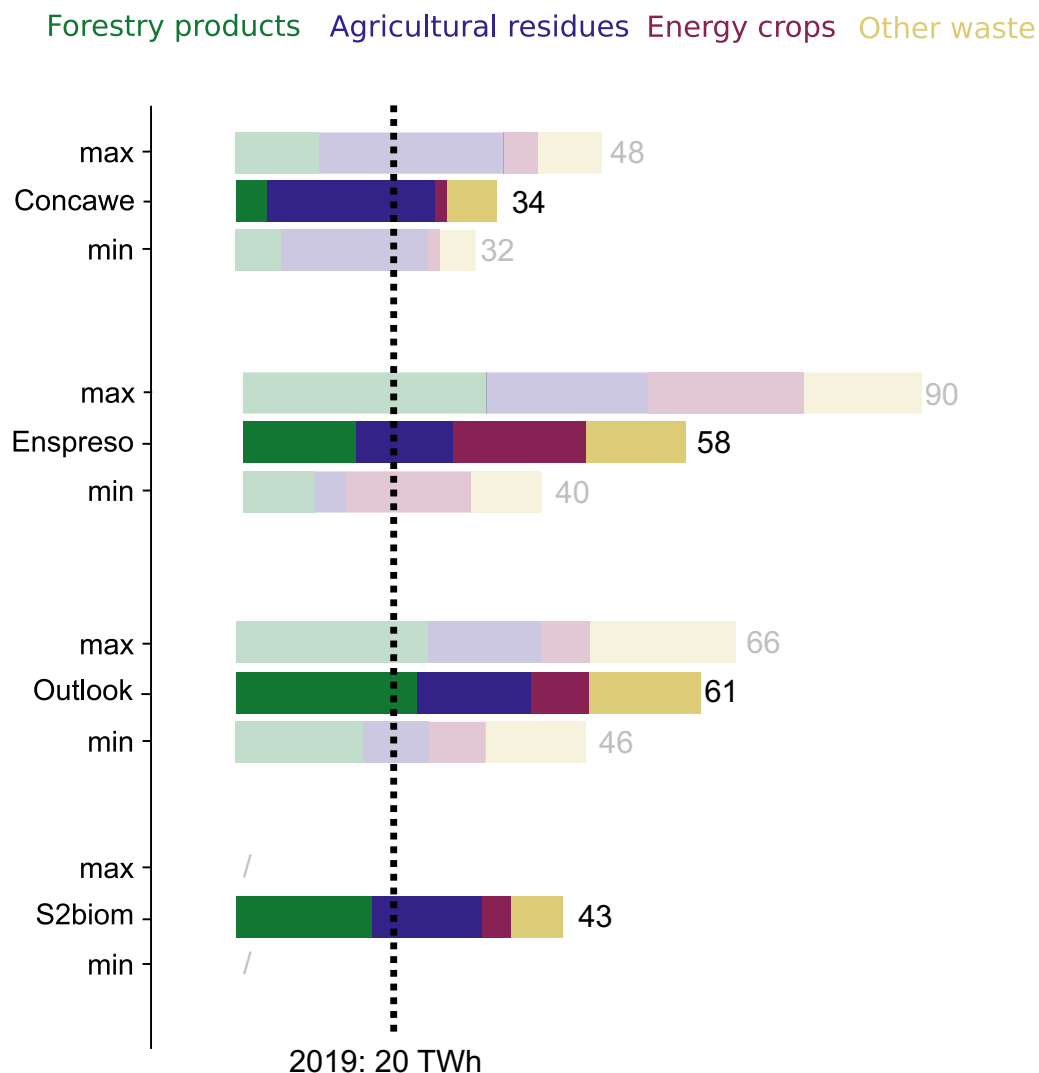
In this paper, the convergences and divergences of the different studies are highlighted and discussed in terms of methods and assumptions, first for the overall potential and then for the feedstock categories (Section “Forestry products”, “Agricultural residues”, “Energy crops”, “Other waste”, “Summary and convergence towards a realistic potential for Belgium”, “Implications for European potential”). The outsiders are discussed to understand the extreme assumptions possible and discuss their implications as illustrative examples. Some other studies are used to discuss specific points, such as the biogas potential with a European or national focus (Scarlat et al., 2018; Valbiom., 2019). Moreover, current biomass production was estimated for Belgium for each category in order to compare it with the various potentials presented in the studies. For this task, various databases were used, including Eurostat (European Commission - Eurostat. Statistics | Eurostat n.d, 2023), Bioenergy Europe (Gauthier et al., 2021), FAOSTAT (Food and Agriculture Organization of the United Nations (FAO). FAOSTAT n.d 2023)

and BiomassFlow (Gurría et al., 2022). By combining data from those multiple sources with critical analysis to cover the gaps and discrepancies, this research aimed to provide a clear understanding of biomass current production in Belgium, which is helpful to facilitate an insightful analysis of the 2030 biomass potential.

## Results and discussion

The potential of each biomass category is analysed alongside the current local production in order to gain a better view of the potential increase in the contribution of biomass. The different categories are the forestry products (Section. "Forestry products"), the agricultural residues (Section. "Agricultural residues"), the energy crops (Section. "Energy crops") and the other waste (Section. "Other waste").

The total Belgian bioenergy potential for 2030 is estimated between 30 and 90 TWh, shared between various resources (Fig. 1)—compared with 20 TWh of biomass for energy produced in 2019. The range for 2050 is similar, but the highest estimate is slightly higher: 30–97 TWh. The general trends for 2030 are thus representative of the general potential for biomass in the near and mid-term future. The key assumptions inducing significant potential variations are (i) the integration of competing uses for forest products and agricultural residues; (ii) the land-use management mainly related to energy crops development (arable or marginal lands for energy crops); (iii) the waste harvest and the use of waste for resources or energy. The highest estimate, reaching nearly 90 TWh (ENSPRESO high scenario), is based on optimistic assumptions in terms of technology efficiency, yield, fertilisation and competing uses. In general,



**Fig. 1** Belgian bioenergy potential (in TWh) in 2030 from the four European studies considered (CONCAWE, ENSPRESO, OUTLOOK and S2BIOM)

this scenario is based on a techno-optimist vision and relies on a higher extraction (lower sustainability constraints and competing uses), higher mechanisation, and boosted yields through fertilisation. This estimate is questionable because of the technical assumptions and related impacts, for example, on the biodiversity (e.g. with higher stump extraction) or the market and the substitution effect (because competing uses are not taken into account). This scenario was considered unrealistic considering the European Green Deal (Imperial College London, 2050). From the same ENSPRESO study, the low scenario consists of 42% energy crops (Fig. 1), which is unusual for a “low” potential scenario. This will be discussed in Section. “Other waste” on energy crops. The smallest estimate of all scenarios (i.e. low scenario from CONCAWE), reaching around 30 TWh, is mainly composed of agricultural residues, which appears unusual compared with other studies (Fig. 1). Additionally, the high estimate for CONCAWE is lower than most of the other reference scenarios (Fig. 1), with a high share of agricultural residues in all CONCAWE scenarios. This lower estimate is due to stricter sustainability constraints in most of the categories except for agricultural residues. Energy crops are only considered on marginal lands. Other waste and forestry products are also smaller due to higher competing uses considered (circularity, reuse, etc.). This is discussed in more detail for each category in the following sections.

Forestry products

For forestry products, the main components used for bioenergy in Europe are residues (primary or secondary) (Camia et al., 2021). Primary residues include all residues that are extracted from the forest, from the logging operation (e.g. chips, stumps, branches, tops) and pre-commercial thinnings, while secondary residues are residues from wood processing and other related industries. Stemwood is roundwood felled and extracted for energy—usually of lower quality than industrial roundwood (Camia et al., 2021). The stemwood also includes wood from coppice, which is typical for fuelwood in Europe (Camia et al., 2021).

- i. Current production

It is complex to represent the current production of forestry products for energy. Indeed, the traceability of the production and use of woody bioenergy is not optimal. There is a lack of clear and complete datasets, which can be explained by a primarily decentralised production and a use mainly for residential heating (Camia et al., 2021). When it comes to industrial uses, the data are usually more accessible and more coherent (Camia et al., 2021). However, by crossing different databases of woody biomass production and uses, the composition of the current production of forestry products for bioenergy can be estimated (Fig. 2). The total figure for current production is estimated from Eurostat energy balance data: indigenous production of *fuelwood, wood residues and byproducts* (around 11 TWh in 2019) (Fig. 2). The stemwood is derived from the FAOSTAT database—*wood fuel* from the *roundwood* category. The primary residues are estimated with the data from BiomassFlow, where all the primary wood going to energy is detailed. From this figure, the amount of stemwood estimated from FAOSTAT has been removed, and this gives thus the estimates for primary residues. Secondary residues are directly given by the BiomassFlow data which leaves a gap in the data: the gap between Eurostat data and the data for energy use in BiomassFlow. This quantity matches the category labelled ‘unreported uses’ of the BiomassFlow database. Most of the time, these unreported uses can be attributed to energy uses as the data are more complex to trace and compile than industrial activity (solid wood products or wood pulp) (Camia et al., 2021). However, the composition of this unreported primary woody energy use is still unclear, but it is most likely mainly roundwood, as it is generally the case at the EU scale (Camia et al., 2021).

