LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT
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Master's thesis 2021

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THE ROLE OF WASTE AND SOLID BIOFUELS IN HEATING AND POWER SECTOR; CASES OF SWEDEN, POLAND AND UK

Examiners: Professor Mika Horttanainen
Post-doctoral researcher Ivan Deviatkin

Supervisors: CEO, Laitex Oy Lasse Kurronen
Director, Sales and Services, Laitex Oy Timo Kupsanen

ABSTRACT

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The role of waste and solid biofuels in heating and power sector; cases of Sweden, Poland and UK

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114 pages, 10 tables, 43 figures

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Keywords: renewable energy, energy recovery, solid biofuels, waste

Energy sector is responsible of major deal of the GHG emissions in EU region. EU's ambitious goal to decarbonize the energy sector requires member states to discover alternative energy technologies to produce low carbon energy. As a renewable energy source solid biofuels and waste have certain roles in the energy generation in the form of energy recovery from waste and solid biofuels replacing coal. Through the waste-to-energy technology also waste management is bound to energy sector and is examined in this study from waste-to-energy point of view.

This Master's thesis was prepared to Laitex Oy to give an outlook of future directions in the renewable energy sector in Sweden, Poland and UK. Special attention is paid to solid biofuels and waste which are the most suitable fuels for Laitex's products.

In Sweden waste and biofuels are important sources of energy especially in heating sector. In 2019 capacity of the WtE plants in Sweden was 6,7 million tons of waste and recovered energy was 19 TWh. Sweden is dependent on imported waste due to the over capacity of the WtE plants. By 2040 the capacity will be decreasing with 500-800 thousand tons compared to situation in 2019 but WtE will still be strong technology in Sweden's energy sector.

About 90% of the total energy supply in Poland in 2019 came from fossil sources. Biofuels and waste are the biggest renewable energy sources in Poland and those fuels will have an important role when Poland is aiming to expand the district heating network in the country and diminishing the use of coal. In 2019 there was 2,9 million tons of MSW incinerated and 4300 TJ energy generated from waste. In 2018 the number of incineration plants was eight, but there are several ongoing projects and also planned ones to increase the number of WtE installations.

Oil and natural gas are dominant fuels in total energy supply in UK. Decarbonizing the heating sector, where natural gas is the most used fuel, is a challenge to UK. Biomass is currently the most used renewable source in heating and in the future, it is considered as a valuable source of energy and when combined with CCUS it is possible to reach negative emissions. In UK there were 54 waste incineration plants with 105 lines in 2020 and the plants treated about 14 million tons of waste generating about 7800 GWh power. The study discovers that WtE will continue as a favorable technology in UK in the near future.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
School of Energy Systems
Ympäristötekniikan koulutusohjelma
Sustainability Science and Solutions

Hanna Saira

Diplomityö

Jätteen sekä kiinteiden biopolttoaineiden rooli lämmitys- ja sähkösektorilla Ruotsissa, Puolassa ja Iso-Britanniassa

2021

114 sivua, 10 taulukkoa, 43 kuvaa

Työn tarkastaja:	Professori Mika Horttanainen Post-doctoral researcher Ivan Deviatkin
Työn ohjaaja:	CEO, Laitex Oy, Lasse Kurronen Director, Sales and Services, Laitex Oy, Timo Kupsanen

Hakusanat: uusiutuva energia, energian talteenotto, kiinteät biopolttoaineet, jäte

Energiasektori on vastuussa merkittävästä osasta EU alueen kasvihuonekaasupäästöistä. EU:n kunnianhimoiset tavoitteet hiilidioksidipäästöjen vähentämiseksi vaatii sen jäsenmailta vaihtoehtoisia energiateknologioita vähähiilisen energian tuottamiseksi. Biopolttoaineilla sekä jätteellä on tietyt roolit uusiutuvan energian tuotannossa sekä energian talteenoton muodossa, että hiilen korvaajana. Jätteiden energian talteenoton kautta myös jätehuolto on kiinteä osa energiasektoria, joten myös jätehuoltoa tarkastellaan tässä työssä energian talteenoton näkökulmasta.

Tämä diplomityö tehtiin Laitex Oy:lle avartamaan tulevaisuuden näkymiä uusiutuvien energialähteiden suunnista Ruotsissa, Puolassa sekä Iso-Britanniassa. Erityisesti työssä perehdyttiin kiinteisiin biopolttoaineisiin sekä jätteisiin, jotka ovat polttoaineina sopivimpia Laitexin tuotteille.

Ruotsissa jäte ja biopolttoaineet ovat tärkeässä asemassa, etenkin lämmityssektorilla. Vuonna 2019 Ruotsin jätteenpolttolaitosten kapasiteetti oli 6,7 miljoonaa tonnia jätettä ja talteen otettu energia jätteenpoltosta 19 TWh. Ruotsi on riippuvainen tuontijätteestä polttolaitosten ylikapasiteetin vuoksi. Vuoteen 2040 mennessä kapasiteetti tulee pienenemään 500-800 tuhatta tonnia vuoden 2019 tilanteeseen verrattuna, mutta jätteenpoltto tulee silti olemaan vahva teknologia energian tuotannossa.

Noin 90% Puolan kokonaisenergiasta tuli fossiilisista polttoaineista. Biopolttoaineet ja jäte ovat suurimmat uusiutuvan energian lähteet Puolassa ja kyseisillä polttoaineilla tulee olemaan tärkeä rooli tulevaisuudessa, kun Puola pyrkii laajentamaan maan kaukolämpöverkkoa ja vähentämään hiilen käyttöä. Vuonna 2019 yhdyskuntajätteitä poltettiin 2,9 miljoonaa tonnia ja jätteestä saatu energia oli 4300 TJ. Vuonna 2018 jätteenpolttolaitoksia oli kahdeksan, mutta käynnissä sekä suunnitteilla on useita projekteja polttolaitosten määrän kasvattamiseksi.

Öljy ja maakaasu ovat hallitsevia polttoaineita Iso-Britannian kokonaisenergian tuotannossa. Hiilidioksidipäästöjen vähentäminen lämmityssektorilla on haaste Iso-Britannialle, jossa maakaasu on eniten käytetty polttoaine lämmityksessä. Uusiutuvista energianlähteistä biomassa on käytetyin lämmönlähde ja myös tulevaisuudessa biomassaa pidetään arvokkaana energianlähteenä, sillä yhdistettynä hiilidioksidin talteenottoon, biomassan avulla on mahdollista saavuttaa negatiiviset päästöt. Vuonna 2020 Iso-Britanniassa oli 54 jätteen polttolaitosta, joissa yhteensä 105 linjaa, ja laitoksissa käsiteltiin noin 14 miljoonaa tonnia jätettä, joista energiaa saatiin 7800 GWh. Tutkimuksesta käy ilmi, että jätteenpoltto tulee olemaan suositussa asemassa myös tulevaisuudessa Iso-Britanniassa.

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Kiitos kotiväki, perhe ja ystävät.

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Hanna Saira

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LIST OF SYMBOLS

Subscripts

EU	European Union
GHG	Greenhouse gas
MSW	Municipal solid waste
WtE	Waste-to-Energy
SRF	Solid recovered fuel
RDF	Refuse derived fuel
CHP	Combined heat and power
ktoe	kilotons of oil equivalent
SEI	Stockholm Environment Institute
RES	Renewable energy sources
BAT	Best Available Techniques
NECP	National Energy and Climate Plan
MWTTP	Municipal waste thermal treatment plant
EfW	Energy from Waste
CLL	Climate Change Levy
BECCS	Bioenergy with Carbon Capture and Storage
CCUS	Carbon Capture, Usage and Storage

1 INTRODUCTION

Energy sector is currently facing a huge transition. Targets of abandoning fossil fuels to control the climate change is forcing the actors in energy sector finding new, renewable solutions to produce energy. At the same time the need for energy is increasing. Energy production from renewable energy sources includes various opportunities and this study examines two of those, energy production by energy recovery from waste and sewage sludge by incineration and utilization of wood by-products, more detailed wood chips and forest residue, in energy production.

Energy recovery from waste is strongly bound to waste management. European Union (EU) waste management plays a big role in controlling the greenhouse gases (GHG) and in transition to circular economy, which both are EU's big goals for the future. EU waste hierarchy defines how the waste management should be prioritized and energy recovery is the second last option in waste hierarchy. This study also investigates the future of energy recovery from waste in EU region and in UK and if energy recovery from waste is supporting EU targets of circular economy. Wood by-products is a conventional but renewable way to produce energy. In this study the strategy for using the biomass as an energy source in selected countries is examined.

Behind the idea of this study is Laitex Oy that offers conveying solutions for energy plants. Laitex's interest is to receive information about biomass and waste utilization as a fuel in energy production in selected European countries to support the strategic decision making in the company. Laitex's special interest is on wood chips and forest residues, residual waste from municipal solid waste and similar waste and sludge from municipal or industrial wastewater treatment plants, because these are the most suitable materials for their material handling systems.

