The energy potential of waste- and woody-biomass for fueling cogeneration plants in Belgium

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1 Introduction

Globally, fossil fuels are steadily being phased out in the electricity sector in favour of renewable energy sources, like wind and solar energy, to lower carbon emissions and reduce the impact of climate change. However, as solar and wind are non-dispatchable energy sources, a combination of demand-side management, energy storage, and backup units must be developed. The latter pillar of the energy transition will consist of flexible power plants that can balance production and demand over time. Natural gas-based power generation units currently fulfil this role as they can rapidly start and vary their power production flexibly and on a large scale. So, to attain net zero emissions in the electricity market, we need to develop alternative, renewable and flexible (heat and) power production units. These could include electrofueled or biomass-fired power plants. The commercialization and use of electrofuels produced from renewable (surplus) electricity and safety stored in gaseous or liquid state, like e-methane, e-methanol or hydrogen/ammonia mixtures, in gas turbines are still in progress as electrolytic hydrogen production is still in the early development stage. Nevertheless, several studies have already shown that the power-to-X-to-power process has several advantages for seasonal energy storage and replacing the natural gas-fired power plants, but over the long term [1, 2, 3]. The chemical sector is the first sector to integrate this renewable hydrogen, as they use natural gas to produce hydrogen, emitting CO_2 during the process. Once this renewable hydrogen production is well developed, the energy and transport sector shall adopt these fuels. Units currently running on renewable fuels such as sustainable biogas, biofuels, solid biomass residues and (partly renewable) waste are already available to fulfil this role to a certain extent. Existing assets can be activated, and their operation could be optimised to partly compensate for the gap between the demand fluctuation and the other intermittent renewable power supply. Retrofits of existing assets can also be considered [4], as well as developing new units if the available resources allow it. Therefore, the FLEX-CHP project aims to quantify the potential contribution of biomass- and waste-fired units to the safety of supply and network balance in Belgium while minimizing the impact on the climate and the environment.

To take advantage of these resources most efficiently, Combined Heat and Power (CHP) units can be used to simultaneously provide flexible electricity services to the grid and, at the same time, heat to satisfy local demand (industry or communities). This will reduce our global dependence on natural gas for heat production. CHP systems are highly efficient, often achieving total energy efficiencies of 40% to 70% by utilizing low-quality heat that would otherwise have limited efficiency or even be lost in conventional thermal power plants [4, 5, 6]. This high efficiency means less fuel is required to produce the same energy, lowering operating costs. However, cogeneration also has disadvantages, as installing cogeneration systems can be capital-intensive, which may deter smaller businesses or facilities from adopting the technology. Although long-term savings can offset these costs, the upfront investment remains a significant barrier for new units [7, 8].

To assess the potential contribution of biomass- and waste-fired units to our future flexible energy systems, we first need to quantify the available resources. This report, therefore, aims to estimate the energy potential of waste and biomass in the future energy landscape for cogeneration plants in Belgium. These results will be used as input to determine if the future Belgian electricity market can consist of flexible cogeneration plants. Biomass can only be used to produce renewable energy if the resource is managed in a sustainable way. This must be certified according to the European and regional legislations, and it obviously impacts the availability and the price of the resource [8, 9]. The sustainability criteria also evolve over time towards stricter requirements. Under the Recast Renewable Energy Directive (RED III), the risk of using forest biomass from unsustainable sources is further reduced. Harvesting stumps and roots, degrading primary and old-growth forests or converting them into plantation forests, harvesting vulnerable soils and clear-cutting are typical practices that are restricted by the legislation, among others. However, it must be noted that stricter requirements also come with additional efforts for producers, importers, exporters, and traders to demonstrate compliance.

Although only part of it can be considered biodegradable and, therefore, renewable, using municipal waste for energy production reduces the volume of waste sent to landfills. This philosophy aligns with the European Union's circular economy goals, which promote recycling, repairing, reusing and waste valorization. For example, in 2022, Belgium produced a total of around 62640 kton of waste, where 81.8% originates from the construction and industry sector, while the residual waste originates from the service sector (10%), households (7.7%) and agriculture (0.4%) [10]. A first estimation on the amount of waste that could be valorized from this 62640 kton, i.e. wood, household waste, sorting waste combustion waste, shows that around 11508 kton can not be recycled or reused (18.4%). Although the availability of this resource will need to be reduced in the future, with continued efforts to avoid landfilling, we can still leverage this final option within the circular economy to enhance the flexibility of our energy system. In this report, we first assess historical production and project future potential of renewable biomass (Section 2). Then, we will present the historical municipal waste (i.e. non-renewable) production and estimate the potential energy valorization based on this waste production in the future (Section 3). Finally, we provide a global overview of Belgium's renewable and non-renewable waste energy potential (Section 4).

2 Biomass potential for cogeneration

In the first subsection, we determine which study is used and identify the most attractive biomass sources for cogeneration. Then, in the second subsection, we discuss the potential of these specific biomass sources between the reported historical values and future estimated ones by 2050. In the last subsection, we summarize our findings and estimate the biomass potential for cogeneration in Belgium.

2.1 Identifying biomass sources for cogeneration

To identify the viable potential of biomass in Belgium for fueling cogeneration units, we need to determine which types of fuels are available and produced in Belgium. The study of Colla et al. [11] analyzed different studies that estimate the biomass potential of European countries with various socio-techno-economic and political scenarios. Within the work of Colla et al. four different energy models were identified, namely the ENSPRESO [12], CONCAWE [13], OUTLOOK [14] and S2BIOM [15] models. First, these models estimate a country's theoretical potential where the maximum energy potential can be harvested from a resource following physical constraints, e.g. land availability and characteristics. Then, a technical potential is determined by considering the harvesting efficiency and other physical limitations for obtaining the resource. Afterwards, via the economic potential estimation, including the equipment and operational cost, the studies reveal the part of the technical potential that can be obtained under economically beneficial conditions. Lastly, by implementing a particular set of social, legal or political conditions, we can establish the total sustainable potential of a biomass source through economic and technical beneficial conditions. The referenced studies examined the long-term potential of various biomass energy sources with scenarios for 2030 (some studies for 2050) by varying technical, economic and socio-political conditions. The study of Colla et al. [11] indicated the ENSPRESO study as a suitable model and database to provide an overall better estimation of several biomass sources for Belgium than the other examined studies. However, specific subcategories, like the primary forestry residues, manure and energy crops, include too optimistic scenarios or unrealistic estimations. Still, the study provides realistic estimations on the other biomass categories described by Ruiz et al. [12]. Therefore, we assumed the ENSPRESO study as the base for estimating the biomass potential for Belgium.