In order to estimate the composition of this unreported category, S2BIOM 2012 data were analysed (Dees et al., 2017). It was shown that the logging residues extracted from the forest usually represent around 10% of the final fellings and thinnings in Belgium. Therefore, by looking at the total roundwood removals of FAOSTAT and applying this 10% ratio, the current primary residues in Belgium should reach around 1–1.2 TWh while they are around 2.7 TWh, according to BiomassFlow. It is, therefore, argued that the FAOSTAT total roundwood is missing some unreported data. Thus, it could be assumed that the majority of the unreported data mentioned by



Fig. 2 Belgian local production of forestry products for energy in 2019 based on different sources: FAOSTAT, BiomassFlow, Eurostat and own methodology (in TWh)



BiomassFlow is composed of primary wood used for energy with 90% stemwood and 10% of primary residues, as in most cases across the EU (Camia et al., 2021). This gives the repartition illustrated in Fig. 2. However, the primary residues represent a higher share (~23%) than the expected ~10% ratio of primary residues compared to all stemwood (material and energy), meaning that the current practices allow higher extraction of primary wood residues than what some EU studies consider with sustainability and technical constraints—already reaching some potential estimates (detailed in Sect. 3.1.2).

From Fig. 2, it can be seen that the roundwood is reaching around 4.6 TWh, i.e. 2.6 times more than FAOSTAT estimates. Yet FAOSTAT data are discussed as incomplete (Camia et al., 2021) and the estimated values are relatively similar since 2000 with only few updates (values are stable since 2011) (Food and Agriculture Organization of the United Nations (FAO). FAOSTAT n.d. 2023). Moreover, the presented estimates of 4.6 TWh make sense when crossing different databases on the use of woody biomass for energy. Indeed, according to Eurostat (European Commission - Eurostat. Statistics | Eurostat n.d. 2023), in Belgium in 2019, 6.5 TWh of solid primary bioenergy was used for residential purposes (i.e. heating). It is assumed that roundwood for energy is mainly used for residential purposes as industries will rather go for secondary residues or primary residues—chips or (imported) wood pellets. The consumption of pellets for residential use was estimated to be 2 TWh according to the Bioenergy Europe pellets report (Gauthier et al., 2021). Therefore, 4.5 TWh of bioenergy (pellet excluded) was used for residential heating. This biomass can be considered to consist mainly of local wood logs as, apart from pellets, there is no significant use of other types of biomass in residential heating. Therefore, this 4.5 TWh matches the proposed estimate of 4.6 TWh for stemwood used for energy purposes (Fig. 2).

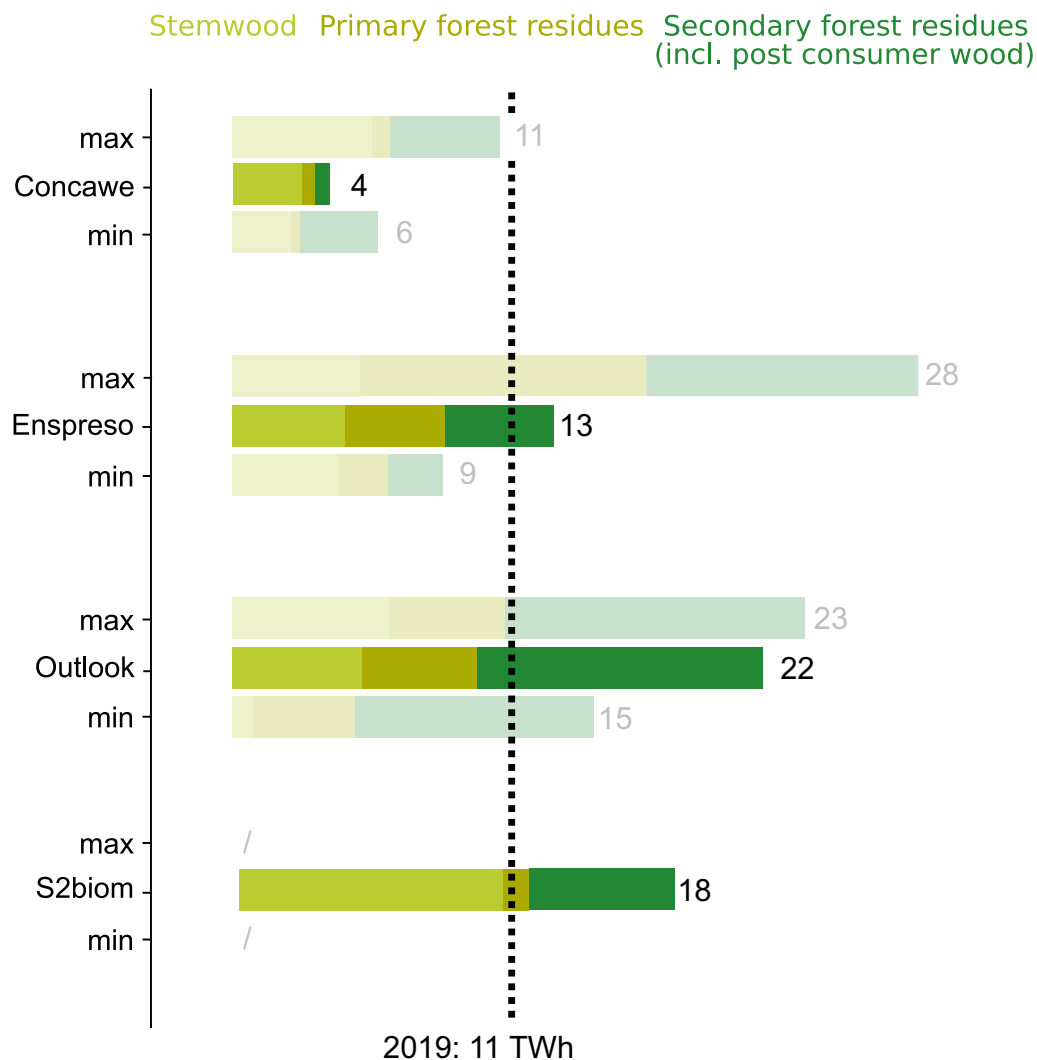
The secondary residues are directly given by the BiomassFlow data, around 3.1 TWh. When cross-checking with FAOSTAT data and applying the 50% ratio (usually considered for residues versus lumber in the sawmill) (Sgarbossa et al., 2020), the results represent between 3.2 TWh and 4.3 TWh of industrial residues currently available. The order of magnitude is comparable to the current use of secondary residues, which means that there may be room to increase the use of currently available secondary residues, but it will not be a game changer if wood extraction for material remains similar. However, if the wood extracted for lumber is exported for the sawmill process abroad, the residues are lost with this export. Therefore, the local wood industry structure has a strong influence on the availability of secondary residues. According to BiomassFlow data (Gurría et al., 2022),

there is no post-consumer wood (tertiary residues) used for energy production in Belgium today, yet this flow goes back into the material industry, which generates byproducts used in energy.

## ii. Potential

From the considered studies, the different estimates for forestry products are compared (Fig. 3). In general, the total potential is estimated to be around 10 TWh, with some higher estimates (> 20 TWh) and the minimal being around 4 TWh. The key assumptions are (i) the competing use for stemwood and residues, (ii) the sustainability constraints and (iii) the wood demand. S2BIOM, in their reference scenario, used the EFISCEN model with minimum competing use for stemwood. Therefore, we could assume that their estimate is the upper limit for stemwood: 10.8 TWh if stemwood from thinnings is included or 7.4 TWh without thinnings (i.e. only stemwood from final fellings). When roundwood production for material use is removed, the stemwood production reaches 4.6 TWh, or 5.8 TWh if the pulp, paper and board industry is not considered in the competing uses (Dees et al., 2017). However, with this upper-limit in sight, we can already put some estimates for stemwood in perspective, such as the high scenarios of the different studies. The order of magnitude for stemwood for energy would thus be around 5 TWh as the maximum potential. The low scenario from OUTLOOK presents a very low stemwood contribution. This is because, in this scenario, they assume no evolution with the historical data (i.e. 2010) according to FAOSTAT, which was shown to be incomplete.