The objective of this study is to

- present the waste and energy strategy of the chosen countries (from the energy recovery/incineration point of view).

- find out the role of the energy recovery from waste (incineration), biomass and sludge in energy production today and in the future.
- find out the used technologies and the most remarkable actors in energy recovery in chosen countries.

2 LEGISLATION AND POLICIES

As a big society and one of the leading economies in the world EU has a remarkable role as a forerunner in decreasing the GHG emissions and control the climate change. EU is tightening its targets in reducing the GHGs in the fight against global warming. EU's strategic program the Green Deal presents EU long term target to be a net zero emitter in 2050 and as a milestone in 2030 emission reduction target is at least 55% compared to 1990 level. To drive the targets and ensure that all policies are heading to the same direction, EU has announced a review of the first European Climate Law which constitutes the framework to reach the objective of climate neutrality. (COM (2019) 640 final, 6.)

As a tool to achieve the EUs Green Deal targets EU has also launched the Energy Union strategy to renew the energy system in EU region. The purpose of Energy Union is to build a system with better energy security observing sustainability and competitiveness and it consists of five dimensions: Energy security, solidarity and trust; a fully integrated internal energy market; energy efficiency; decarbonising the economy and research, innovation and competitiveness. (Eurostat. 2020, chapter 1.) Current energy system in EU, including production and use of energy, covers over 75% of the EU's GHG emissions, so it is obvious that energy sector is also responsible of a great deal of emission reductions and the sector requires development throughout the system. To achieve the ambitious targets that EU has set, the energy sector is facing a transition which means decarbonizing and developing the current energy system towards renewable energy sources and fading out the fossil fuels. (COM (2019) 640 final, 6.) In 2018 the biggest share (36 %) of the energy mix in EU region was produced from petroleum products, including crude oil and products refined from it. Natural gas (21 %), solid fossil fuels (15 %, coals and products derived from coals), renewable energy (15 %) and nuclear energy

(13 %) followed with smaller shares. Figure 1 illustrates the composition of energy mix in EU in 2018. It is worth noticing, that all energy is not produced in EU since energy imported from third countries covered 55 % of the total available energy in 2018 and the fact that there are huge differences between Member States in the shares of different energy sources. (Eurostat. 2020, Section 2.1.)

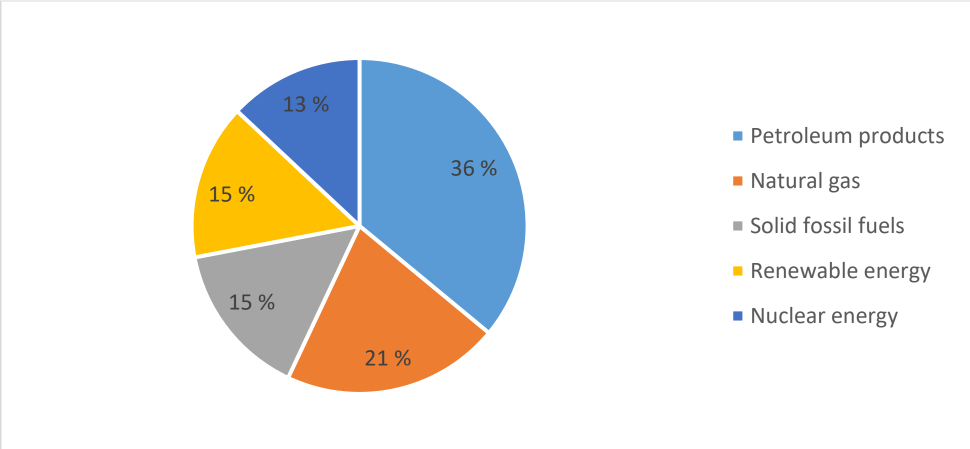

Figure 1. Sources of energy mix in EU in 2018. (Eurostat. 2020, Section 2.1.)

Besides the current available technologies of renewable energy EU will also focus on breakthrough technologies in key industrial sectors such as clean hydrogen, fuel cells and other alternative fuels, energy storage, carbon capture, sequestration and utilization to help decarbonizing the energy sector. (COM (2019) 640 final, 6.)

Emission Trading System (ETS) is a cornerstone of EU policies in striving towards the climate targets. ETS is a cap and trade system which covers all EU countries, and it is aiming to reduce the use of fossil fuels by pricing the greenhouse gas emissions. The system defines the target to annual emissions for each Member State and the target is not allowed to cross. The limit for emissions gets lower every year and finally should reach the national reduction target. ETS covers CO_2 emissions from power and heat generation, energy-intensive industry sector (e.g. oil refineries, cement and pulp) and commercial aviation within the European Economic Area, but also nitrous oxide and perfluorocarbons in certain sectors. Companies, that belong in the ETS, can emit the same amount of emissions annually that they have allowances for. Companies can buy more allowances or trade them if they have more allowances than needed. (European Commission. 2021a.)

The sectors that do not belong to ETS have to be included in the national plans for emission reduction. This regulation concerns sectors like transport, buildings, agriculture and waste. (European Commission. 2021b).

National GHG inventories and emission factors are calculated according to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. When considering the fuels this study involves, the guideline states that CO_2 emissions from combustion of biomass materials, like paper, food or wood waste, shouldn’t be included in national total emissions because they are biogenic. In the case of waste, the shares of fossil and biogenic carbon need to be known to be able to calculate the emissions. (Intergovernmental Panel on Climate Change (IPCC). 2019.)

At the moment EUs Urban Waste Water Treatment Directive doesn’t instruct about the energy use of the sewage sludge. However, there is a revision ongoing to this 1991 published directive so it would comply better to today’s EUs strategies. Especially EU strategy for Energy Systems Integration that instructs for studying the potentials of energy efficiency and energy production from the wastewater. This revision is still in preparation and is not finalized. (European Commission. 2020a, 1.)

2.1 Waste hierarchy, Towards circular energy

EU’s waste hierarchy is a cornerstone of waste management and policies and is an important part in transition to circular economy. Directive on waste (Waste Framework directive) presents the waste hierarchy that prioritizes the order how the waste management needs to be executed in EU Member States. (European Commission. 2021c.) The waste hierarchy is presented in Figure 2.

Figure 2. EU waste hierarchy. (European Commission. 2021c.)

Priority in waste hierarchy is to prevent generation of waste. If waste can't be prevented it needs to be re-used, recycled, or recovered and impacts on environment needs to be minimized. The disposal is the final option in waste management which should be avoided. The aim is trying to recycle the material so that minimum amount of virgin material would be needed in the future.

The priority in waste hierarchy is to prevent the generation of waste. Less waste would be generated if the products would be more durable, and they could be repaired and reused and that could be affected with production planning; as much as 80 % of the environmental impacts are determined in product design and planning phase. As a tool to prevent waste and produce products to be more resource efficient, climate neutral and fit to circular economy, EU is proposing a sustainable product policy legislative initiative. (COM (2020) 98 final, 3-4.)

To control the implementation of the waste hierarchy in Member States EU has set several directives. Directives effecting a lot on waste management and this way on waste-to-energy (WtE) are Waste Framework directive and Landfill directive which are aiming for increasing the reuse and recycling rates and decreasing waste ending to the landfill. In the Waste Framework Directive target for reusing and recycling of municipal waste is 65%

by weight by 2035. (European Commission. 2021c.) The Landfill Directive was amended on 2018 and it seeks to limit the share of MSW landfilled to 10% by 2035. Nations can utilize their own economic instruments in achieving the waste management system according to the waste hierarchy. ((EU) 2018/850.)

Regarding to the Waste Framework Directive Each of the EU Member States needs to deliver their national waste management plan which are assessed with feedback by EU. This study presents the most important issues of national plans of Sweden and Poland from the waste-to-energy point of view in the later chapter. As a previous Member State of EU, the similar document for UK will be presented.

2.2 Role of waste-to-energy in the circular economy

In 2017 EU Commission released a communication COM (2017) 34 final "The role of waste-to-energy in the circular economy". In this bulletin EU defines that financing to new technologies in waste sector should be directed according to the waste hierarchy, to prevention, recycle and reuse before energy recovery. This would mean that financing to new incineration plants using residue waste as a fuel will be limited; new investments should be well justified to be accepted. The alignment bases on the presumption that the amount of residue waste will decrease due to the regulations for separate collection of waste and recycling targets EU has set. With limiting the financing, the over capacity of waste incineration plants will be avoided and concentration on developing the recycling technology could be strengthened. However, Member States are in the different phase on developing the waste management system to be in line with EU's waste hierarchy. There are huge variations in combustion capacity between Member States and there are still countries that rely more on landfilling than others. (COM (2017) 34 final, 2-6.)