The ENSPRESO study considers three main sectors for producing renewable energy via biomass: agriculture, forestry and waste (Figure 1). For the agricultural sector, biomass resources are divided into energy crops, manure, and primary, secondary, and solid agricultural residues. The biomass in the forestry sector is classified into roundwood production, as well as primary and secondary residues. Finally, the waste sector produces bio-energy in the primary and tertiary residues categories [12]. The ENSPRESO documentation shows that the authors have already defined suitable

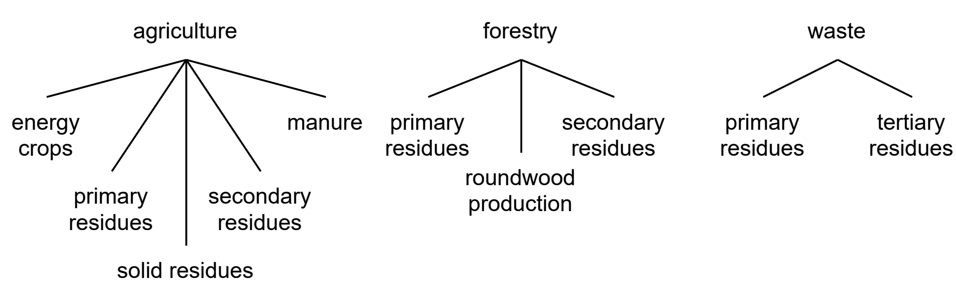

Figure 1: Overview of the three biomass sectors ENSPRESSO considers with their respective subcategories for renewable energy production.

fuels for industrial cogeneration or electricity/heat production purposes as energy end-use. In this documentation, the mass-to-energy conversion (via the mean lower heating value) of each biomass source is described by Ruiz et al. in Annex 5 [12]. The following solid-fuel biomass resources identified by the ENSPRESO study are selected for cogeneration:

Biomass from agriculture (JRC-EU-TIMES code: MINBIOAGRW1)

- Agricultural solid residues: (biomass from pruning, straw/stubble and olive pitting): Residues from agricultural cultivation, harvesting and maintenance activities. Other solid agricultural residues (pruning, orchard residues) include straw and stubbles and biomass from olive pitting.

Biomass from forestry (JRC-EU-TIMES code: MINBIOFRSR1, MINBIOFRSR1a and MINBIOWOOW1)

- Primary forestry residues (logging residues): aggregated fuelwood and chips from primary residues. Forest biomass residues additionally harvestable from forest (top, branches, stumps and early pre-commercial thinnings),
- Primary forestry residues (landscape care): potentials outside agricultural permanent cropland,
- Secondary forestry residues (woodchips): cultivation and harvesting/ logging activities in forests, like branches, roots, and other wooded biomass.

Biomass from biodegradable waste (JRC-EU-TIMES code: MINBIOMUN1)

- Primary residues (biodegradable waste): public greens (roadside verges)
- Tertiary residue (biodegradable waste): municipal solid waste (renewables), other waste (abandoned grass cuttings, vegetable waste, shells/husks).

The selected fuel sources are considered in this study as their applications are suitable and convenient for cogeneration via combustion in the industry sector. The residual bio-energy sources in ENSPRESO imply a more competing use in either the transport sector, i.e. bioethanol production, the residential sector, i.e. heating via wood pellets, or energy valorization via gasification, e.g. biogas or hydrogen production. In addition to the selected biomass resources from ENSPRESSO, three sustainability scenarios influence the total biomass available for cogeneration: high, medium, and low bioenergy availability. Each scenario assumes different levels of biomass demand and sustainability measures. The high bioenergy scenario considers high biomass demand and stimulation measures, leading to increased biomass production and use. This results in more significant biomass mobilization and utilization compared to other uses. The medium bioenergy scenario represents a continuation of 2010 trends with moderate stimulation for bioenergy production, focusing on sustainable and resource-efficient biomass use. It avoids biomass types with high sustainability risks and allows room for competing uses outside the energy sector. The low bioenergy scenario prioritizes resource-efficient biomass use over energy sector needs, with strict sustainability criteria and fewer stimulation measures. Competing uses for biomass, such as material conversion, have higher priority than energy use to stricter policies. We refer to Table 3 of Ruiz et al. [12] for details on the scenarios' assumptions for each biomass type's critical parameters and limitations on the feedstock and land area. Colla et al. [11] concluded from their study that ENSPRESO provides a good indication of the biomass potential but presents too generous assumptions in terms of collection of primary forestry residues, manure and energy crops for all high bioenergy scenarios. Therefore, we excluded the high scenario results from this study. In addition, we adopt the estimated production of each biomass from the analysis of Colla et al. [11] of the year 2019.

2.2 Historical production and future potential

Potential of agricultural solid residues: When comparing the results of ENSPRESO [12] and the production of 2019 [11] for the selected agricultural biomass, we observe that the Belgian production is following the low scenario (Figure 2). As the potential of the selected agricultural biomass in 2010 started at 2.04 TWh, by 2019, the production had decreased by 61.3% (1.22 TWh). This trend implies that the energy recovery via incineration or combustion for electricity and/or heat production has decreased due to policies and competing uses over the years. Following this low scenario, the energy potential by 2050 can be estimated between 1.22 TWh (current production) and 0.98 TWh for agricultural residues.

Potential of forestry residues: We concluded from the study of Colla et al. that the high scenario from ENSPRESO is unlikely on the primary forest residue potential

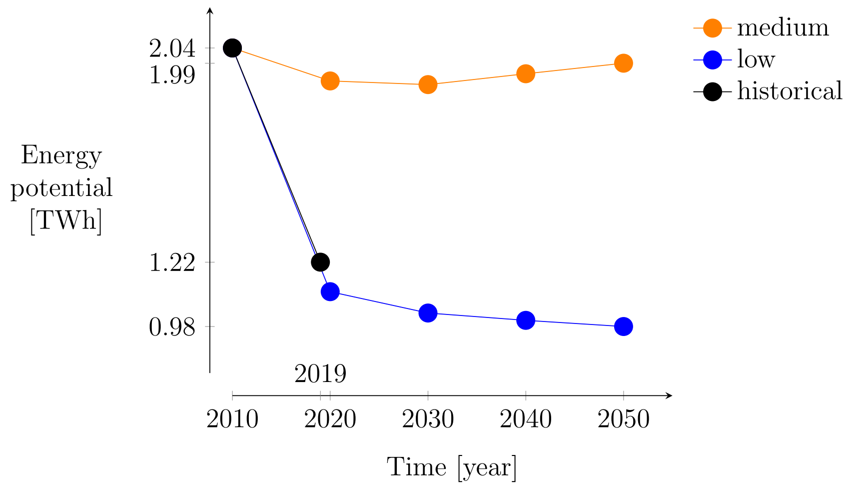

Figure 2: Medium and low scenarios of the potential agricultural residues (olive pits, pruning and straw/stubble) compared to the historical production.

as it was assumed there is no limitation for stump and residue extraction. At the same time, no competing use is considered [11]. This unlikely choice is also perceived when comparing the historical values for this biomass source and the scenarios (Figure 3). Between 2010 and 2019, a 70.4% decrease (from 10.31 TWh to 3.05 TWh) in energy availability is recorded. We define the potential of logging residues by the low scenario, meaning we estimate that a potential of energy valorization via logging residues will be between 3.05 TWh (current production) and 1.13 TWh (ENSPRESO 2050).

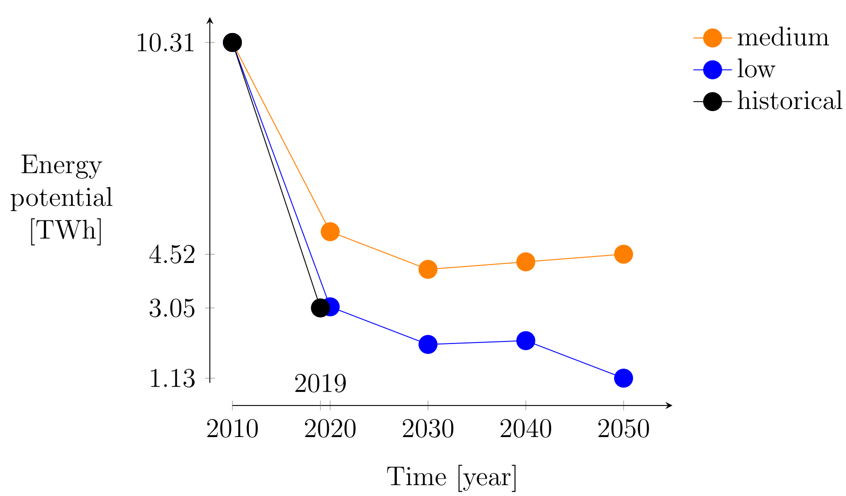

Figure 3: Medium and low scenarios of the potential logging residues from primary forestry residues compared to the historical production.