The forestry data for the reference CONCAWE scenario are smaller than for the low CONCAWE scenario. After further analysis, this inconsistency remains unexplained. However, they developed their methodology for forestry product potentials based on statistical data and assumptions, while most of the other EU studies (including the three other studies analysed in this work) used the EFISCEN model (Verkerk et al., 2016) to estimate the forestry product potential. This model considers a more complete method (forestry area, age, volume, growth, forestry practices and management—more details are available in Verkerk et al., (2016)) and thus a more precise output. Therefore, the forestry product estimates from studies using the EFISCEN model seem more reliable. The forest area available for wood supply is considered based on historical trends; thus, either a very slight increase in Belgium (the forest area has now stagnated since 2010 (United Nations., 2010)) or a stagnation, considering that any new forest area has a limited impact on the 2030 potential due to the young age of this forest (Dees et al., 2017).



**Fig. 3** Belgian local potential of forestry product for bioenergy in 2030 (in TWh) from the four European studies considered (CONCAWE, ENSPRESO, OUTLOOK and S2BIOM)

The high scenario of ENSPRESO presents the largest value and is considered too optimistic. Indeed, for forest residues, this scenario considers no competing use, while the reference scenario of ENSPRESO considers 60% of competing use. Moreover, no limitation for stump and residue extraction is considered, while for the other scenarios, there are restrictions and lower rates. Thus, it seems that the high scenario from ENSPRESO is very optimistic on the primary residues potential due to generous extraction and competing use assumptions. The OUTLOOK estimates for primary forest residues do not include the competing uses, which makes those numbers optimistic. The low potential scenario from ENSPRESO seems thus the most reasonable in terms of competing uses (55–60% depending on the products) and extraction

rate considerations (stump extraction excluded and low extraction rate), with a potential increase to reach the reference scenario by improving mobilisation of residues (from 2 to 4 TWh).

Secondary residues are residues from the wood industry (sawdust and other wood residues), black liquor from the paper industry, and post-consumer wood, also known as tertiary biomass. The wood residues from industries can be estimated if we assume that 50% of the stemwood going to the industry will end up as a residue (Imperial College London, 2021). The estimated potential of secondary residues in the form of sawdust or equivalent is, therefore, around 2 to 4 TWh—if final fellings are used for material use and residues from the sawmill (sawdust and other residues) from S2BIOM are considered. If one

utilises historical data on industrial roundwood from FAOSTAT and applies this 50% ratio, it gives a theoretical potential of around 3–4TWh of sawdust technically already available today. The OUTLOOK scenarios and the high ENSPRESO scenario are much more optimistic due to increased forest production, increased related wood processing activities and smaller competing use considerations, e.g. in ENSPRESO high scenario: 0% of competing use for secondary residues (while from 60 to 80% of competing use is considered for reference and low scenarios). For the black liquor and the other industrial wood residues, those potentials are mainly related to industrial development and are assessed considering historical data and trends in the different studies. The post-consumer wood (PCW) is based on EFSOS-II studies where they develop scenarios for PCW following historical trends with increasing potential from around 50 Mm<sup>3</sup> to nearly 70 Mm<sup>3</sup> for EU28. S2BIOM has the more precise figures for those categories and estimates PCW up to 2 TWh in Belgium in 2030, considering competing use and recycling. In total, the secondary residues thus have a realistic potential of around 4 TWh to 6 TWh.

Additionally, landscape care wood could be added to this forestry products category even though it is not considered in all studies. For ENSPRESO and OUTLOOK, this feedstock has a potential from 0.7 TWh to 2 TWh. The estimate rises to 4 TWh in the high ENSPRESO scenario. The specific assumptions are not developed in the study, but as for the other sub-categories for this scenario ‘high’, the assumptions are, in general, too optimistic; thus, we preferred to exclude this estimate.

iii. Conclusion on the forestry product potential.

In summary, the realistic potential for forestry biomass is presented in Table 2. When comparing the discussed potential illustrated in Table 2 with the current use of forestry products for bioenergy, we can conclude that there is little margin for an increase in the woody biomass for bioenergy in Belgium. The main part of the increase could come from secondary residues. The stemwood and primary residues are indeed already well exploited for bioenergy in Belgium. The forest stock is slightly increasing in total in Belgium, but the country

presents a high share of fellings when compared to net increment (> 90%—higher than the EU mean), meaning that Belgium is already exploiting nearly to its full potential its forest ecosystem and the forest area is stable when compared with 2010 (and minimal increase when compared with 1990) (Europe, 2022a; PanoraBois Wallonie, 2021). Thus, there is no significant increase potential in primary forestry products. However, primary residues could slightly increase to reach 4 TWh by improving mobilisation and increasing extraction as developed in the reference scenarios of ENSPRESO. For the secondary residues, the increase could come from the sawdust of wood processing and by rising the post-consumer wood recovery and energy use in industries, for example. More transparency on forestry for energy data is required to validate the stemwood for energy use to ensure that the full potential (~5 TWh) is indeed already exploited or that an increase is possible.

Agricultural residues

This category includes byproducts from agriculture and livestock, such as straw manure, but also pruning. Those products depend on specific dynamics related to their main products and competing uses in agriculture (for fertilisation, for example).

i. Current use

Based on data from Eurostat for biogas production from anaerobic fermentation (for residues from arable crops and other residues) and statistics from the European Biogas Association (EBA) stating that 35% of the biogas from anaerobic digestion in Belgium is from manure (Europe, 2022b), we could retrieve the current production of agricultural residues with the three different categories (Fig. 4). Here, other residues refer to the Eurostat category *animal waste* used dry as fuel (not for digestion).

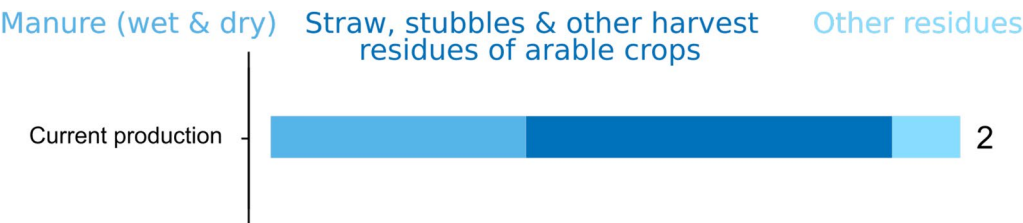
ii. Potential

The potentials retrieved from the considered studies are illustrated in Fig. 5. The highest estimates in this category are the CONCAWE scenarios, where even the low scenario results in a total potential of around 19 TWh. However, this low scenario is the lowest overall estimate (reaching around 30 TWh)—mainly composed of agricultural residues (Fig. 1). The removal rate of field residues (40%) and prunings for energy (50%) is higher than for ENSPRESO. The category is mainly composed of manure (~10 TWh) and cereal straw (~5 TWh). For the manure, this estimate is less conservative than the low ENSPRESO scenario, while the same methods are used based on similar models (i.e. CAPRI (Britz & Witzke, 2014) and Miterra model (Oenema et al., 2009).