There is a debate on the background whether the WtE should be considered as an appropriate and environmentally sustainable way to treat waste or not. It is said that a lot of waste that could be recycled is currently incinerated and in some countries treatment of MSW leans too much on incineration. Increasing capacity of incineration plants would further limit the enthusiasm in reuse and recycling. On the other hand, there are arguments claiming that amount of waste is about to increase, and all waste can’t be reused or recycled and would require another treatment option. (Zero Waste Europe. 2019, 4). Cewep, Confederation of European Waste-to-Energy plants, has made a calculation in 2019 that with the existing targets and policies in the year 2035 142 million tons of residual waste will not be recycled or landfilled and would need other proper treatment capacity. In 2019 waste-to-energy incineration capacity for residual waste in Europe was 90 million tons and co-combustion capacity is around 11 million tons. According to Cewep’s calculation there would be 41 million tons of residual waste in 2035 which would need another alternative treatment if there were no increase in incineration capacity. (Confederation of European Waste-to-Energy Plants. 2019.)

3 FUELS

Transition to renewable fuels in energy production can be carried out with various options from incineration of renewable fuels to wind and solar energy or different breakthrough technologies. Laitex Oy operates on energy sector manufacturing the conveying solutions to energy plants. The company has business around the Europe and while the European nations are on different stages in energy transition also the use of different fuels in waste-to-energy plants varies. The customers’ plants have been incineration plants that use conventional fossil fuels but are increasingly changing the fuels to renewables in every country. In this study concentration is on fuels that are the best for Laitex’s equipment, and this chapter presents the selected fuels but more detailed report on country level practices about the use and policy instruments of different fuels will be presented later in this study.

3.1 Waste-to-energy

Waste has been treated thermally over a hundred years. At first, the purpose of incinerating the waste was to reduce the volume of waste and to destroy the pathogens, though electricity and heat were produced in a few facilities already at the beginning of the 1900s. Soon the injurious effects to the air and ground were realized and incineration met public opposition. After 1950’s when first air pollution filters were installed to incineration plants, the evolution to today’s high technology waste-to-energy plants has been enormous. Today the goals of thermal treatment of waste are still the same as they were in the early stage of incineration, but modern waste management system and legislation requires a lot more. In addition to volume reduction and hygienisation, environmental protection, mineralization and immobilization of hazardous substances, resource conservation and affordable costs and public acceptance are the main objectives for incineration plants today. (Brunner & Rechberger 2015, 5-10.)

Population in the world is growing all the time and hand in hand with that is the generation of waste. In 2019 225 million tons (502 kg per capita) municipal waste was generated in EU27 area. 24% of the total municipal waste was landfilled, 27% incinerated (with and without energy recovery), 30% material recycled, 17% composted and 2% had other treatment. The Figure 3 presents the development of the municipal waste treatment per capita in 1990-2019 in EU region, but it also shows how the waste was treated. Municipal waste incinerated had risen from 30 million tons to 60 million tons between the years 1995 and 2019 while landfilling has fallen 56% from 121 million tons to 54 million tons. The main reason for such a big fell in landfilling is EU legislation, mainly packaging and packaging waste and landfilling directives. These amendments have also had impact on raising the share of incinerated waste. (Eurostat, 2021). The amount of landfilled MSW in EU will be diminished further due to the landfilling directive that allows Member States to landfill only 10% of generated MSW by 2035. ((EU) 2018/850). In 2018 primary energy production from municipal solid waste in EU was 418 PJ. (Statista. 2021a.)

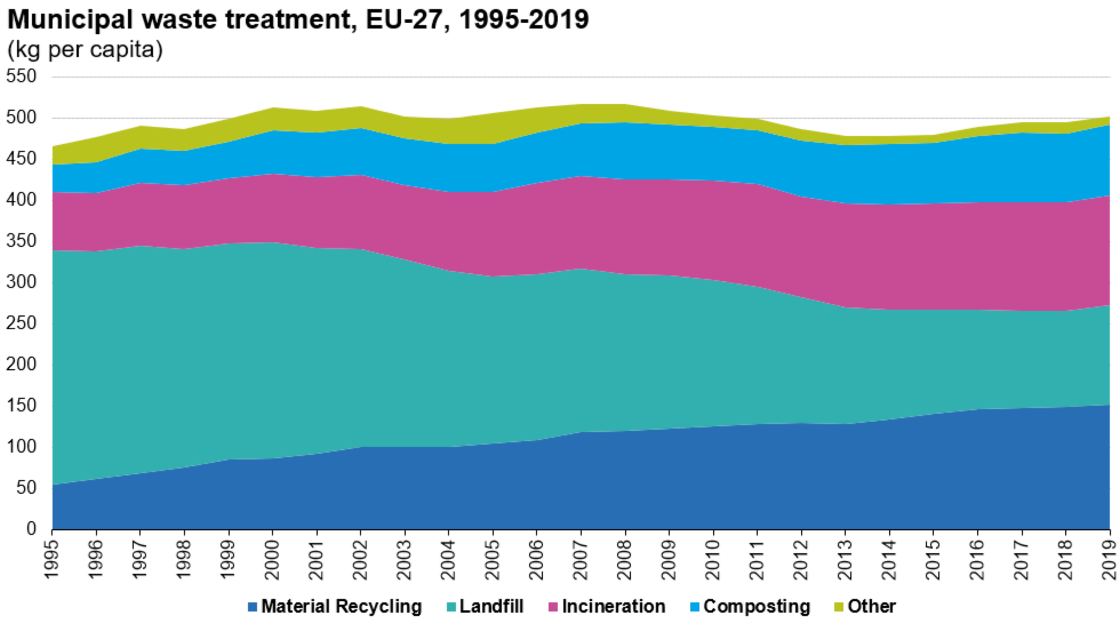

Figure 3. Municipal waste treatment, kg per capita, EU27, 1995-2019. (Eurostat. 2021c).

The waste that is incinerated in the waste-to-energy (WtE) plants is the waste that according to the waste hierarchy can't be reused or recycled. This so-called residual waste comes from the wastes like MSW and similar waste, like commercial waste, but also industrial waste. In its policies (COM (2017) 34 final, 3) EU defines waste-to-energy processes as follows: co-incineration of waste in combustion plants and in cement and lime production, waste incineration in dedicated facilities, anaerobic digestion of biodegradable waste, production of waste-derived solid, liquid or gaseous fuels and other processes including indirect incineration following a pyrolysis or gasification step. These processes are placed differently in the EU waste hierarchy based on their environmental impacts. For example, anaerobic digestion is regarded as a recycling but waste incineration and co-incineration with no or restricted energy recovery is regarded as disposal. Incineration with energy recovery is considered as recovery. (COM (2017) 34 final, 4.) In this study focus of waste-to-energy processes is on thermal treatment of waste and as a definition, in this study waste-to-energy term is used to comprehend only the thermal treatment processes.

In the Figure 4 can be seen the situation of waste-to-energy plants and the amount of thermally treated waste in Europe in 2018. In total there were 492 waste-to-energy plants in 2018 of which France (121 plants) and Germany (96 plants) stands out with the biggest amount of facilities inside their borders. These two countries cover 44% of the total European WtE plants and 42 % of the total amount of treated waste. Total amount of treated waste in the 492 facilities was 96 million tons in 2018. As a comparison, in 2010 there was 452 WtE plants in Europe, so there has been increase of 40 plants in eight years. (Confederation of European Waste-to-Energy Plants, 2021b.)

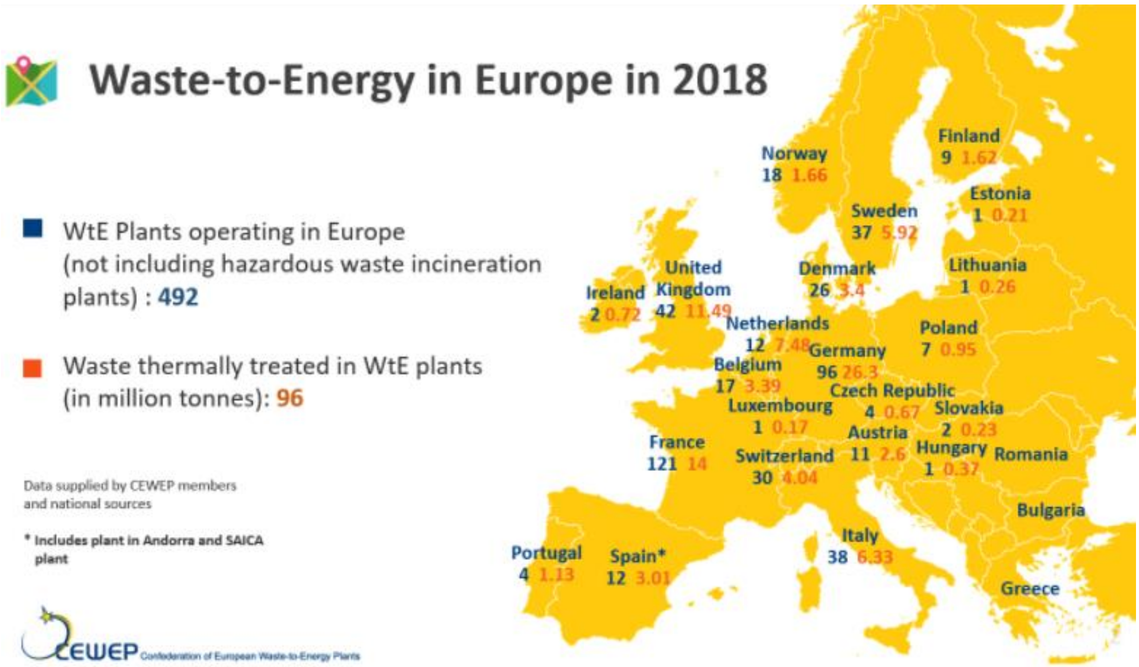

Figure 4. Waste-to-Energy plants in Europe, 2018. (Cewep, 2021b).