We need to include the sawdust potential for the woodchips and pellets potential to compare the secondary forest residue production of 2019. These results show an increase in woodchips, pellets and sawdust of 31.1% between 2010 and 2019 (Figure 4). ENSPRESSO also expected an increase in this secondary forest residue potential for the low and medium scenarios, where we can conclude that the actual production lies close to the low scenarios and will behave accordingly in the future. The ENSPRESO model also indicates that in the historical value in 2010, 17.9% (0.51 TWh) of the described biomass potential consisted of sawdust. Following the medium and low scenarios, this sawdust fraction increases to 33.2%. Based on the same fraction, we assume that in 2019, the woodchips and pellet production was around 2.48 TWh (Figure 4). When considering the fuel suited for cogeneration, namely solely woodchips and pellets, we deduced the future potential via ENSPRESO. The low scenario prescribes the potential of woodchips and pellets with a downward trend by ENSPRESO as the competitive use with other industries will increase over time. This results in a potential energy valorization of woodchips and pellets between 2.48 TWh (current production) and 0.74 TWh (ENSPRESO 2050).

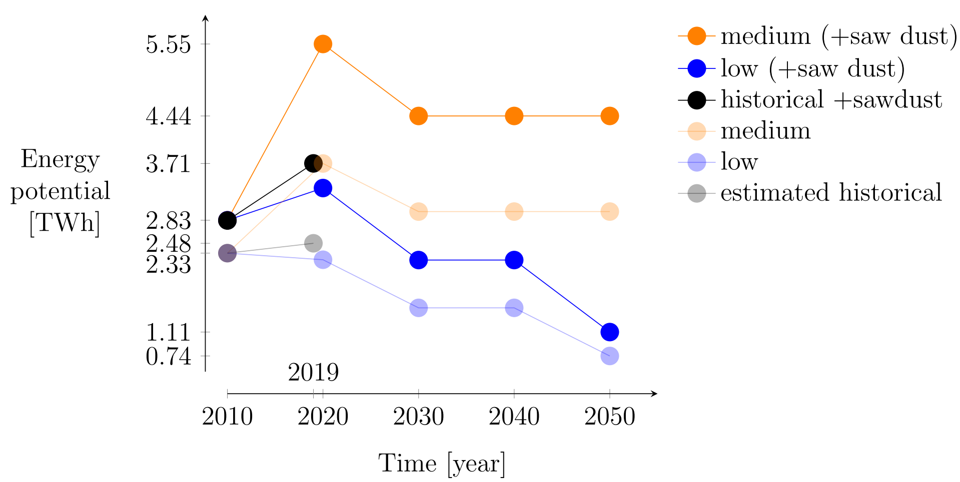

Figure 4: Medium and low scenario of the potential woodchips from secondary forestry residues compared to the (estimated) historical production with and without sawdust.

As there is no historical data available for the energy potential of landscape care (primary forestry residues), we can only rely on the historical value of 2010 and the simulated results of ENSPRESO (Figure 5). The absence of recorded data might partly be explained by the fact that this represents only 8.3% of the possible energy potential in the primary forest residues when compared to the energy potential of 2010 from

ENSPRESSO. We observe within this energy potential category that the medium and low scenarios follow the same trend as the woodchips and pellets energy potential (Figure 4). This solid biomass's future (and current) production follows the low scenario. This assumption estimates that the future energy potential in 2050 will be between 1.14 TWh (2010 production) and 0.4 TWh.

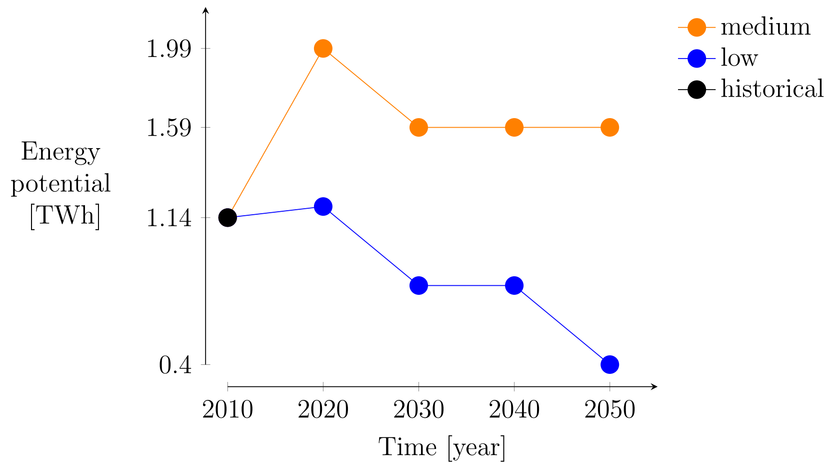

Figure 5: Medium and low scenarios of the potential landscape care from primary forestry residues compared to the historical production.

Potential of biodegradable waste residues: Colla et al. [11] determined the energy potential from biodegradable waste, i.e. roadside verges, renewable municipal solid waste and other waste, in 2019 was 5.08 TWh. This production is considerably below the low scenario of ENSPRESO with an energy gap of 1.26 TWh (Figure 6). Compared to the low ENSPRESO scenario and the historical one, we can notice that the conditions and competitive use for energy purposes between the predicted and actual estimations are more extensive than expected. This gap can be explained by a combination of increased competing use for non-energy applications (more than 80% for primary waste and more than 50% for tertiary waste) and a lower collection ratio (less than 20% for the primary residues). Our analysis estimates that the energy potential for biodegradable waste in 2050 will be between 8.11 TWh and 5.08 TWh (based on the 2019 production).

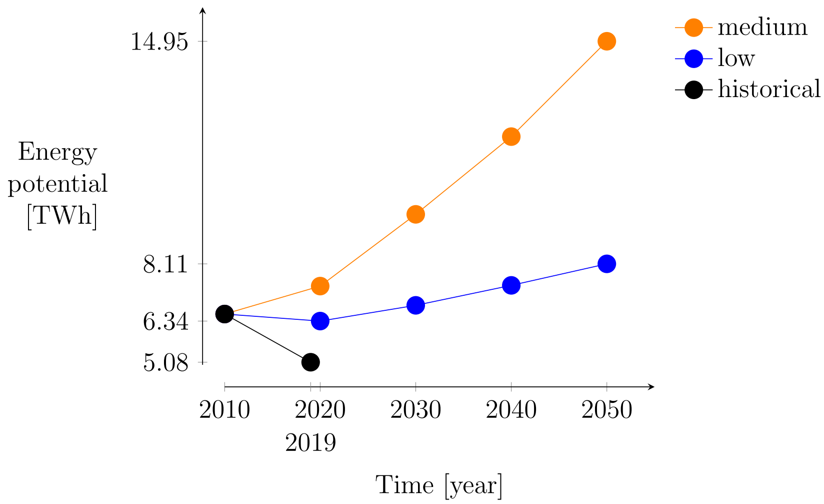

Figure 6: Medium and low scenarios of the total potential of biodegradable waste compared to the historical production.