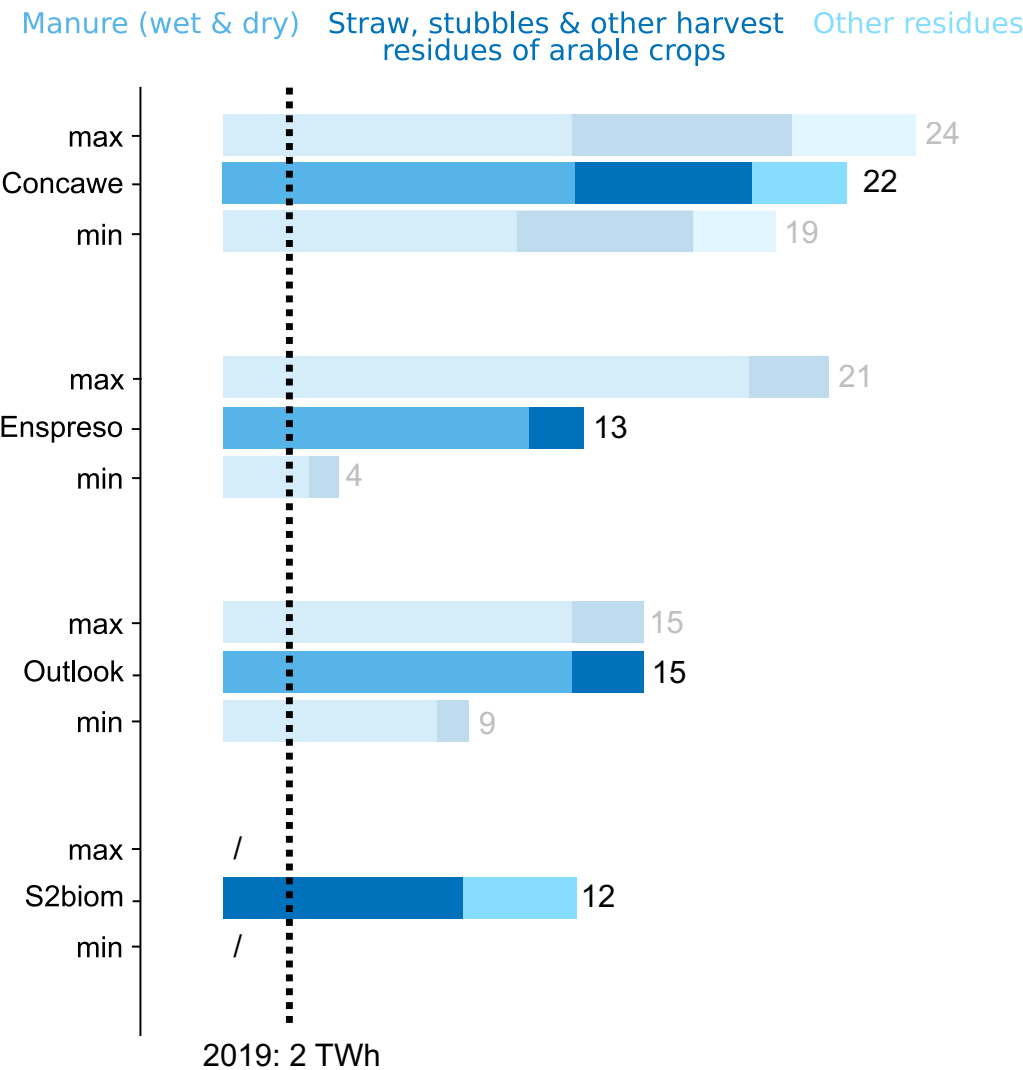
**Table 2** Final estimates for the Belgian forestry product potential for bioenergy in 2030 (in TWh)

|                     |         |
|---------------------|---------|
| Stemwood            | ~5      |
| Primary residues    | 2–4     |
| Secondary residues  | 4–6     |
| Landscape care wood | 0.7–2   |
| Total               | 11.7–17 |





**Fig. 4** Belgian local production of agricultural residues for energy in 2019 based on different sources: Eurostat, Bioenergy Europe, EBA and own methodology (in TWh)



**Fig. 5** Belgian local potential of agricultural residues for bioenergy in 2030 (in TWh) in the four reference studies (CONCAWE, ENSPRESO, OUTLOOK and S2BIOM). Note: S2BIOM only studies lignocellulosic material; thus, manure is not part of their estimates

The divergences lie in the assumptions on the inputs: in CONCAWE, all farms with at least 200 livestock units (LSU) are considered for the collection of manure for energy purposes compared with 500 for the ENSPRESO. Additionally, 75% of competing use is considered for dry manure in the low ENSPRESO, while 50% is considered in CONCAWE. This different competing use illustrates the partiality of the assumptions, as a reader, we have no

tool to evaluate which scenario is more pragmatic while the two studies seem to disagree on what should be a low scenario for manure potential. And the difference is quite significant as the ENSPRESO low scenario estimates the manure potential to around 3 TWh, i.e. 7 TWh lower than the CONCAWE lowest estimate.

When digging into manure potential, a local study focusing on biogas potential in Belgium estimates that manure could contribute up to 4.4 TWh (Valbiom., 2019). This order of magnitude is perfectly in line with other estimates from the literature, where the authors evaluated the realistic potential of biogas from manure based on livestock composition: 4.5 TWh (Scarlat et al., 2018). For the ENSPRESO, CONCAWE and OUTLOOK estimates, a lower threshold is considered in terms of the size of the farm to be eligible for manure collection (all manure collected for farms of sufficient size). This threshold varies with the scenarios but is fixed to 200 LSU for all the reference scenarios (also for CONCAWE, where the reference scenario has the same threshold as CONCAWE's low scenario but with additional assumptions for higher collection efficiency). 50% of dry manure and all wet manure produced by these farms are considered available for anaerobic digestion. In (Valbiom., 2019), the farm size threshold was not considered, but the collecting ratio was set to 44% for dry manure and 53% for wet manure. This assumption can explain the difference as 93% of pig farms in Belgium are larger than 200 LSU and 67% of pig and cattle farms together (European Commission - Eurostat. Agricultural production - livestock & meat - Statistics Explained n.d, 2023), inducing a large difference in the potential estimates. In (Scarlat et al., 2018), the authors considered the spatial concentration of manure production with different collection radii, collection ratios (depending on the species, the farming system and practices) based on livestock and poultry statistics for the 2009–2013 period. Their methodology seems robust and more sophisticated than that of the EU biomass potential studies. Biogas plant capacity and spatial distribution of feedstock were considered, and the methodology is thus more complete than the threshold of LSU. Therefore, the order of magnitude (4.5 TWh) of the resulting potential is considered more reliable. The total technical potential estimated by Scarlat et al., (2018) reaches around 5.6 TWh, still way smaller than the 10 TWh from EU studies based on the Miterra model results (based on CAPRI data). The different EU studies consider the extrapolation of farm numbers and structure from Eurostat data. Considering available data for Belgium, farms larger than 200 LSU increased by 10% between 2005 and 2010 and +14% between 2010 and 2020. It should be noted that this is mainly

due to a change in the farms structure as the total livestock unit is slightly declining (– 2% between 2010 and 2005). Therefore, larger farms are becoming increasingly important, leading to an increase in the amount of manure that can be collected for anaerobic digestion according to these methodologies. This 10 TWh potential implies larger farms which may raise the question of the sustainability and social impacts (e.g. meat and dairy consumption, fewer farmers, larger farms). In this study it is thus argued that a reliable potential estimate for manure is around 5 TWh, and up to 6 TWh if the harvesting ratio is increased.

For residues from arable crops, the S2BIOM estimate is very high. It is mainly composed of cereal straw (64% of arable crop residues in S2BIOM). The CONCAWE estimates for cereal straw are relatively similar to the ones of S2BIOM (around 5 TWh). CONCAWE is considering competing use (e.g. for animal bedding), while the S2BIOM base scenario does not consider competing use, yet it includes consideration for keeping the organic content of the soil constant. It seems thus that the CONCAWE estimate is too high when considering the methodology and results of S2BIOM. For ENSPRESO estimates, the low scenario considered a strict extraction rate and similar competing use than today; for the high scenarios, the extraction rate is higher and the competing use is reduced to a minimum (between 10 and 20%). Those assumptions seem more accurate and appropriate; we could then consider the reference scenario of ENSPRESO for arable crop residues as reliable potential: 1.9 TWh (extraction rate stabilises at the current common practices and competing use similar to today).

Other residues are byproducts from agricultural product processing, such as cereal bran, and residues from fruit tree plantations. For ENSPRESO, the prunings from fruit trees are included in the other harvest residues, and the secondary residues from the agricultural process are, for their part, included in the waste category, and it is not possible to distinguish their exact contribution. This example illustrates the complexity of comparing studies with various nomenclature and classification. Those residues, however, play a small role in the overall potential. It seems that CONCAWE is overestimating their potential due to optimistic assumptions in terms of the harvesting/recovery ratio for the residues related to potatoes, sugar beets and cereal brans. Indeed, S2BIOM estimates that 3.7 TWh of cereal bran could be available but without considering any competing use, while they mention that there is a large competing use for animal feed mainly (up to 70%). CONCAWE, on its side, considers only 20% of competing use for those secondary residues, which is probably optimistic. If we consider an arbitrary and conservative 70% of competing use of the CONCAWE

potential, the other agricultural residues could reach between 1 TWh and 1.6 TWh.

iii. Conclusion on agricultural residues potential.

For the agricultural residues, the potential for increase of residues from arable crops is relatively small compared with current production (around 1.2 TWh), the major increase could be covered by manure (Table 3). Indeed, a significant expansion may arise from a 5- to sixfold surge in manure production, but this hinges on substantial assumptions regarding the evolution of the agricultural sector and the recovery of manure. Here, all the studies are based on perspectives founded on historical trends, i.e. no major change is expected in the landscape, but the size of farms is becoming larger. However, other scenarios could exist, for example, if Belgium decides to produce more food for local use (diversify the production) with different agricultural practices and land allocation and reduce intense breeding for more extensive practices (decreasing the manure easily harvestable for biogas). The agricultural residues category clearly shows that the final figures imply a specific vision and development of the agricultural sector, which is not neutral in the transition and should be discussed carefully to ensure sustainable systems for energy and food production.