At this point it should be noted that millions of tons of waste have been exported outside the EU in the past decades. In addition, losing the resources from our own economies, harmful environmental and health impacts have been caused to the destination countries that usually lack decent waste treatment. EU is planning actions to prevent the waste export to third countries and developing further its own recycling systems to be able to take care of all wastes generated in EU region inside the boarders. (COM (2020) 98 final, 14-15.)

When incinerated there is always impacts on environment. The biggest environmental impacts of waste-to-energy are the emissions in the air, waters and soil in the form of fly ash and bottom ash and the residue from air pollution control devices. The amount and property of ashes and residues depend on the quality of the used waste, used technique and chemicals. The bottom ash needs a proper treatment because they include metals, chlorine, sulfides and oxides. From bottom ash it is possible to separate materials that can be utilized further, for example metals are possible to recycle. The amount of bottom ash depends on the quality of waste but is usually between 10-30% of mass of the fuel. The bottom ash can be utilized in constructions for example in landfills or roads and reduces the use of virgin materials. Fly ash and the air pollution control residues are hazardous waste because of the high content of the heavy metals and chlorine. After stabilizing, the residue ends up to the landfill of hazardous materials. (Energiateollisuus Ry. 2015, 9). However, with the use of waste in energy production can be replaced the use of fossil fuels which reduces the GHG emissions, but it also increases the self-sufficiency in energy production. (Energiateollisuus Ry. 2015, 9.)

3.1.1 Solid recovered fuel and refuse derived fuel

The residual waste that can't be reused or recycled is directed to incineration. Waste can be incinerated in mass-fired combustion system where pre-treatment of the waste is minimized, but to make waste more homogenous and increase the energy content, the waste still needs processing. Solid recovered fuels (SRF) are treated by mechanical treatment or mechanical biological treatment from solid non-hazardous waste. SRFs can be produced from household waste but also from commercial and industrial waste as well as construction and demolition waste. In addition, some single waste streams like rubber or dried sludge may be used too. SRF is used as a fuel or as a co-fuel in power plants or cement kilns and combined heat and power plants to produce electricity and heat by gasification or incineration. (European Recovered Fuel Organisation. 2016.)

SRF is a name used for recovered fuels which properties follow the requirements of European standards for SRF. The standard EN15359 sets the requirements for quality, specifications, and environmental performance that fuel needs to fulfil. Refuse derived fuel (RDF) is a common term for other waste fuels that are made of waste fractions that remain after other waste treatment operations. RDF is not standardized fuel and the properties that European standard requires are not determined. (European Recovered Fuel Organisation. 2013.)

Table 1 presents the classification system for SRF by standard SFS-EN 15359 which includes the European standard EN 15359. The system is based on an economic (NCV, net calorific value), a technical (chlorine content) and an environmental (mercury content) characteristic. Net caloric value presents how much energy the fuel includes, and this way gives an economic aspect for the fuel. Characteristics are divided to five classes by limit values for each class. The class code for a fuel can't be expressed by using only one factor but using all characteristics. Standard SFS-EN 15359 (2014, 17.) gives an example of a classification: "The class code of a SRF having a mean net calorific value of 19 MJ/kg (ar), a mean chlorine content of 0,5 % (d) and a median mercury content of 0,016 mg/MJ (ar) with an 80th percentile value of 0,05 mg/MJ (ar) is designated as Class code NCV 3; Cl 2; Hg 2."

Table 1. Classification system for solid recovered fuels. (SFS-EN 15359. 2016).

Classification characteristic	**Statistical measure**	**Unit**	**Classes**				
			1	**2**	**3**	**4**	**5**
Net calorific value (NCV)	Mean	MJ/kg (ar)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Classification characteristic	**Statistical measure**	**Unit**	**Classes**				
			1	**2**	**3**	**4**	**5**
Chlorine (Cl)	Mean	% (d)	≤ 0,2	≤ 0,6	≤ 1,0	≤ 1,5	≤ 3
Classification characteristic	**Statistical measure**	**Unit**	**Classes**				
			1	**2**	**3**	**4**	**5**
Mercury (Hg)	Median 80th percentile	mg/MJ (ar) mg/MJ (ar)	≤ 0,02 ≤ 0,04	≤ 0,03 ≤ 0,06	≤ 0,08 ≤ 0,16	≤ 0,15 ≤ 0,30	≤ 0,50 ≤ 1,00

Apart from classification, standard SFS-EN 15359 requires certain features to be specified for the fuel. These are origin of the waste, particle form and size of the SRF, ash content (dry bases), moisture content as received, net caloric value and chemical properties such as chlorine content as dry bases and content of heavy metals. One important property of SRF which is not mandatory in the standard is the biomass content that can be used to calculate the emissions of biomass and fossil carbon dioxide per unit SRF and then determine the emissions of the plant with the fuel or fuels it is burning. This is important when considering the emission trading system and the fact that the share biomass doesn't include the system.

Manufacturing of SRF requires different pre-treatment depending on if the waste is from households, from commercial and industry or from construction and demolition sector. According to Nasrullah et. al. (2014a, 2166) the mechanical treatment methods used to produce SRF are for example shredding, screening, magnetic and eddy current separation, pneumatic separation, optical sorting and near infrared sorting. When using waste from households as a raw material it requires more pre-treatment operations than other mentioned raw materials. In household waste there are wastes like glass, metals, biowaste, aluminium and PVC to be separated. Commercial and industrial waste comprises mainly from paper and cardboard and plastics (Nasrullah et. al. (2014a, 2167) while waste from construction and demolition sector includes wood, soil, metallic waste and stone-like material. (Finnish Environment Institute. 2004, 17.) Source separation is an important phase for all waste streams to diminish the need for pre-treatment and residues at the production plant of SRF. To have a scope of the yield of SRF, Nasrullah et al. (2014a, 1406) carried out the study in Helsinki metropolitan area and the results show that 62% of mass input of the commercial and industrial waste was recovered to SRF. Same kind of study was completed to construction and demolition waste and the yield of SRF was 44% of the mass of the total waste input. (Nasrullah et al. 2014b, 2166.)

The composition of the SRF depends on the origin of the waste and it may vary a lot. There are some important characteristics that have effect on combustion process and the equipment at the plants but also to air pollutions and heat or electricity yield for example. Properties such as NCV, moisture content, volatiles fraction, particle size, ash content and heavy metals are important when talking about the quality of the SRF. According to Alakangas et. al. (2016, 205) SRF’s NCV (as received) varies between 13-35 MJ/kg, moisture content 25-36 % (mass-%) and ash content 3-7 % (mass-%). When comparing the NCV (ar) for example to coal (NCV ar 24,3-25,1 MJ/kg) it can be seen that at its best the amount of heat or energy generated from SRF is bigger than with coal (completed combustion) which makes it a good option in replacing the coal from the energy yield perspective.

Table 2. Characteristics of SRF. (retold after Alakangas et. al, 2016, 205).

Fuel	NCV (ar, as received) MJ/kg	NCV (dry matter), MJ/kg	Moisture content, mass-%	Ash content (dry matter), mass-%
SRF	13-35	17-37	25-36	3-7

Moisture content of the fuel has effect on the incineration process for example lowering the combustion temperature and this way effects on the generation of air pollutions. The big share of biowaste in SRF increases the moisture content. The particle size varies depending on the application; power plants use rather smaller particle size than for example cement kilns and boilers that can handle larger particles. SRF has about 50-65% biogenic content (on energy basis) which means that fuel is renewable with that same share and it is partially considered as carbon neutral fuel. (Iacovidou E. et. al. 2018, 537.) Composition of the fuel can however be demanding to use. Fuels produced from waste are challenging mainly due to the high content of chlorine, alkaline and heavy metals. The equipment in the energy plant are exposed to corrosion and blockages are also possible. Handling the waste derived fuel is usually challenging and always includes healthy and hygienic risks as well as odors to the surrounds. Due to the high amount of heavy metals the end use of the ashes is also more complex. (Alakangas et. al. 2016, 199.)

3.2 Biomass

Solid biomass that is used for energy production are residues from forests and uncultivated lands, energy crops, wastes and residues from industry, agriculture, forestry and biomass from municipalities. These feedstocks are used to produce both electricity and heat and are used in co-combustion with other, usually fossil, fuels or as a single fuel. From primary energy production in EU in 2018 the produced energy from solid biomass (excluding charcoal) was 95,3 million metric tons of oil equivalent (about 4057 PJ) which covers 15% of the total primary energy production. (Statista. 2021b.) According to International Renewable Energy Agency (IRENA. 2019, 69) EU has a big potential in increasing the production of biomass and this way generating energy from residues. The potential is based on the calculation that currently not all of annual growth of the forest is harvested but left in the forest. With increasing the level of harvested forest to 100%, 1360 PJ (378 TWh) primary energy could be generated from logging and processing residues in EU28.