2.3 Summary of the bio-energy potential in Belgium

As observed in the previous section, the overall historical trend of available biomass in Belgium for energy valorization follows the lower scenario of ENSPRESO. With these observations, we can estimate the total bio-energy suited for cogeneration in the future. When we consider all biomass sources defined in subsection 2.2, excluding landscape care while including sawdust, we estimated that in 2019, 13.1 TWh of biomass was valorized for electricity, heat or a combination of both (Figure 7). Viewing the trend between 2010 and 2019, we expect that in the best-case scenario, the production will stay stable from 2019, or the low ENSPRESO scenario will provide a higher estimate for a particular biomass source. In the worst-case scenario, we take the minimal estimation of 2019 or the low ENSPRESO scenario. With these assumptions, we estimated that the future bio-energy potential for energy valorisation in 2050 lies between 16.1 TWh and 8.3 TWh when considering sawdust and excluding landscape care (Figure 7).

If we exclude the sawdust from these scenarios and include the landscape care from the forest, we observe the same trend for the best and worst-case scenarios (Figure 8). In this estimation of the selected bioenergy sources, we estimate a potential between 8.3 TWh and 16.5 TWh to produce electricity and heat. To conclude, as the use of biomass in other industries grows, i.e. recycling, and the regulations of these sources for energy production become more strict, i.e. RED III, we can assume that the available biomass in 2050 will be around 8.3 TWh. This value means that the available bio-energy

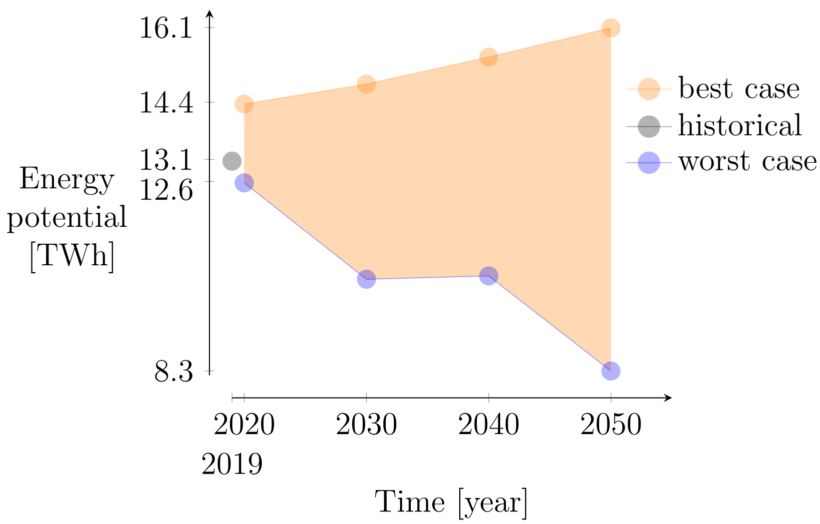

Figure 7: Estimation and recorded biomass potential including sawdust but without landscape care utilized for cogeneration in Belgium.

potential from biomass will decrease further in the future by 36.6% compared to the value reported in 2019.

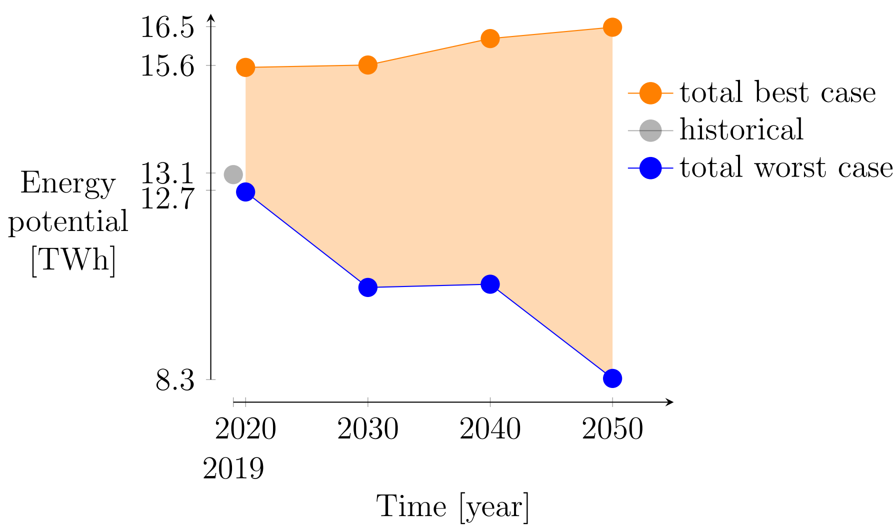

Figure 8: Estimation of total biomass potential (with landscape care) and historical value of 2019 with sawdust and without landscape care

3 Municipal waste potential for cogeneration

The Belgian Waste-to-Energy (BW2E) federation states that the number of waste power plants heavily relies on the available burnable waste [16]. As Belgium is heading towards a circular economy, the primary objectives are reducing waste and re-using, repairing, refurbishing and recycling existing materials and products [17]. So, this waste management philosophy would eventually lead to a reduction in the waste-to-energy plant facilities. For now, waste-to-energy from non-renewable municipal solid waste provides a solution to minimizing landfills while regaining materials that can not be recycled in their existing form (Figure 9). In addition, electricity, heat, or both can be generated from these waste materials via industrial burners driving steam cycles to avoid incineration without energy recovery. For the Waste-to-Energy (WtE) management in Belgium, three agencies (one for each autonomous region) coordinate these waste streams where *Brussels Environment* does this for Brussels, *Wallonia* for the Walloon region and *OVAM* (Openbare Vlaamse AfvalMaatschappij) for the Flemish region. In the first section, we analyze the historical trend of each region's non-renewable municipal waste generation in Belgium. For sake of completeness, we do not report the waste

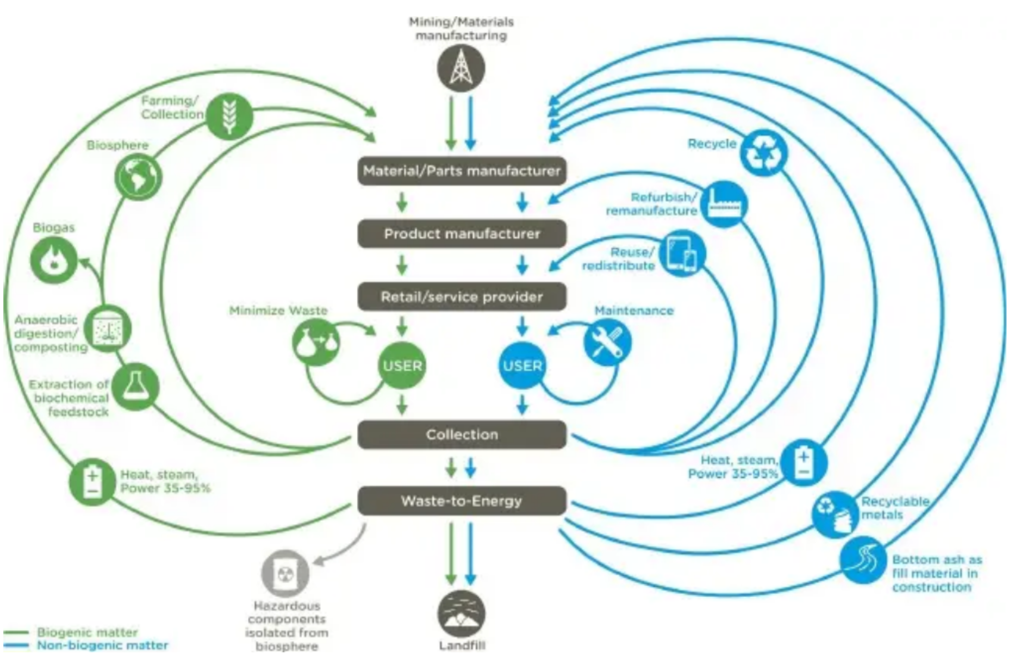

Figure 9: The circular economy aims to create a closed-loop system where materials are continually cycled through processes like extraction, production, use, collection and recycling, therefore minimizing our waste production [18].

streams that the Belgian waste management agencies do not collect. This means that certain waste streams produced by industries are internally used for energy valorization and could, therefore, not be estimated. Afterwards, based on a study done by the BW2E sector federation, the future potential of these non-renewable waste energy sources for WtE plants is evaluated. Lastly, we summarize our findings and estimate the potential for non-renewable waste energy in Belgium.