Energy crops

Energy crops are all the crops with energy as primary end-use. They can be of different sorts (sugar-rich, oil-rich, starch-rich or lignocellulosic) with different characteristics for cultivation and transformation. Some might require fertilisation and/or irrigation, while others are less demanding of inputs (e.g. miscanthus)

**Table 3** Final estimates for the Belgian potential of agricultural residues for bioenergy in 2030 (in TWh)

|                                                            |       |
|------------------------------------------------------------|-------|
| Manure (dry and wet)                                       | 5–6   |
| Straw, stubbles and other harvest residues of arable crops | ~ 2   |
| Other residues                                             | 1–1.6 |
| Total                                                      | 8–9.6 |

(Hillier et al., 2009), inducing different implications for the agricultural system. Another important factor for the energy crops category is the land allocation and assumptions. While some consider energy crops on any available land, others prefer to limit them to the so-called marginal lands to reduce land competition with food production (Haberzettl et al., 2021). It raises sensitive and ethical issues of land allocation and related interactions with our ecosystems, which are useful to keep in mind for a broader perspective (Gamborg et al., 2012).

i. Current production

Estimating the current production is not straightforward as the Eurostat data for biogasoline and biodiesel includes fuels produced in Belgium as well as imported feedstock and is thus a wrong indicator for local potential. In Belgium, around 3 TWh of biogasoline (from sugar–starch crops) and around 2.4 TWh of biodiesel (from oil crops) were produced in 2019, according to the Eurostat database (European Commission - Eurostat. Statistics | Eurostat n.d, 2023). The share from local feedstock need to be estimated in order to evaluate local production of energy crops. A study from Sia Partners (Partners, 2020) documented the origins of the feedstock used for the Belgian production of bioethanol and biodiesel, where 31% of the production of bioethanol is from local feedstock (mainly wheat), and only 3% of biodiesel production is from local feedstock (used cooking oil and rapeseed). The current local production can, therefore, be estimated at around 1 TWh (Fig. 6). Currently, the production of lignocellulosic crops is negligible in Belgium—around 355 hectares of culture, i.e. less than 30 GWh with optimistic yield and conversion assumptions (Europe, 2019).

ii. Potential of energy crops

Energy crops keep a relatively low share of the potential for Belgium except in the ENSPRESO estimates (Fig. 1). While energy crops are seen as a major option to increase bioenergy potential on an international



**Fig. 6** Belgian local production of energy crops in 2019 based on different sources: Eurostat, Sia Partners (Partners, 2020) and own methodology (in TWh)

scale, it seems that they are less relevant for Belgium. This can be explained by the population density of the country and, thus, the competition for land-use allocation.

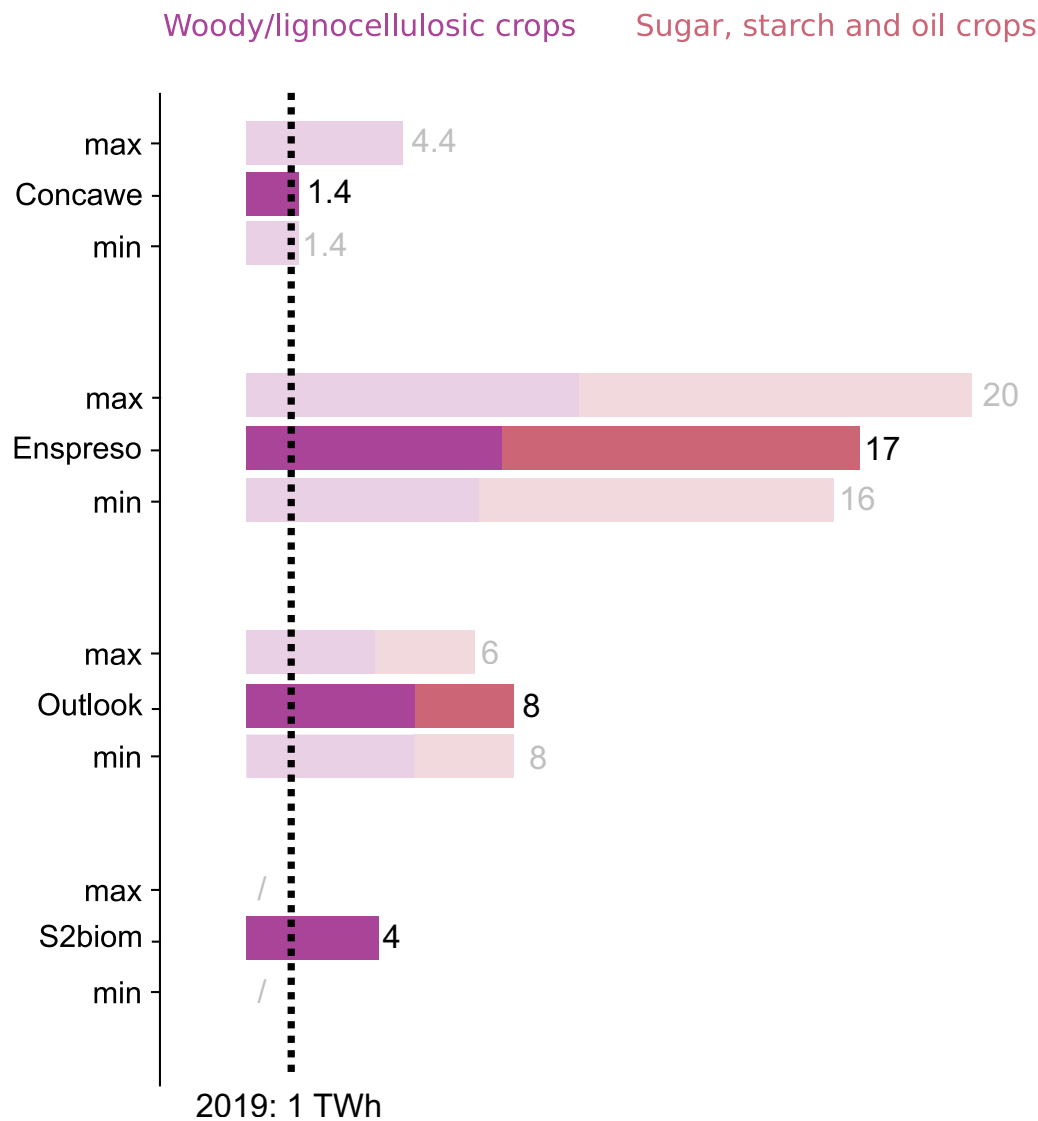
In the ENSPRESO scenarios, arable land is considered for first-generation energy crops with competition for feed and food production based on the CAPRI model results. Moreover, irrigation for those cultures is considered for the reference and high scenarios, which might be problematic knowing the water management issues and the risk of drought due to climate change in the different Belgian regions (Jones et al., 2003). The energy crops category in ENSPRESO low scenario is composed of 52% bioethanol sugar beet and this number evolves only very slightly from low to high scenario (from 8.6 to 9.4 TWh) due to an additional 10% of land area dedicated to energy crops. 27% of the energy crops are grassy crops (e.g. miscanthus), which is relatively high. However, more surprisingly, the contribution of those crops drops in 2050 compared to the 2030 estimates (from up to 7 TWh in 2030 to a maximum of 1 TWh in 2050), with no further explanation. This drop is not observed for bioethanol estimates—based on the results from the CAPRI baseline scenario (Britz, 2004) which considers historical trends (production and demand). In Belgium, bioethanol production from sugar beets has been increasing in the last decades (Britz, 2004), and forecasted demand was initially high based on the European projection published in 2013 (Commission, 2013). However, this trend will most likely stop in the coming years. Indeed in 2015, the EU parliament put a cap on the first-generation biofuel use for mobility: *“a 7% cap for first-generation biofuels that could be included in 10% renewable energy target for the transport sector by 2020, with a possibility for member states to set a lower cap”* (Erbach, 2022). This cap was revised downwards to 3.8% for 2030 by the European Commission (Parliament, 2009). Given this new policy based on land-use competition and its impact on food security, the significant contribution of bioethanol expected in ENSPRESO does not seem relevant anymore. For the grassy energy crops, it is also a result taken from CAPRI, but the demand is exogenously fixed and assumes no land competition. In ENSPRESO, the results are cross-checked with the land availability based on released land according to CAPRI results (Ruiz et al., 2015). The drop in grassy crops can thus be explained by a lower exogenous demand or a limitation of land availability in their considerations. Note that those estimations for grassy crops would require between 2 and 3.2% of Belgian territory (considering miscanthus with a yield of 17t/ha and 4.45MWh/t), while sustainable marginal lands cover only 0.7% according to the data from Vera et al., (2021) as discussed in Colla et al. (2023). Thus, ENSPRESO estimates

for energy crops are more optimistic than those of other studies (Fig. 7) and the assumptions in terms of practices and land allocations appear to be too generous.