In this study the focus of solid biomasses is on wood chips and forest residues. When using the biomass as a fuel in thermal treatment the most important characteristics are elemental composition, ash content, volatile matter content, moisture content, heating value and bulk density. Properties of the fuel vary depending on wood species, where the feedstock comes from and of which part of the tree it is made of. A high moisture content causes decreased efficiency and lowers the heating value of the fuel. The NCV (ar) of different wood chips varies between 6-18 MJ/kg, however the NCV (dry matter) is 18,5-20 MJ/kg no matter which part of the tree the chips are made of. Moisture content of the different feedstock vary too and preferable moisture content in medium or large plants producing heat should be 40-55% while smaller CHP (combined heat and power) plants should use the fuel with moisture content 15 % or less to have sufficient energy efficiency. The particle size of the fuel is also an important feature and has a big effect on the functionality of the plant. The right size of the particle depends on the size of the plant and the technology used, but usually the length of the chips should be between 30-40 mm. (Putula, J. & Hilli, A. 2017, 1-3). There are different possibilities to classify wood fuels according to their quality, origin or trade name, for example ISO standard for solid biofuels (SFS-EN ISO 17225) or Unified bioenergy terminology by FAO (Food and Agriculture Organization of the United Nations). (Alakangas, E. et al. 2016, 65).

A new international study “EU Biomass Use in a NetZero Economy” (Material Economics. 2021, 8-9) from June 2021 explores the role of biomass in the future EU economy. Biomass use has had a huge growth in the 21st century in EU region. Between years 2000-2019 the increase in biomass use has been 150% mostly due to the introduction of policy incentives that drive phasing out the fossil fuels. Currently 40% of the biomass use is directed to material use and 60% is used for energy purposes. The use of biomass in various purposes is about to further increase and depending on the climate scenario, biomass used for energy and materials would be 70-150% higher by 2050 that it is today. The study estimates that a gap between biomass supply and demand in 2050 could be 40-70% which indicates that direction of biomass use needs to be reconsidered and prioritized.

The study presents a framework for prioritizing the biomass use and considering where it has the highest value. The study analyses the major uses for biomass in current applications, but also in future scenarios, like fiber production, chemicals production, passenger and freight road transport, aviation, shipping, industrial heating, building heating, power, and negative emissions. Shortly put, the result of the study is that biomass used as a material is more valuable than typical energy uses. For example wood is already used according to the hierarchy timber first, fiber second and energy use third. Study also states that long-term role for biofuels in a road transport and in shipping will be limited, but instead will have a potential role in aviation. Biomass use in energy sector will be specialized and small but still total volume makes it one of the top uses of biomass. (Material Economics. 2021, 38-40; 68.)

3.3 Sewage sludge

Sewage sludge is a residue from wastewater treatment and as a biomass it is a renewable option to replace the use of conventional fossil fuels in energy production. Sewage sludges origin from municipal and industrial water treatment plants. Forest industry also produces sludge, and they mostly utilize the sludge in combustion plants to produce energy in their own facilities. Utilizing the contents of sewage sludge is increasing as a part of EU legislation and strategy towards circular economy. Sewage sludge contains valuable nutrients that can be recycled but it also includes energy that can be utilized thermally, by incineration, pyrolysis and gasification, or biologically, by composting and anaerobic digestion. There are, however, legislation that restricts the utilization of sewage sludge due to the pathogens and harmful substances. (Pöyry Finland Oy. 2019, 9-10.) Thermal treatment methods produce end products like char and gases, which can be used as a fuel in heat or power production, but also bio-oils that can be refined further to transportation fuels for example.

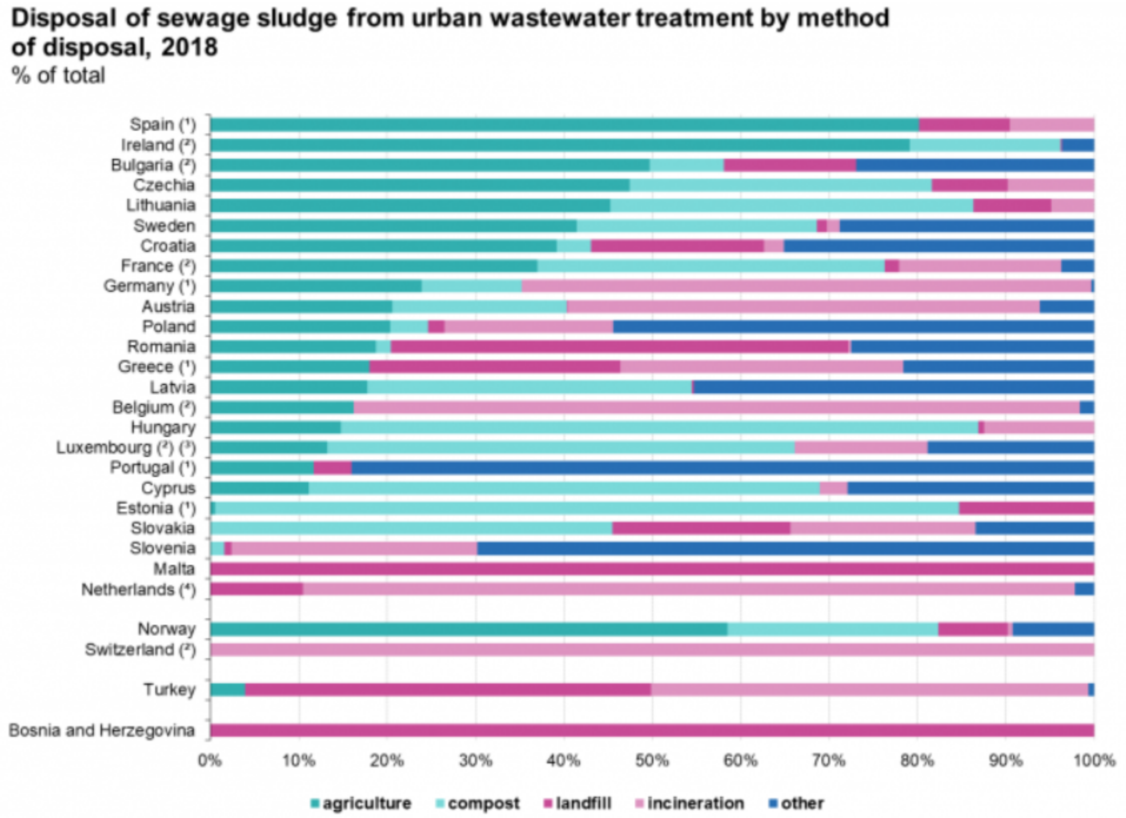

Figure 5. Disposal of Sewage sludge from urban wastewater treatment by method of disposal, 2018. (Eurostat. 2021d.)

The Figure 5 shows the situation of how sewage sludge has been treated in EU countries in 2018. Reported methods are agricultural use, compost, landfilling, incineration and other. The variation between the member countries is huge; for example, Switzerland incinerates all the sludge while Malta and Bosnia and Herzegovina landfilled all in 2018. Sweden incinerated very small share, only 1,2% but used agriculture as a main method with 41,1% share. Poland incinerated 19,1% of all sludge and 54,4% was treated with other methods. There is no recent data from UK available. (Eurostat. 2021c.)

3.4 Technologies

There are several thermal or thermochemical treatment methods available, in commercial use and under development too. Solid waste, solid biomass and sewage sludge are all fuels that are usable with small pre-treatment or they can also be further refined to different fuels, like pellets, to improve the properties of the fuel. All these fuels can be used as co-fuel or use as a single fuel in electricity production or combined heat and power (CHP) production. Here are presented the technologies that are used for thermal treatment of solid waste, solid biomass and sewage sludge.

The most common combustion methods for solid waste are combustion in mass-fired combustion where pre-treatment of the material is minimal, or fluidized bed combustion where pre-treated fuel can be combusted. With incineration methods it is possible to reduce up to 90 % of the waste volume and 75 % of the mass. Technology used for mass combustion is usually grate combustion in which the fuel is fed on the moving grate and is mixed during the combustion. The combustion air is added to the system below the grate. The variation in the particle size occurs and the feedstock may include hazardous material as well. The efficiency of the grate combustion is lower due to the lack of pre-treatment of the fuel. Fluidized bed combustion is another common combustion technology where various fuel like coal, solid waste and sludge for example can be operated. Fluidized bed combustion has relatively high efficiencies, but it requires pre-treatment of the fuel to reach more homogenic composition and smaller particle size and this way higher efficiency. In fluidized bed combustion the fuel floats in the sand bed (could be also limestone) in boiler and the air that fluidizes the bed is blown from the below mixing the sand and the fuel. The most common types are circulated and bubbling fluidized bed boilers. Compared to grate combustion the emissions to air are notably lower in fluidized bed combustion. (Tchobanoglous et. al. 1993, 618-623; Sustainable Sanitation and Water Management. 2021.) Both combustion technologies can be used also for solid biomass as well as for sewage sludge.