3.1 Historical production of waste in Belgium

For this waste processing, 17 waste-to-energy plants exist in Belgium, where 1 is located in Brussels, 4 in Wallonia and 12 in Flanders (Figure 10). The Belgian WtE plants have a total yearly capacity of 3638 kton, where the plant in Brussels has a capacity of 496 kton, the Walloon plants 804 kton and the Flemish plants 2338 kton[1] (Table 1). First, we discuss the historical waste processing in Brussels, then Wallonia and Flanders.

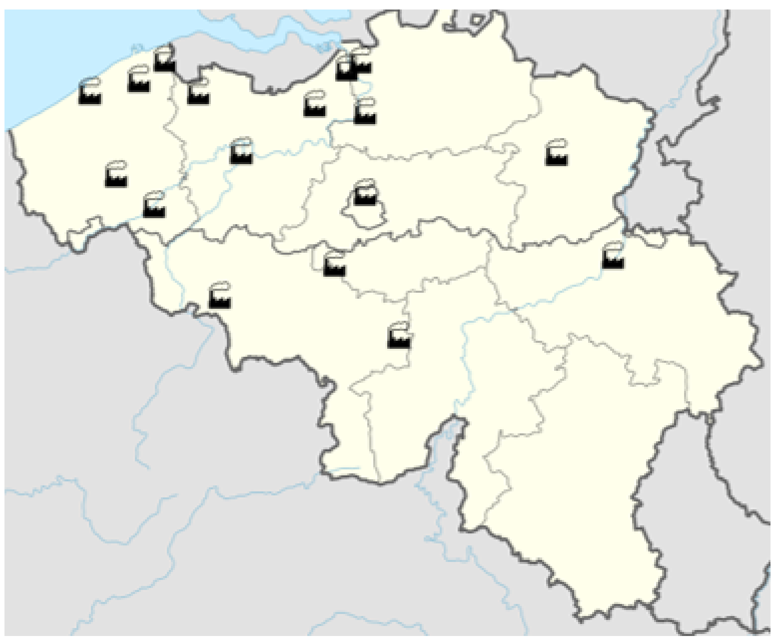

Figure 10: Seventeen waste-to-energy plants currently exist in Belgium, with a total yearly capacity of 3638 kton for burnable municipal and industrial waste [20]. Municipal waste streams that are internally valorized by companies are not reported.

[1]This value is the total Flemish waste capacity in 2022 reported by OVAM, including municipal and industrial waste plants. In the 2022 report of OVAM, the licensed capacity for municipal waste was 1985 kton/year [19].

Table 1: List of Belgian waste plants for each region with their corresponding yearly waste processing capacity.

Name	Location	Region	Waste capacity [kton]	References
Net Brussel	Neder-Over-Heembeek	Brussels	496	[16]
IVBO	Brugge	Flanders	208	[19]
Indaver	Doel	Flanders	384	[19]
IVM	Eeklo	Flanders	105	[19]
IVAGO	Gent	Flanders	102	[19]
IMOG	Harelbeke	Flanders	85	[19]
IVRO / MIROM	Roeselare	Flanders	69	[19]
ISVAG	Wilrijk	Flanders	159	[19]
Biostoom Beringen	Beringen	Flanders	200	[19]
IVOO	Oostende	Flanders	78	[19]
Biostoom Oostende	Oostende	Flanders	183	[19]
SLECO	Antwerpen	Flanders	466	[19]
Stora Enso	Gent	Flanders	300	[19]
IPALLE	Thumaide	Wallonia	264	[21]
inBW-UVE	Virginal	Wallonia	110	[22]
Intradel	Herstal	Wallonia	320	[23]
Tibi	Pont-de-loup	Wallonia	110	[24]

Waste in Brussels: For the WtE plant in Brussels, the recorded data from the plant shows that the energy valorization from municipal waste steadily decreased by 14.4 kton between 2010 and 2021, while the recycling and composting/fermentation of materials steadily increased by 13.5 kton for the same period (Figure 11). In reference, Net Brussels also reported the municipal waste collected in Brussels (for energy valorization and recycling and composting/fermentation of materials) between 2014 and 2019. In these data, we observe a small difference in the municipal waste for energy valorization (an increase of 1.11 kton) and for recycling and composting (a decrease of 0.44 kton) between 2014 and 2019. These two datasets reveal that there are gaps between the two material streams, as the data from the WtE plant shows the incoming waste, and the data from Net Brussels shows the generated waste. The recently recorded energy valorization from company waste shows an increasing trend between 2018 and 2020 by 19 kton [25]. From these municipal and company waste data (reported by the WtE plant) between 2018 and 2020, we estimate that the waste going to energy valorization is between 468 kton and 480 kton, which is close to the maximum reported yearly capacity of the plant, i.e. 496 kton. In comparison, Net Brussels estimated the total

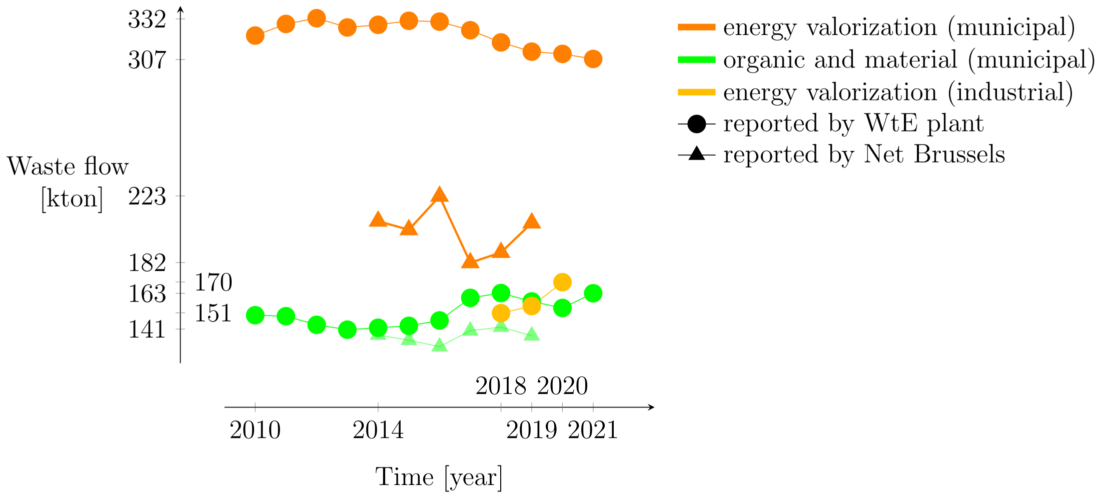

Figure 11: Historical evolution of recyclable (organic and material) and energy valorization of municipal and industrial waste collected by Bruxelles Propreté/Net Brussel between 2014 and 2019 and the WtE plant in Neder-Over-Heembeek between 2010 and 2021. Landfill and incineration without energy recovery are not reported here as these quantities are marginal (around 2.2 kton/year).