The OUTLOOK scenarios also present first-generation energy crops but in a limited amount because they applied an availability factor limiting the land dedicated to energy crops from 3 to 10% of arable lands depending on the scenarios (with irrigation limited or excluded). The high scenario of OUTLOOK presents smaller potential due to stricter assumptions regarding land availability (higher share of fallowing required) and irrigation (totally excluded for energy crops). In their study, the high scenario does not necessarily mean less conservative in terms of sustainability but instead additional support for increasing biomass mobilisation (efficiency, yield, etc.). S2BIOM also considered lands no longer used for agriculture based on the CAPRI model with additional filters based on European directives for nature and biodiversity protection. Afterwards, the crop suitability for the land available is evaluated. They estimate a potential of around 3.7 TWh. Finally, CONCAWE only considers marginal lands (unused, degraded and abandoned lands) with nature and biodiversity protection constraints. A share of availability is applied on those lands, from 25 to 75%. The low and reference potentials are similar in Belgium with no given explanation, while the high scenario is precisely three times the low potential, reaching 4.4 TWh. The order of magnitude of energy crops on lands with limited competing use seems thus to be between 1.5 and 4.4 TWh. Their low estimates match the order of magnitude of Colla et al. (2023). In (Colla et al., 2023), the authors estimated the potential of miscanthus grown on Belgian marginal lands (with sustainability criteria and a yield threshold) at 1.4 TWh. With those considerations, we could re-estimate the energy crop contribution to the order of magnitude of 1.5 TWh if only sustainable marginal lands are considered and an additional 1 TWh–2 TWh if arable land is used for energy crops (e.g. starchy, sugar, grassy or oil energy crops). In (Valbiom., 2019), they studied the potential of biomethane production with intermediate energy crops and grass making a significant contribution (~5TWh). It is an interesting option that limits the land-use competition and could also contribute to enhancing soil quality. Those specific energy crops are not included in the studies considered here and could thus be a missed potential. This category deserves a specific study to evaluate its implications in terms of competition for feedstock and land use.

### iii. Conclusion for energy crops

The prospects for the contribution of energy crops for bioenergy in 2030 are summarised in Table 4. The order of magnitude of lignocellulosic crops on marginal



**Fig. 7** Belgian local potential of energy crops for 2030 (in TWh) in the four reference studies (CONCAWE, ENSPRESO, OUTLOOK and S2BIOM)

**Table 4** Final estimates for the Belgian energy crops potential for bioenergy in 2030 (in TWh)

|                             |         |
|-----------------------------|---------|
| Lignocellulosic crops       | ~ 1.4   |
| Sugar, starch and oil crops | 1–2     |
| Total                       | 2.4–3.4 |

lands is around 1.4 TWh. Additionally, if energy crops on arable lands are allowed, based on the potential studies and current production, the order of magnitude of those crops seems to be around 1 TWh -2 TWh (to avoid a significant impact on land competition and sustainability). It gives a total potential of around 3.4 TWh of energy crops. Nevertheless, it is complex to estimate

precisely. Indeed, it depends on many aspects, notably the evolution of agriculture structure and the food and feed market, and on the way the Belgian arable lands are allocated depending on the production objective: to promote local food consumption or to promote economic competitiveness on the global market. In general, a conservative approach in favour of sustainability entails the viewpoint that no arable land should be utilised for the production of biofuels, thus restricting the energy crops on marginal lands, i.e. mostly lignocellulosic crops. However, it can be nuanced by the land allocation strategy, agricultural practices and pragmatic considerations that if all arable lands are not needed for food or feed while the renewable energy demand



remains unfulfilled, biofuel can be a viable option. However, this is provided that the greenhouse gas effect of the biofuel actually allows it to have positive impacts on the energy transition (Benoist et al., 2012). Intermediate energy crops could have a positive impact on the potential, yet they are not part of the standard estimates and should be further studied.

### Other waste

This category includes the waste from households, industries and collectivities. This group is correlated to population and waste collection and treatment in place. The logistics for the mobilisation of those wastes can be costly due to their disparity and high moisture content, depending on their exact nature.

#### i. Current production of other waste.

The current production is directly extracted from Eurostat data (Fig. 8). Belgium is already using a significant part of the waste potential and has good practices in waste management when compared with other European countries. The sludge is usually burned for energy in Belgium and, therefore, is not reported in the category sewage sludge gas from Eurostat. When checking the Walloon statistics of sewage sludge valorisation (SPW, 2022) and converting it into energy, it gives only a few tens of gigawatt hours of sewage sludge valorised in energy through combustion. Hence, we can assume that it is negligible also at the Belgian scale and probably included in the renewable waste (municipal or industrial) as the sewage sludge gas referred precisely to gas produced from anaerobic digestion. According to Elbersen et al., (2016), 45% of the sludges (household and industrial) are used for energy (combustion mainly), while the rest is mainly used in agriculture.

#### ii. Potential of other waste

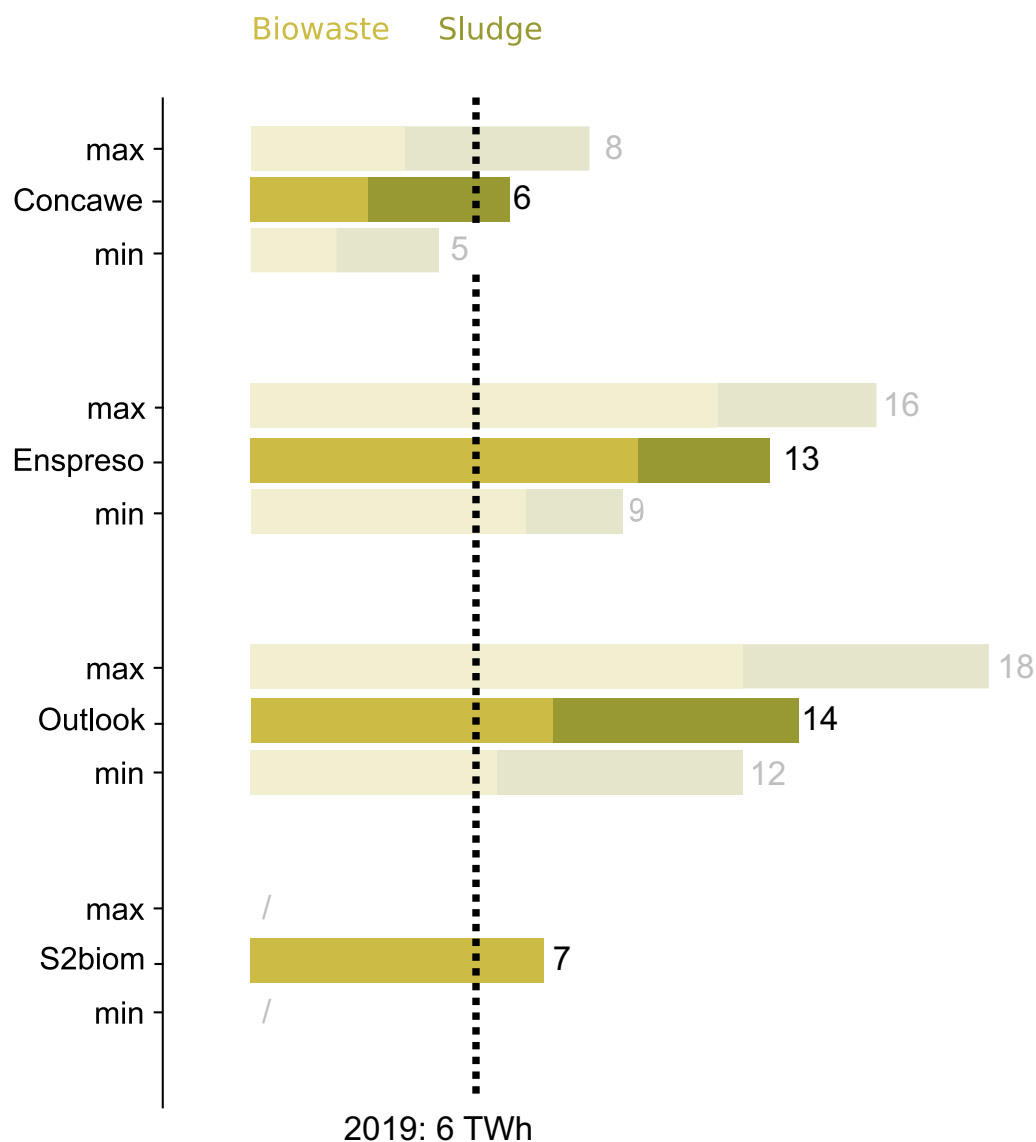
The other waste potential categories are illustrated in Fig. 9 and are gathered in two groups: sludge and bio-waste (which includes all waste from organic matters, i.e. municipal, industrial and public greens). S2BIOM does not include sludge as the study is focusing on

lignocellulosic feedstock. The impacting factors here are the recycling quota (competing use), the collection ratio and the population development (for renewable municipal waste). The level of detail is different among the studies, but the aggregation for biowaste are of the same order of magnitude, at least for the low potential scenarios at around 6–7 TWh, except for CONCAWE. CONCAWE assumed a larger share of recycling municipal waste (60%) based on the EU Circular Economy Package (Commission, 2021; Delvigne et al., 2015), reducing the available feedstock. In practice, this share might apply more particularly to the non-renewable share of municipal waste rather than to the renewable part. This reasoning can explain why their estimate is significantly lower than the others for the biowaste. The high scenario from the OUTLOOK study considers the considerable potential of vegetal waste (household and business activities) as available for energy production with anaerobic digestion that allows the combined production of energy and valuable digestate. In a similar way, the ENSPRESO high scenario considers a better collecting ratio for the different feedstocks (e.g. public greens or roadside verges) and a high share valorised in energy.