Alternative technologies for conventional combustion-based incineration are gasification and pyrolysis. Combustion is a thermal treatment with the presence of oxygen, but in pyrolysis oxygen doesn’t appear. Pyrolysis is one of the used thermal treatment methods to produce gases, solid fuels like charcoal or liquid fuels like bio-oil from the pre-treated solid waste. Pyrolysis takes place at the temperature of 250-700 °C and the used temperature depends on the purpose of the final product. Yield of the charcoal is around 30% of the dry biomass, but the yield is dependent on the circumstances, pressure, residence time and the temperature. Gasification is a technology of partial combustion of organic substances to produce gases to be used as a fuel or as a feedstock. There are many gasification processes that could be used for MSW or sewage sludge and reactors like fluidised bed gasifier, current flow gasifier, cyclone gasifier and packed bed gasifier are used. For gasification process it is important that the properties of the waste are kept in the certain limits, and this is why pre-treatment is important for MSW. Gasification takes place in 500-1600 °C. (Benavides, J. et al. 2019, 57-59.)

Besides the treatment of waste, gasification and pyrolysis have both also additional objectives like converting certain waste fractions to syngas and reduce flue gas volumes and this way reduce the requirements of cleaning requirements of flue gases. Pyrolysis and gasification can be used also to recover the chemical value of the waste instead of the energetic value and products may be used as a feedstock for other processes. Gasification, pyrolysis and combustion are however more likely combined and integrated in the same installation and then energy value is recovered. (Benavides, J. et al. 2019, 57-59.)

Sewage sludge has not that long history in energy production and is more like in developing phase on that field. However, the potential of the sludge in energy production and its valuable contents has been discovered and among the tightening legislation and demands for circularity sludge is now more investigated feedstock. Pöyry Finland Oy (2019, 23-24) has made a study about the thermal treatment methods for sludge in Finland. The presented techniques are already in commercial use or close becoming to the market. In the Figure 6 the options are detailed, and the utilizing possibilities are presented. Thermal treatment methods presented are thermal drying, HTC (hydrothermal carbonization), torrefying and pyrolysis, gasification and combustion.

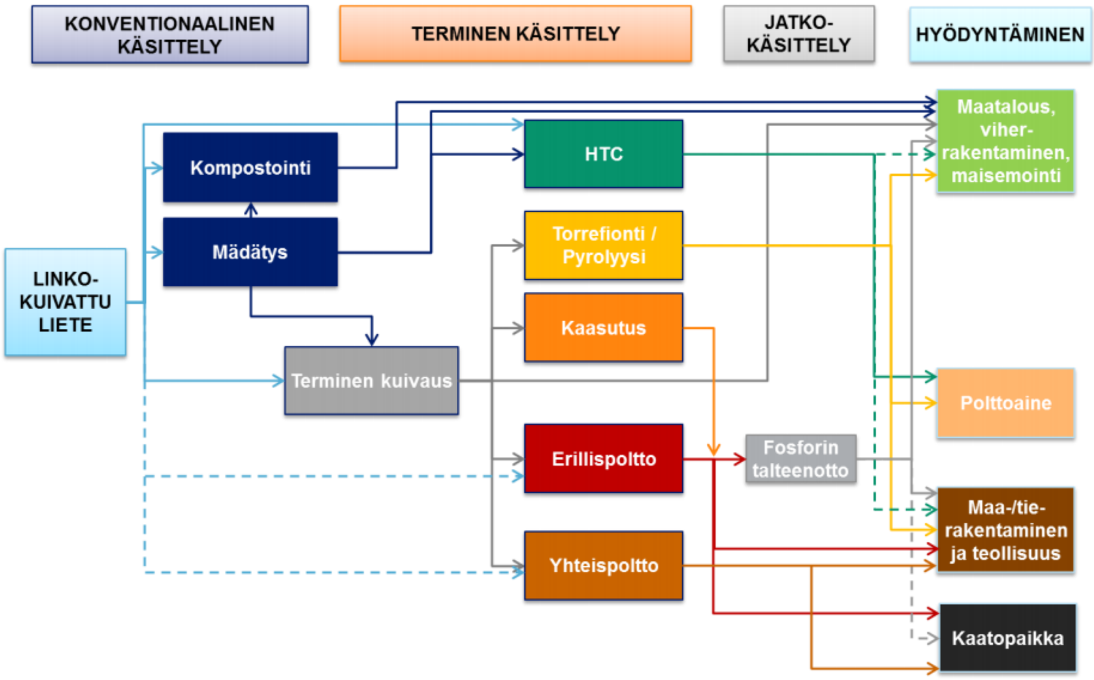

Figure 6. Thermal treatment technologies of sewage sludge. (Pöyry Finland Oy. 2019, 24).

Thermal drying is used as a pre-treatment method for other thermal treatment methods, but thermal dried sludge can be used in soil improvement without any other treatments too. In thermal drying moisture of the sludge is reduced with heat which reduces the mass, increases the heating value, stabilizes and makes the handling and transportation of the material easier. After the thermal drying dry matter content depends on the purpose of the use and it may vary from 40% to 90% (total solids). (Pöyry Finland Oy. 2019, 25.)

Hydrothermal carbonization is a process where moist sludge is treated in anaerobic circumstances, high pressure and 180-250°C temperature. The end products are liquid reject, gas and dried solid matter, which can mechanically be dried to 50-70% dry matter. The main product is the solid matter (char) that, for example, can be further refined to pellets. Its caloric value is high enough to be used as a single fuel in combustion. Calorific value for HTC treated sewage sludge is usually about 12-15 MJ/kg. (Pöyry Finland Oy. 2019, 34-36.)

Torrefying and pyrolysis are both thermal treatment methods where sludge is thermally decomposed in anaerobic conditions. In the process the chemical composition of the organic material changes and the moisture leaves. Products from both of the processes are char, gaseous products and steam, which after cooling transforms to liquid oil products. Char produced from sewage sludge with pyrolysis is dried to 80-90% dry matter and can be used in soil improvement, in composting, as a filtration material (in water treatment) or as a fuel. The difference between the two methods is that temperature in torrefying process is lower than in pyrolysis. However, torrefying is not common method and torrefying from sewage sludge has been studied only a little. The method is mostly used for ligno-cellulosic biomasses like wood chips or bark. (Pöyry Finland Oy. 2019, 39-42; 45-49.)

In gasification process biomass is gasified in high temperature, 800-900 °C, with limited oxygen to produce gas that can be utilized as a fuel. There are several gasification techniques and the most important are fixed bed gasification, fluid bed gasification and entrained flow gasification. Depending on the technology 60-80 % of energy content of sewage sludge can be converted to product gas. Gasification plants that use sewage sludge as a raw material are operating though plants that use wooden materials are more common. (Pöyry Finland Oy. 2019, 55-59.)

Thermally pre-treated sludge can be used as a fuel in incineration plants and there are several technologies available for sewage sludge incineration. The most common used technology for biomasses and for sludge is fluidized bed technology but also grate firing is used for sludge. (Pöyry Finland Oy. 2019, 63-64).

Suitable thermal treatment methods for wooden solid biomass are combustion, gasification and pyrolysis, combustion being the widest used method. The end products from the gasification and pyrolysis processes are the same as presented earlier, gaseous, liquid and solid products to be used as a fuel in energy production or to be refined for transport sectors needs for example. Combustion and gasification are primary conversion technologies used to produce heat electricity or both (CHP). The efficiency of the power plant can be increased above 80 % by also utilizing the thermal energy from combustion instead producing only electricity. (Malico. 2019, 968-971.)

4 SWEDEN

Sweden is one of the Nordic countries and it has 10,28 million inhabitants. The GDP of Sweden in 2019 was 530,88 billion USD (The World Bank. 2021b) and per capita 51 615 USD (The World Bank. 2021a.) In 2018 CO_2 per capita in Sweden was 5,4 tonnes of CO_2 eq which was the second lowest result in EU region after Liechtenstein (4,8 tonnes of CO_2 eq). (Eurostat. 2021b.) Circular material use rate was 7%. Circular material use rate (circularity rate) is % of the total material use and it measures the share of material recovered and fed back to the economy. The higher the rate is the more secondary materials replace the primary raw materials and this way reduces the environmental impact. (Eurostat. 2021a).