Brussels generated (industrial and household) waste destined for energy valorization was 422 kton (in 2020) and 432 (in 2021). We assume that this discrepancy comes from the fact that a part of this additional recorded waste is imported from Flanders, Wallonia or other foreign countries. This means that the plant in Brussels does not have the opportunity to operate flexibly as the total waste valorisation is at the plant's capacity. When the volume of waste streams decreases over time, the potential to operate flexibly becomes larger. Regarding other waste processing practices in Brussels without energy recuperation, Net Brussels reported a small fraction of the total generated waste goes to landfills (around 1.3 kton/year) or incineration (around 0.91 kton/year).

Waste in Wallonia: There are four WtE plants in Wallonia that process municipal waste (from domestic and industrial origin) with a total yearly capacity of 804 kton[2]. The COPIDEC report shows the historical trends of each waste flow collected from municipals and small businesses (Figure 12) [26]. Overall, we see an increase in total waste production of 238 kton (from 1713 kton in 2010 to 1951 kton in 2020). During this time, the production of organic recycling decreased by 49 kton (from 253 kton to 204 kton),

[2]Some reports show that the total waste capacity is 940 kton, where the Ipalle WtE plant (in Thumaide) can (theoretically) process up to 400 kton [22] instead of the reported 264 kton by BW2E [21].

while its material recycling increased by 44 kton (from 740 kton to 784 kton). For energy valorization, an increase of 248 kton was recorded (from 594 kton to 842 kton). Finally, for incineration (without energy recovery) and landfill, we observe a decrease of 83 kton (from 83 kton to 0 kton) and an increase of 10 kton (from 44 kton to 54 kton), respectively. These historical values show that the most significant increase over 10 years in Wallonia originates from an increased waste valorization. The reported waste for energy valorization of 2020 (842 kton) lies above the technical limit of 804 kton/year (reported by the BW2E) for the 4 plants in the Walloon region. The discrepancy could be explained by the fact that at least 38 kton of waste is exported to other regions or neighbouring countries. When considering the maximal capacity of 940 kton, we observe a margin of 94 kton. In addition, (non-)hazardous industrial waste is not included in this report, which could result in a surplus of waste compared to the capacity of the Walloon WtE plants. Like the plant in Brussels, the Walloon WtE plants cannot operate flexibly as there is an excess of total municipal waste compared to the plant's capacities.

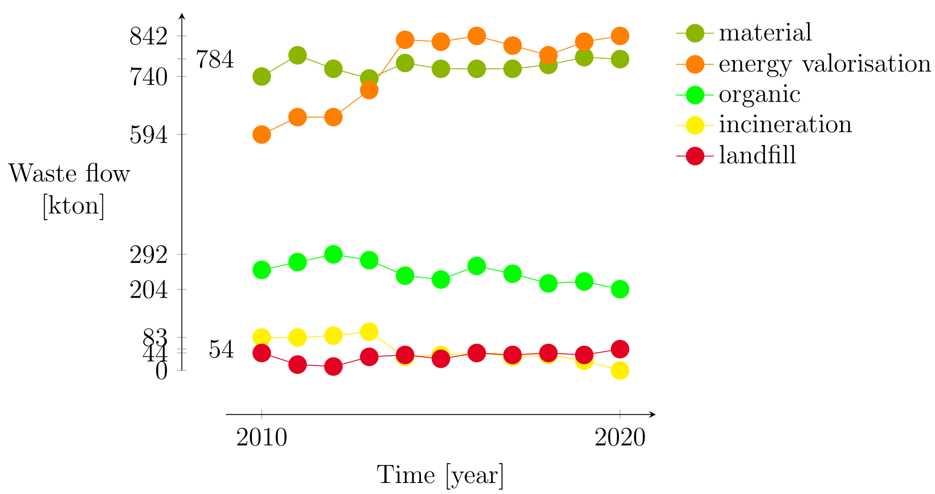

Figure 12: Historical evolution of organic processing, material recycling, energy valorization, incineration and landfill from municipal waste for Wallonia between 2010 and 2020 [26].

Waste in Flanders: For Flanders, 12 WtE plants convert waste from different origins (municipal and industrial) into electricity, and some provide additional heat to local communities or industries. From these 12 plants, 9 facilities are allowed to process municipal waste from households. Although a fraction of the capacity of the residual 3 plants (Biostoom Oostende, SLECO and Stora Enso) is used to burn municipal waste, the primary purpose of these plants is processing industrial waste, e.g. woody waste, (sewer) sludge, medical waste and other (non-)hazardous waste residues. The theoretically licensed capacity of these Flemish plants for municipal waste in 2022 is 1985 kton [19]. For the municipal waste streams, OVAM reported the historical trends between 2010 and 2018 in their circular economy report (Figure 13) [27]. The total mu-

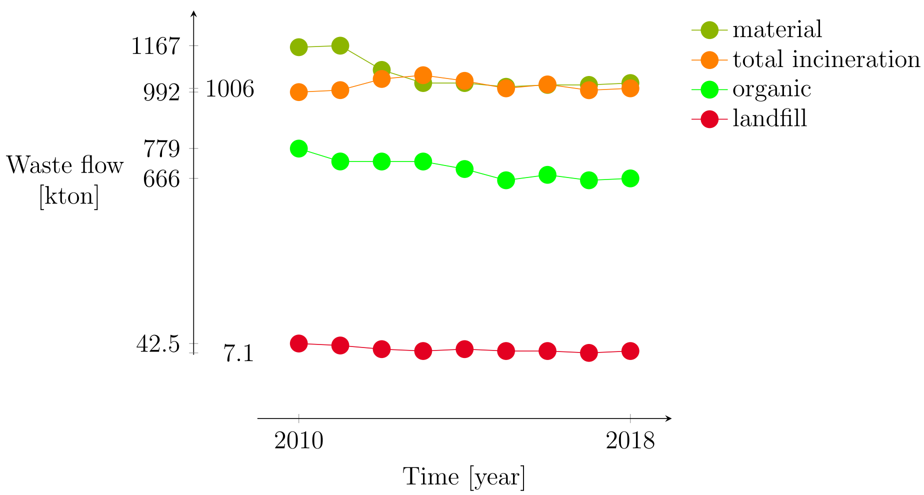

Figure 13: Historical evolution of municipal waste in Flanders for organic, material, total incineration and landfill between 2010 and 2018. The incineration time series considers the waste streams for energy valorization and (co-)incineration (from Figure 41 in [27]).

nicipal waste in Flanders decreased between 2010 and 2018 by 262 kton (from 2974 kton to 2712 kton). The most significant decrease comes from recycling material (135 kton), and the second most significant decrease is from organic waste processing (113 kton). The total waste processing via incineration (including waste with and without energy recovery) has increased by 14 kton, while landfills have decreased by 28 kton. Regarding the time series of total incineration from the circular economy report [27], we can separate the energy valorization and incineration via the yearly reports of OVAM [19], where they provide these municipal waste streams from households and communities. In addition, these reports indicate the municipal waste from industries. Based on these yearly reports, we can provide an overview of the total municipal waste supply (domestic and industrial) and the valorized portion for Flanders between 2015 and 2022 (Figure 14). In this dataset, we distinguish between the total Flemish production of municipal waste, the valorized part (top of figure), and the municipal and industrial waste supply (bottom of figure). Overall, we observe an increase in waste supply by 147 kton, where the valorized waste follows the same trend, although a sudden decrease occurred by

82 kton in 2022. Details on the final destination of the residual burnable waste stream (the difference between the total Flemish supply and the valorized stream) were not provided by OVAM. However, three options for processing the residual burnable waste are provided: a part can be exported to a Walloon cement kiln (for co-incineration) exported to another region/country for energy valorization or used in a landfill. When looking at the supply side, we observe that municipal waste was reduced by 16.4 kton between 2012 and 2022, while in the same period, the industrial waste (similar to municipal waste) increased by 164 kton. OVAM also reported this phenomenon where less municipal waste is generated due to improved sorting rules for households and small businesses. Still, an increase in municipal waste from industries counterbalances this effect. We observe that the historic energy valorization of municipal waste (domestic and industry) is close to the licensed yearly capacity of 1985 kton (in 2022 [19]), which