For the sewage sludge, the different estimates are around the same order of magnitude from 2.5 to 4 TWh. ENSPRESO's low scenario for sludge (2.5 TWh) is considering potential with current recycling quotas and competing use while in their high scenario (4 TWh) all sludges are used for energy (the reference scenario is in between). OUTLOOK study mentions that it considers regional data to include competing uses and recycle rates in order to remove them from the potential in the case of Belgium. Still, their estimate is higher than the others: ~6 TWh. Their estimates rely on the assumption that 60% of total sludge is organic, while they mention this assumption could be too high for some cases, explaining the higher estimates. For ENSPRESO scenarios, the precise method for sludge is not detailed, yet Belgium shows a high potentials for this category among EU countries. This is related to the wastewater treatment process, collecting ratio and historical trends. Historically, Belgium has a large production of common sludge among EU countries (Delvigne et al., 2015). This is due to municipal



**Fig. 8** Belgian local production of other waste for energy based on Eurostat (in TWh)



**Fig. 9** Belgian local potential of other waste for bioenergy in 2030 (in TWh) in the four reference studies (CONCAWE, ENSPRESO, OUTLOOK and S2BIOM)

**Table 5** Final estimates for the Belgian other waste for bioenergy (in TWh)

|          |        |
|----------|--------|
| Biowaste | 6–7    |
| Sludge   | 2.5–4  |
| Total    | 8.5–11 |

sewerage water but also from organic sludges from industries such as food, pulp and paper.

iii. Conclusion for other waste

It seems that a significant increase is possible in the energetic valorisation of common sludge (Table 5), while for

the other biowaste, the potential increase is more limited as Belgium is already using a large part of its waste. Still, the collecting ratio could increase for some vegetable waste for anaerobic digestion to increase further the biowaste contribution. However, this represents a logistic challenge for the collection process. Moreover, the competing use for organic waste might increase in the future in the context of the bio-economy (i.e. increases of molecules and material from organic and renewable sources).

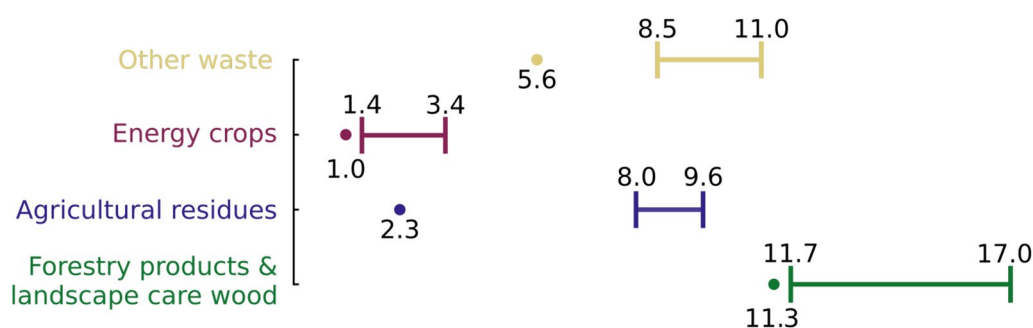
### Summary and convergence towards a realistic potential for Belgium

In conclusion, according to our analysis, Belgium's complete realistic potential is situated in the lower-ranged scenarios described in the different analysed studies, namely between 30 and 41 TWh (Fig. 10). This range indicates still an increase in the total potential compared to the one in 2019, which was 20.2 TWh. Our detailed estimates for each resource category differ from all studied scenarios. However, if one had to choose a single study as the source of data, the reference scenario from ENSPRESO could be considered an excellent but optimistic compromise for most biomass categories. It still presents too generous assumptions in terms of collection of primary forestry residues, manure and (mostly) energy crops. For the energy crops category, the estimates are out of the realistic range, according to our discussion, due to over-optimistic assumptions for land allocations and agricultural practices. According to the analysis of this work, energy crops in Belgium are only a tiny part of the potential, while the central part is from forestry products. Comparing our final potential estimates with the current production, local bioenergy could increase by 50% to 100% in Belgium. In practice, the forestry potential is already well exploited except for the secondary residues. The prominent increase could come from energy valorisation of manure and sludge. However, it requires implementation for collecting and valorising that feedstock. Biogas could be produced from these resources; it is an interesting fuel to handle (for heat, electricity or upgrading to biomethane for grid injection) and the byproduct (digestate) is still valuable (e.g. for agriculture inputs). The large potential from manure valorisation assumes that Belgium will keep the same agricultural landscape with important livestock production and that the farms will increase in size, easing the manure collection and valorisation. This point is arguable and depends on the vision of national agriculture, as meat and dairy

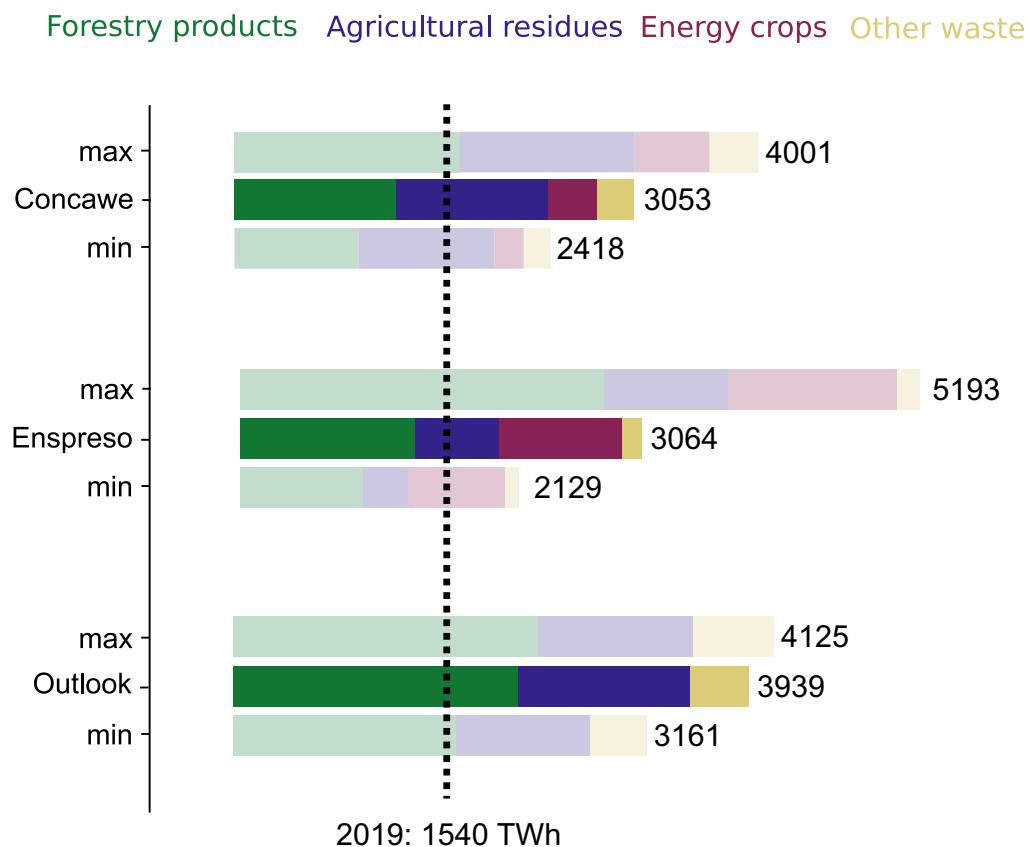
consumption might need to decrease in time to mitigate climate change and biodiversity loss (Commission, 2021; Stoll-Kleemann & Schmidt, 2017). This topic was under the spotlight in 2023 with the revision of the EU Industrial Emissions Directive which aims at reducing the nitrogen pollution and would tend in practice to decrease the number of livestock in some regions (for example in Flanders and the Netherlands) (Haahr, 2024; JRC, 2024). It also depends on the broader vision for Belgian agriculture in the future, for example, focusing on increasing its auto-consumption ratio or adapting itself to the global food market to ensure competitiveness (CEreAl. Plan d'action vers plus de résilience., 2022; Les Greniers d'Abondance, 2020). This illustrates the debatable aspect of bioenergy potential studies due to its structural implications for society. This discussion shows that bioenergy potential estimates depend on political visions for the key sectors (waste, forestry and agriculture). Indeed, it induces specific management and considerations at the national scale to ensure reaching a given potential. The current discussions about the potential of bioenergy could, therefore, be an opportunity to re-open the political debates about an integrated management of our environmental resources. It might be the opportunity to re-think our vision of forestry and agriculture to anchor the biomass potential in a sustainable vision of human and non-human interactions to overcome the human-nature dualism in order to ensure a sustainable future (Heikkurinen et al., 2021).