What can be seen for example from the CO_2 emissions per capita is that Sweden is already on the good road in decarbonizing the country and over half of the used energy is from renewable sources. In 2018 it was the top country in EU; 54.6% of the energy used came from renewable sources. The biggest renewable sources in energy supply are biofuels and waste and hydropower; biofuels and waste are mostly used to produce heat and hydro is used in electricity production. (Sweden. 2020.) Heating in Sweden is mostly supplied with district heating which is heavily bioenergy based while electricity is mostly produced from hydropower and nuclear. (IEA. 2021b.) The sources of total energy supply (coal, natural gas, nuclear, hydro, wind and solar etc., biofuels and waste and oil) can be seen in the Figure 7 which shows the development of each source between 1990 - 2019. Within the period the total energy supply in Sweden has increased with 3,9%. The biggest increase has been with wind, solar, etc. and biofuels and waste and the biggest decrease has been with fossil fuels, coal and oil.

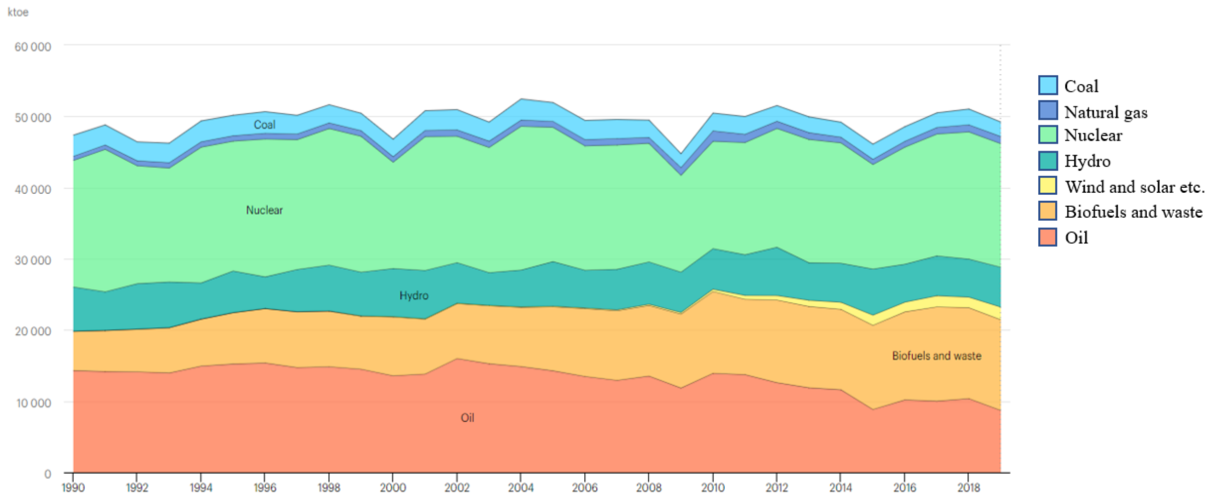

Figure 7. Total energy supply by source in Sweden, 1990-2019. (IEA. 2021b).

The Figure 8 compares the shares of each source in 1990 and 2019 of the total energy supply. The figure clearly shows the trend in the use of renewable energy sources. Of fossil fuels only natural gas has grown slightly, coal and oil has decreased.

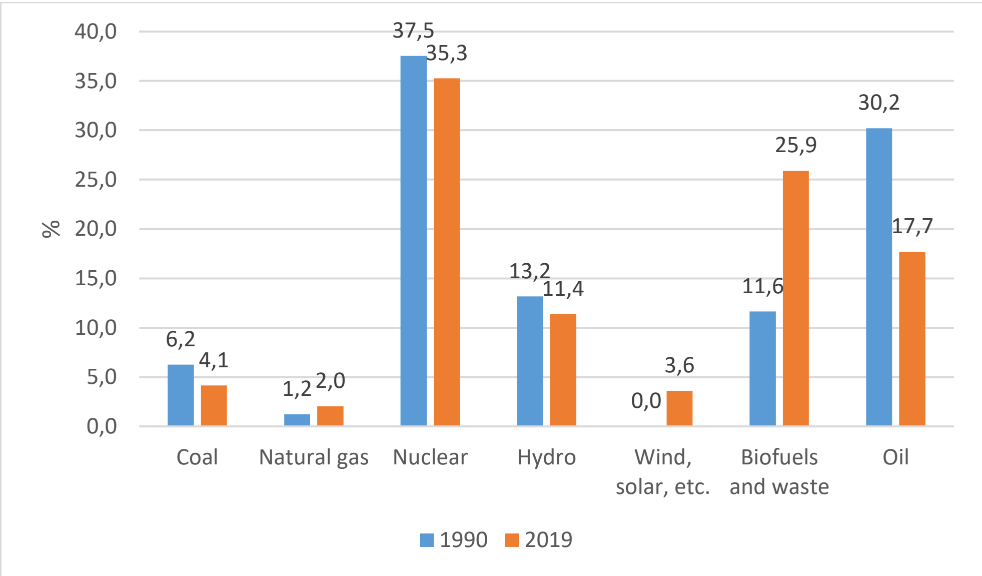

Figure 8. Share of energy supply by source in Sweden, 1990 and 2019. (Calculated after IEA.2021b).

4.1 Sweden's energy and climate policy

The most important legislation related to the environment and sustainable development in Sweden is the Swedish Environmental Code (808/1998) which constitutes a framework legislation to environmental protection. It came into force in 1999 and it comprises of 7 sections including large number of ordinances and regulations. (Naturvårdsverket. 2021a.) Sweden's energy and climate policy is following the pillars of EU policies and aims in combining the sustainable, competitive and secure supply of energy. The report of Sweden's energy and climate policy is following the five dimensions of EU's Energy Union. Sweden wants to be a leader in environmental and climate issues and aims to be the first fossil fuel free nation in the world and in addition, by 2040 all electricity generated in Sweden should be from renewable sources. (The Ministry of Infrastructure. 2020, 4-5.)

Ambitious future objectives are included in the four main climate policy targets named in the national energy and climate policy (The Ministry of Infrastructure. 2020, 15-16):

- an overall environmental quality target, with no specific deadline, to help limit rise in global average temperatures
- A long-term Swedish emission target for 2045
- Intermediate targets for Swedish emission outside the EU's emission trading scheme for 2020, 2030 and 2040
- A special intermediate target for greenhouse gas emissions from national transport (except for national aviation which belongs to the EU ETS) for 2030.

Long-term targets includes cutting the net GHG to zero by 2045 meaning that GHG must be at least 85% lower in 2045 compared to 1990 level. An example of Sweden's national intermediate target for non-ETS sector is to reduce GHGs by 2030 63% compared to 1990 level, which contributes 59% reduction compared to 2005 level. Target that EU set to Sweden by 2030 was 20% of the 2005 level by 2030 which means that Sweden's own targets are way more ambitious, and when realized, Sweden will overachieve the EU targets.

The target for share of renewables in 2030 is set for 65% of the final energy consumption by EU and Sweden doesn't have any additional national target. The target is for all energy consumption, including electricity, heating and transport. The Swedish government doesn't name or give any specific targets to different renewable technologies for the future, but the market development will show the used technologies. (The Ministry of Infrastructure. 2020, 20.)

4.1.1 The reference scenario

The Swedish Energy Agency's EU Reference Scenario includes estimations about the Sweden's energy consumption and generation in 2030. The reference scenario from 2016 is a key analysis tool of European Commission and it provides a benchmark of current policy and market trends in the areas of energy, transport and climate action. With the tool policy makers are able to analyse a long-term scene based on current policies. It should be noted that reference scenario doesn't consider the policies that took effect after 2016.

According to the scenario total consumption of bioenergy increases to 161 TWh in 2030, which is 4 TWh more than in 2020 so after year 2020 the increase in consumption of bioenergy is quite small. Bioenergy consumption in heating and cooling sector would increase with 12 TWh from 2017 to total 121 TWh in 2030 and 9 TWh of the increase would be covered with solid biofuels, mostly due to the increase in heat generation in district heating plants and heating in housing and service sector. The total electricity generation capacity in Sweden will be increasing from 39 GW in 2017 to 45 GW in 2030. Between the period two nuclear reactors are expected to be decommissioned. The biggest increase in capacity is with wind energy 5 GW and solar energy 2 GW between 2017-2030. Bioenergy consumption in electricity sector increases only with 2 TWh between 2020-2030 and solid biofuels cover most of the increase. (The Ministry of Infrastructure. 2020, 21-23.) The Figure 9 shows how the consumption of biofuels was divided in 2005-2017 and estimated steady increase in consumption of bioenergy between years 2020-2030 in all sectors. Solid biofuels and renewable share of waste are the most used biofuels according to the scenario.