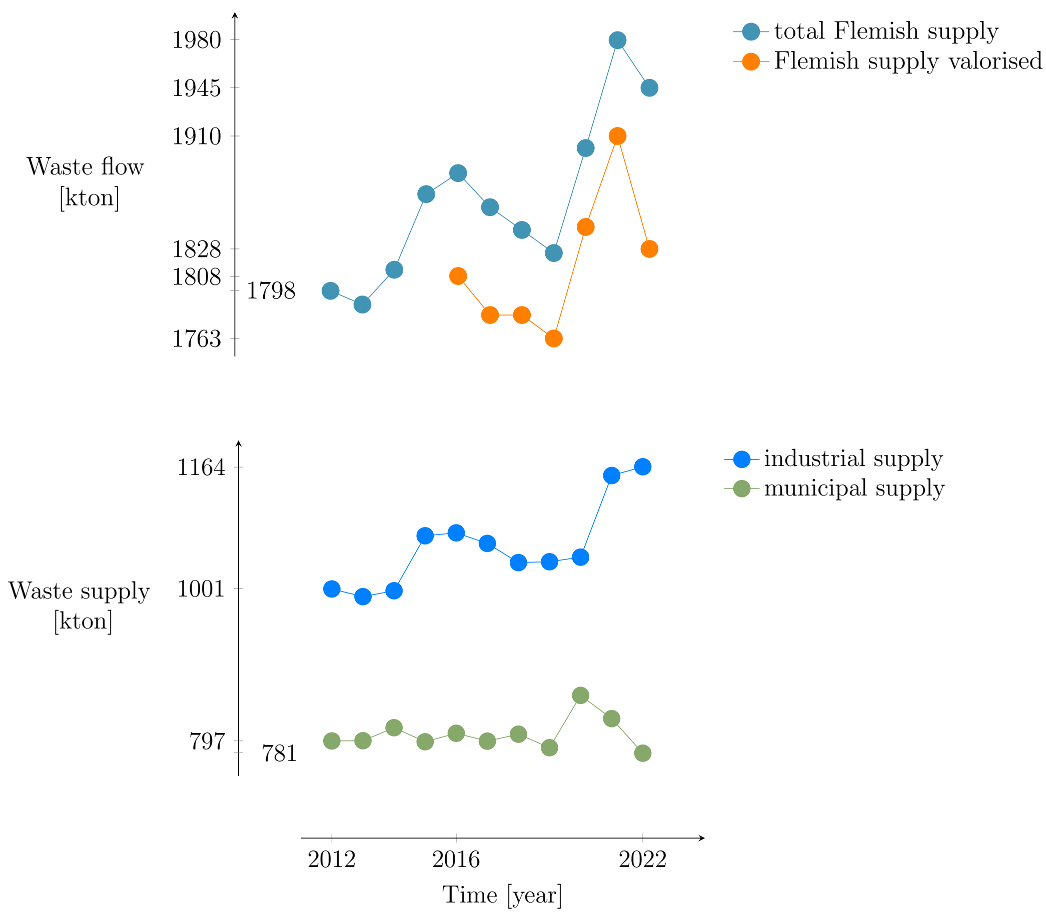

Figure 14: Supply of Flemish municipal (domestic, bulky and public) and industrial waste between 2012 and 2022. Starting from 2016, we observe that between 94% and 97% of the total Flemish supply goes to Flemish waste-to-energy plants.

means, in theory, there is an under-capacity of waste valorisation in Flanders. However, in practice, the reports of OVAM show that Flanders import waste from other neighbouring regions, resulting in an overcapacity of waste valorisation for the Flemish WtE plant [19].

3.2 Future potential of non-renewable waste for cogeneration

As presented before, the future energy production from non-renewable waste will depend on the available burnable waste. As each Belgian region organizes its waste management independently, the trends of available energy will differ for each region in the future. For example, the Flemish region aims towards a circular economy by 2050 where nothing is wasted. While in Wallonia, by 2025, the region will focus on separating organic waste from raw municipal waste [28]. As these regional decisions impact the capacity of available burnable waste, the BW2E sector federation studied the future trends and the uncertainties that affect the total available waste potential for Flanders [29]. In this BW2E study, four out of eighteen studied uncertainties were identified as significantly impacting the future potential of non-recyclable waste. These uncertainties are the effectiveness of the policy on waste separation and raw materials, the evolution of environmental tax and waste pricing, the usage of waste as a fuel in cement kilns and the potential over- or under-capacity of regions and neighbouring countries [29]. The impact of the policy and waste separation involves the policies targeting waste separation and selective collection of organic waste and plastics, intending to reduce waste from municipals and industries. For the evolution of environmental taxes and waste pricing, the volumes of residual waste are impacted when the environmental levy and tariffs on waste incineration increase. The study expects a more significant effect on industrial waste than municipal waste. Regarding the cement kilns, substantial amounts of combustible residual waste from Flanders and Wallonia are processed in Walloon cement kilns, which have a large capacity to handle more waste. The future role of cement kilns in the future waste-to-energy market largely depends on policy decisions regarding waste processing via these cement kilns. Lastly, changes in over- or under-capacity within Belgian regions or neighbouring countries, such as reduced waste or capacity reductions, could affect the import and export volumes.

From these uncertainties, four scenarios were created to anticipate the possible evolution of waste by 2040. Within these scenarios, the study also included population growth, economic development via the gross domestic product and the phasing out of landfills. The first scenario considers no policy impact while no other processing routes are available to manage the waste. Expressly, the scenario assumes an increase in waste due to economic and demographic growth, the use of waste as fuel in the cement industry is inhibited, and its export is reduced while dumping of burnable waste has been phased out. These assumptions result in an under-capacity of waste plant capacity in Flanders in 2040 of around 730 kton [29]. In the second scenario, waste production is reduced due to an effective policy, but no other processing routes are available to manage the waste. With this scenario, the effect of economic and demographic growth is mitigated. At the same time, the use of waste as fuel in the cement industry is slowed down, and exports are declining. Again, the burnable waste dumping is phased out. In this scenario, the study reveals an approximate over-capacity of the Flemish WtE plants of around 480 kton in 2040 [29]. The third scenario assumes no policy impact but an increase in waste potential via other processing routes. Like with the first scenario, there is a waste increase in economic and demographic growth, but there is a need to use waste as fuel in the cement industry. This scenario leads to an insufficient capacity, similar to scenario 1, of around 730 kton in Flemish WtE plants following a waste export, processing in the cement industry, or possibly to increase landfills [29]. In the fourth and last scenario, scenarios two and three are combined, where the circular economy objectives are achieved. At the same time, there is an increase in waste potential due to economic and demographic growth. These two assumptions compensate for each other, but the cement industry can use waste as an unlimited fuel source. This scenario leads again to an over-capacity of Flemish WtE plants, similar to scenario 2, of around 480 kton [29]. It must be noted that the BW2E study considers all types of waste flows in Flanders, i.e. municipal, industrial, sludge, incineration via cement kilns, landfill and export, for the future waste potential. However, we can assume (via scenarios 1 and 4) that the same order of magnitude can be expected for the increasing or decreasing trend regarding municipal waste. Still, we can estimate the upper and lower boundary of the future waste potential, namely a 480 kton over-capacity and a 740 kton under-capacity by 2040. Still, with the under-capacity of 480 kton, the Flanders WtE could have the opportunity to provide flexible services to the electricity grid without closing any plants. To the authors' best knowledge, similar studies have yet to be carried out in the Brussels or Walloon regions. However, we can anticipate that there will be no significant change in waste potential in the future for both regions as 5 out of 18 WtE plants are located in Brussels and Wallonia (34.9% of the Belgian waste plant capacity).