### Implications for European potential

From this national perspective, the convergences and divergences of the different studies have been highlighted, offering valuable insights for analysing the EU's potential. Figure 11 illustrates the different potentials. S2BIOM was not included because of the different scope of feedstock (only lignocellulosic) for the general analysis. Discrepancies in the level of detail across studies at the European



**Fig. 10** Final estimates of main bioenergy category potential for 2030 (ranges) and 2019 local production (dot) in Belgium in TWh. The total potential is then from 30 to 41 TWh compared with 20.2 TWh in 2019



**Fig. 11** EU27+UK bioenergy potential in 2030 (in TWh) in three reference studies (CONCAWE, ENSPRESO, OUTLOOK). Note: The OUTLOOK study does not give the European details for energy crops, which are included in the agricultural categories, and therefore considered as agricultural residues in this study. This makes one-to-one comparisons between studies difficult

scale pose challenges for comprehensive comparisons. For instance, the OUTLOOK study does not give European details for energy crops, which are included in the agricultural categories, and therefore considered as agricultural residues in this study. This makes one-to-one comparisons between studies difficult for energy crops. As shown for Belgium, the ENSPRESO high scenario is too optimistic and can be qualified as unrealistic.

Forestry products are the main feedstock of the European potential. CONCAWE scenarios at the European level compares to the Belgian estimates in a different way than the other scenarios, especially for forestry products. This is due to the fact that they have a distinct methodology with improved mobilisation for the countries having a large biomass potential and/or a cheap biomass cost, which is not the case for Belgium. The OUTLOOK scenarios are very optimistic due to low or no competing uses considered. As discussed for Belgium, the order of magnitude of the reference scenario from ENSPRESO seems correct but a bit optimistic about primary residues. In the case of the EU, it matches with the estimates of CONCAWE which is

around 1300 TWh. In this estimate, both studies agree that stemwood would cover between 40 and 46% of the potential, while the rest is from primary and secondary residues with different repartitions depending on the assumptions of harvesting ratio and competing uses.

For the agricultural residues, the CONCAWE scenarios present high estimates, similar to the Belgian case study. Indeed, those estimates are of the same order of magnitude as OUTLOOK scenarios in which energy crops are accounted for in this category. The reference scenario from ENSPRESO is more appropriate, as in the Belgian case study, with a potential of around 650 TWh. Around half of this potential comes from manure and the other half from solid agricultural waste (e.g. straw and stubbles with an extraction rate of 30% and competing uses considered at 50%). However, as discussed for Belgium, the manure estimates might be too optimistic considering the farm structure assumed (increasing number of large farms) and the collecting ratio (50% for dry manure and 100% from all farms with more than 200 livestock units for wet manure). If

the low scenario from ENSPRESO is considered for the manure, the potential is around 450 TWh.

Energy crops are difficult to compare as OUTLOOK scenarios do not allow their distinction. However, the high estimates from ENSPRESO can be regarded as very optimistic. Thus, other estimates near this number can also be disqualified, i.e. the high scenario from CONCAWE and the reference from ENSPRESO scenario, as discussed for Belgium. Given the conclusions drawn for energy crops, we argue that it is more realistic to consider CONCAWE's lower estimates, i.e. a potential between 225 and 372 TWh with crops only on 25% or 50% of the marginal lands.

The other waste potential highly depends on each national situation and policy in terms of waste management and population development. OUTLOOK was discussed as optimistic in terms of the organic waste ratio in the statistics. It was shown that, for Belgium, the order of magnitude of the low and reference scenarios of ENSPRESO were realistic. This corresponds to a European potential of around 100 TWh–150 TWh, depending on the waste generation trends, the recycling ratio and the evolution of water treatment (and related sludge production and uses).

In total, the realistic potential for EU27+UK in 2030 is around 2000 TWh–2500 TWh, which is in the lower range of the different estimates (Fig. 11). When comparing with current bioenergy production (~1540 TWh produced in 2019 in EU27+UK), it means an increase between 30 and 62% (European Commission - Eurostat. Statistics | Eurostat n.d, 2023). Forestry products are already well exploited, but a slight increase of around 15% to 20% is possible. The main increase could come from agricultural residues, as in the Belgian case study. Nevertheless, as highlighted in the previous discussion, increasing the contribution of agricultural residue implies specific collecting practices and the related assumptions on the farm's structure.

This paper then showed that the EU studies and estimates need to be analysed carefully as some rely on basic and straight methodology and/or assumptions that can lead to inaccurate potential assessments, or that can have strong impacts beyond the energy sector (e.g. biodiversity, agricultural structure, forestry management and landscape, waste generation and treatment). The estimates of some of the key parameters, while having a large impact on the assessed potential, partially rely on arbitrary and strong assumptions, e.g. the land area available for energy crops, the 1% annual yield increase for lignocellulosic crops in the high potential scenario in ENSPRESO, the waste generation and competing use estimates, or the manure production and harvesting rate expectations. Additionally, it is important to keep in mind

that these are the potentials that could be available provided that the required efforts are put in place. Assessing the specific economic viability of each feedstock is complex as it is dependent on the market conditions and the relevant policies. Furthermore, the economic viability depends on the specific value chain of each biomass resource. For some feedstocks, the supply chains are already (at least partially) in place and the market values are known (e.g. sawdust from wood industries) while for other feedstocks, such as some lignocellulosic crops, the supply chain still needs to be designed and implemented, leading to uncertain market prices. The challenges for the actual development of the various feedstocks are thus not to be neglected (on different aspects such as logistic, administrative, social and environmental) and should be considered carefully by policy makers in order to ensure consistent and sustainable development of bioenergy.

## Conclusion and general perspectives for bioenergy potential

In this study, different bioenergy potential estimates for 2030 from EU studies were discussed, with national details. This paper presents an in-depth example of Belgium; a similar methodology can be replicated for other countries. It was shown that the range of estimates of those studies is large (30–90 TWh for Belgium) and relies on many assumptions with strong implications for the agricultural, forestry and waste sectors. A realistic range of potential is derived from this work by analysing the different sub-categories, the current production and comparing with some specific studies (for a given feedstock or region), for the cases of Belgium and Europe: 30–41 TWh and 2000 TWh–2500 TWh, respectively. This range is based on current forestry and agricultural management, a conservative approach for sustainability criteria and competing uses, and also on coherent development in relation to the current bioenergy production. Our final potential matches the final estimates of some EU studies scenarios, but the internal composition is different. However, the reference scenario from ENSPRESO could seem like a good compromise for most feedstocks (energy crops excluded)—still with optimistic assumptions, mainly in terms of collection assumptions for primary forestry residues and manure. For the energy crops category, the estimates are out of the realistic range, according to our discussion. This work highlights the importance of analysing and discussing the bioenergy potential estimates in order to determine a realistic potential. The results of such analysis are crucial to energy planning and to have a clear understanding of the implications in terms of forestry, agriculture and waste management. It was highlighted that bioenergy potential estimates depend on political visions as they imply



specific systems which have broader implications, such as the diet or the agricultural practices (e.g. small farms with significant manual work or large farms with large mechanisation). It is of paramount importance to keep that in mind when working on energy system modelling as this has further implications in terms of implementations and externalities (e.g. social or environmental). This work calls for more transparent discussions on those implications to broaden the considerations and the perspectives—also related to nature perceptions and their implications for current ecological crises.

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#### Author contributions

M.C.: conceptualization, analyses, writing original draft, K.V.: figures preparation, manuscript revision, J.B. and H.J.: supervisions, analyses and manuscript revision. All authors reviewed the manuscript.

#### Data availability

Data sharing is not applicable to this article as no new data were created in this study. All data are extracted from the mentioned references and presented in the tables of the article.

#### Declarations

#### Competing interests

The authors declare no competing interests.

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