3.3 Summary of waste energy potential in Belgium

In conclusion, the waste energy potential can be assessed when converting the waste mass to energy, using 10 GJ/ton as its calorific value (Figure 15). We considered 10 GJ/ton waste, like OVAM, because it considers the average calorific value of municipal waste as this value changes over time, depending on the origin of the waste and the quality of the waste (high or low calorific waste) burned for energy valorization. In the past, we observed that municipal waste from households and bulky and public waste origin increased in Wallonia from 1.65 TWh to 2.34 TWh, and Flanders from 4.95 TWh to 5.08 TWh. While in Brussels, a decrease occurred over 10 years (from 0.89 TWh to 0.85 TWh). However, for Flanders, a decrease in municipal waste is observed, but it is nullified by industrial waste similar to municipal waste. With the results of the BW2E study, we can conclude that the future potential of non-recyclable waste for Belgium depends on the effectiveness of the (circular) waste policy, the economic and demographic growth and the use of waste in cement kilns as a fuel source. For Flanders, we estimate that the future potential of municipal waste will be between 3.88 TWh and 7.11 TWh. As no study has been performed for Wallonia and Brussels, we estimate that the future energy potential will stay the same for these regions. So, for Wallonia, we state that there will be an energy potential of 2.34 TWh based on the 2020 energy production. With the same logic, for Brussels, we state that there will be an energy potential of

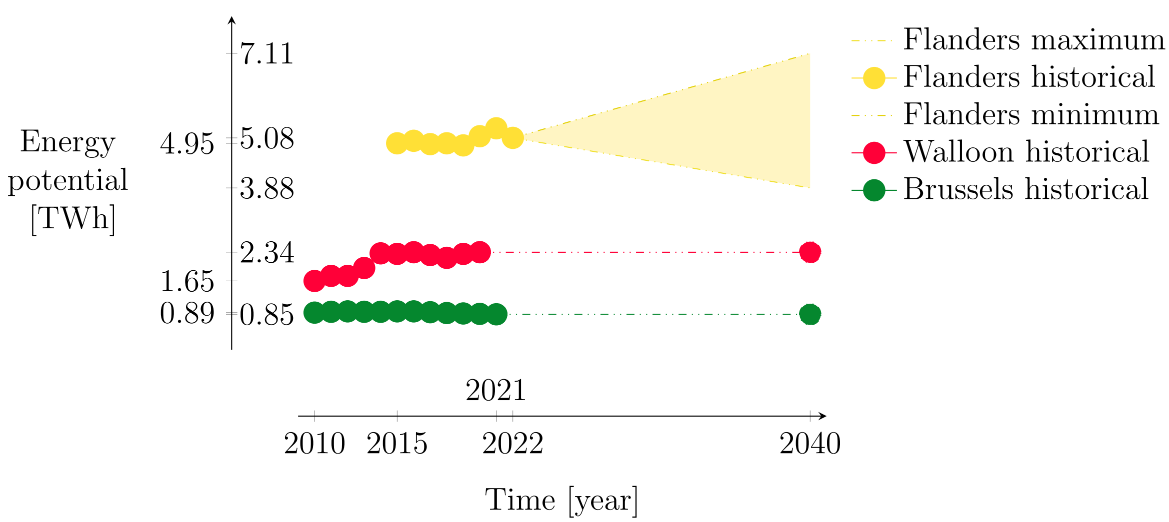

Figure 15: Historical and future estimate of the non-renewable energy potential of the three regions in Belgium. We expect no significant change in the potential for the Walloon and Brussels regions as there are no case studies for the future potential. While in Flanders, the waste potential in 2040 depends on the proposed scenario.

0.85 TWh based on the operation of 2021. Based on these assumptions, we estimate the future energy potential of non-recyclable waste in Belgium between 7.1 TWh and 10.3 TWh.

4 Conclusion

When combining the results of the previous sections, we can assess the total energy potential of the future Belgian cogeneration fleet operating on renewable and non-renewable, non-recyclable waste. However, an issue arises when combining the results originating from the woody municipal waste (Section 3) and the biodegradable waste residues (Section 2). As was presented in Section 3, the woody waste from municipals is already included in the analysis. Meanwhile, in Section 2, the potential of biodegradable waste residues includes renewable municipal solid waste, roadside verges and other waste, which means there is an overlap between the two categories. So, to evaluate the complete energy potential from both resources, we excluded the biodegradable waste residues (Figure 6) from the total biomass potential (Figure 8). With this assumption, we determined a total energy potential of 16.1 TWh in 2019, where 49.8% originates from renewable waste. By 2040, the final energy potential from waste, originating from renewable and non-renewable, non-recyclable resources, depends on the future policies and the effectiveness of the circular economy of each region. When the biomass potential becomes more restricted, we can assume that the energy potential will decrease, whereas if the current policies remain the same, a relatively small increase of 0.80 TWh will occur. As was depicted by the BW2E study, four parameters will determine the evolution of the non-renewable, non-recyclable waste energy potential, i.e. the effectiveness of regional waste policies, the evolution of environmental tax and waste pricing, usage of waste as a fuel in cement kilns, and the over- and under-capacity of waste processing plant in regions and neighbouring countries. From the total waste potential, we observe a reduction by 22.0% (to 12.5 TWh) by 2040 when biomass is restricted and a decrease in the waste valorisation from non-renewable, non-recyclable resources is realised. The most significant decrease originates from renewable waste, which accounts for 72.1% (2.55 TWh of the 3.53 TWh decrease). In the other extreme scenario, the total energy potential of waste resources increases by 18.9% in 2040 (to 19.1 TWh) when the biomass potential remains the same as the values reported from 2019, while the municipal waste generation increases. In this case, 73.7% (2.24 TWh of the 3.03 TWh increase) originates from the non-renewable, non-recyclable waste.

In conclusion, estimating the future energy potential of renewable and non-renewable, non-recyclable waste is a complex challenge that depends on many input parameters and conditions to predict the exact quantities. A more precise and validated Belgian dataset (for all regions) for measuring the renewable and non-renewable, non-recyclable waste streams in Belgium could better estimate the current energy potentials and reduce the uncertainty of future energy potentials. This report identified an uncertain energy potential gap of 6.6 TWh for the future total waste potential for cogeneration in Belgium by 2040. From this uncertain energy potential, 3.3 TWh comes from renewable waste and 3.2 TWh comes from non-renewable, non-recyclable waste. With this uncertain energy potential, there is an opportunity for the existing cogeneration fleet to continue operating under different conditions when there is an under-capacity of renewable or non-renewable, non-recyclable waste. Currently, this existing renewable and non-renewable, non-recyclable cogeneration fleet provides electric power to the Belgian grid as must-run plants. As in the future, an under-capacity of waste is possible, we expect some of these plants will provide flexibility services to the electricity market, e.g. automatic or manual Frequency Restoration Reserve (FRR) services, probably in combination with the Capacity Remuneration Mechanism (CRM) to ensure sufficient capacity to the electricity grid in the future. Based on this report, we anticipate that the municipal WtE plants will run as must-run units as the municipal waste generation has to be reduced on the producer side, i.e. a reduction in industrial and household waste is necessary. In the case of the Belgian renewable waste plants, this fleet will have a higher probability of operating flexibly in the short term as the availability of these resources will be reduced in the future.

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