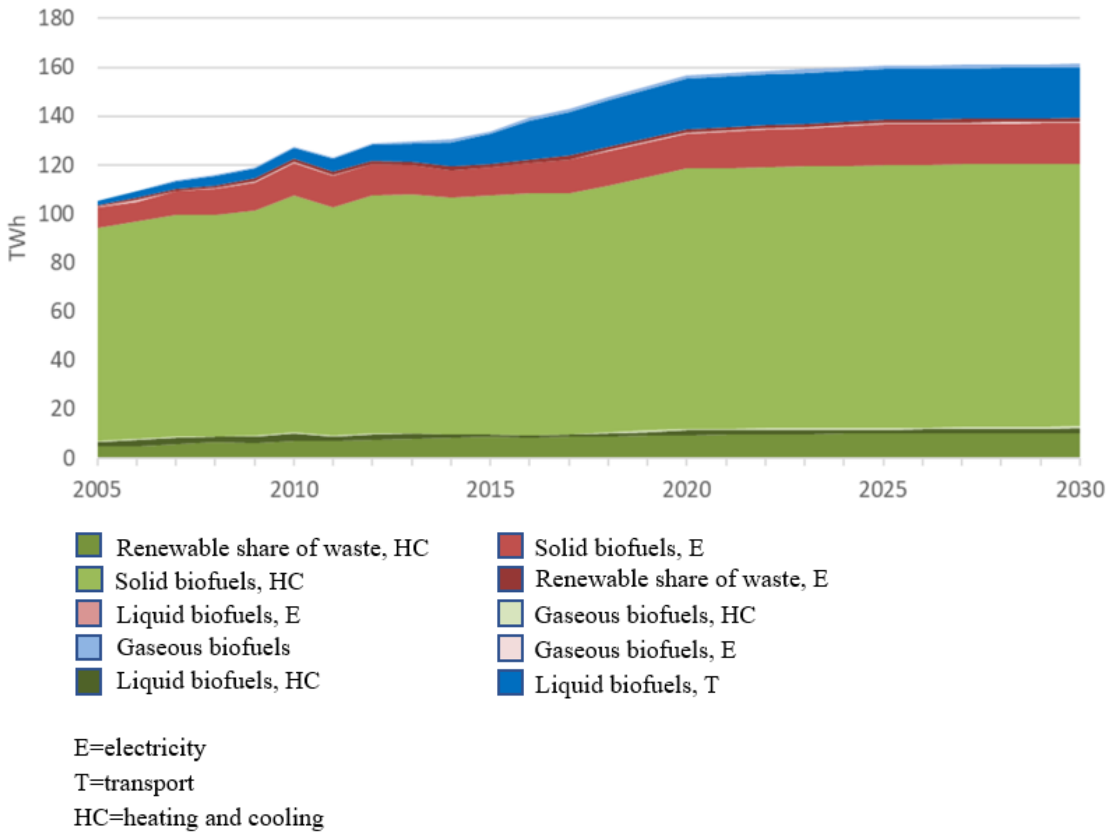

Figure 9. Bioenergy consumption in the Heating and Cooling, Electricity and Transport sectors from 2005 to 2017 by type of biomass and assessment in Sweden according to the EU Reference Scenario up to 2030 [TWh]. (The Ministry of Infrastructure. 2020, 23).

The Figure 10 is based on EU reference scenario giving an outlook of total input of different energy carriers to years 2016-2040. The most remarkable changes are the decrease of the nuclear power and the increase of solar and wind power. It is estimated that about 60% of the nuclear power in Sweden is phased out around 2040. The higher electricity prices will effect on the increase of wind power from 2030 onwards and solar power follows with higher share. (The Ministry of Infrastructure. 2020, 146.)

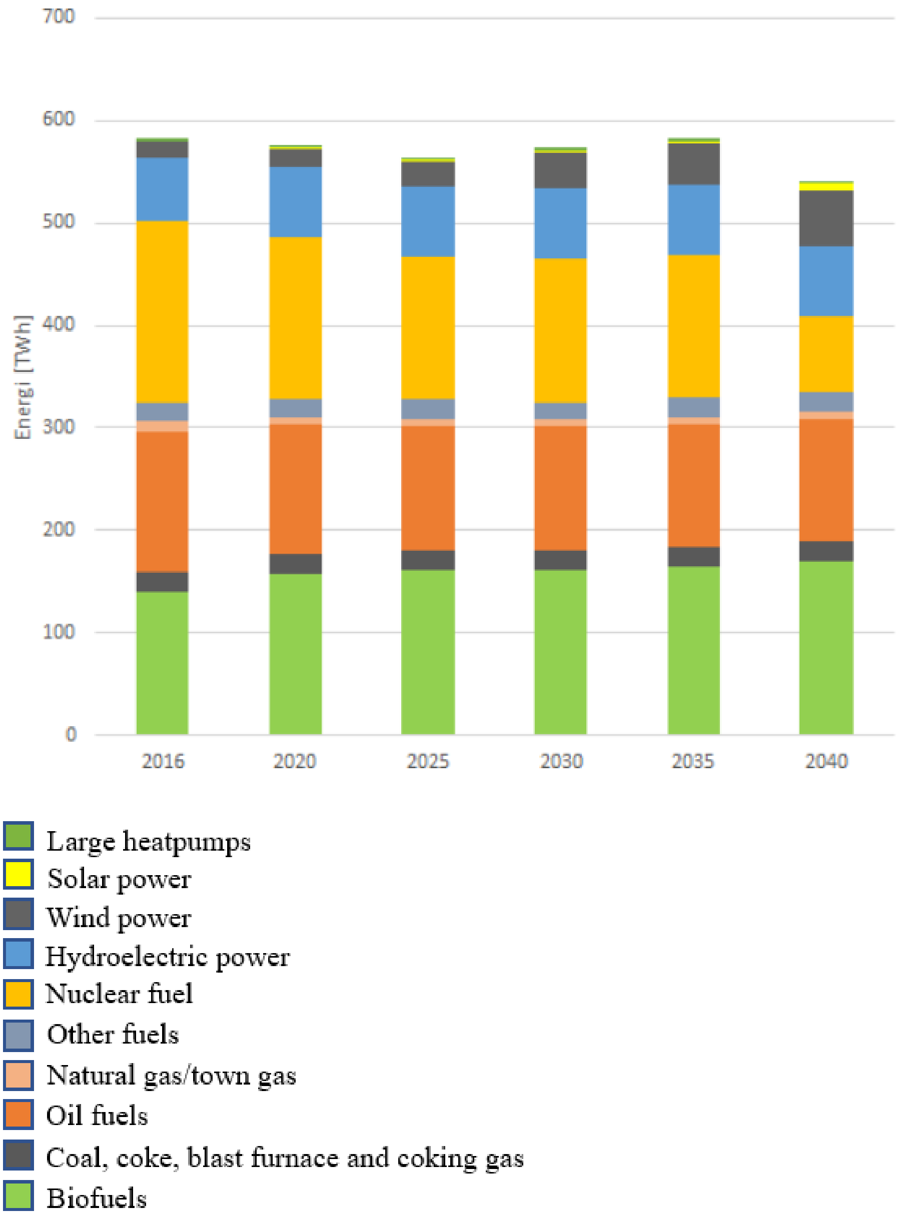

Figure 10. Total input by energy carrier in Sweden, according to the EU baseline scenario, TWh, 2016-2040. (The Ministry of Infrastructure. 2020, 146).

4.1.2 Policy instruments

In addition to EU policies Sweden has their own national policy instruments to achieve the ambitious climate goals they have set. In 2018 54,6% of the used energy in Sweden came from renewable sources which Sweden's rich supply of biomass and hydro power also contribute well. Sweden has several incentives to promote the use of renewable sources and diminish the use of fossil fuels in heat and power production.

Key policies that Sweden has on the field of energy supply are energy and carbon tax, waste incineration tax, electricity certificates, wind power initiative and support for solar energy. One of the most important tools to increase the growth of renewable electricity is the electricity certificate system which is a market-based quota system where certificates are earned by energy production from renewable sources and then certificates can be traded. The Electricity Certificates Act demands energy suppliers to prove that certain quota of the supplier energy is from renewable sources. Demand to the market is created by requiring retailers or users to acquire certificates according to their sales or consumption. Since 2012 Sweden has composed the electricity certificates system together with Norway. (Sweden. 2020.) The Swedish Government has decided to continue the electricity certificate system until 2045. (The Ministry of Infrastructure. 2020, 59).

To reach the 100% renewable electricity target by 2040 Sweden has a support system for photovoltaic cell systems and tax reduction for microgeneration of renewable electricity. These are for individuals as well as for companies and is aiming to increase the renewable share of produced electricity. Also, strategy to expand the wind power is necessary to reach the renewable energy target and it is under development. (The Ministry of Infrastructure. 2020, 60-61). Swedish Wind Energy Association (2021, 6-7) is estimating that wind power will increase from today’s 30 TWh to 120 TWh in 2040 at least. Assessment of the total need in 2040 would be around 200 TWh so the wind energy is playing a remarkable role in future electricity generation.

Carbon taxation, which Sweden has had since 2018 to all sectors that do not belong to EU ETS, has also remarkable role in decarbonization the Swedish energy sector. The taxes effecting in heating are carbon and energy taxes which are levied of the supply, import and production of the fossil fuels and basically fuels from renewable sources are excluded from the tax. The tax is based on the fossil content of the fuel and increases in stages. Since 1991 the tax has been increasing from SEK 0,25/kg CO_2 to SEK 1,18/ kg CO_2 (2019). (The Ministry of Infrastructure. 2020, 41-42.)

In April 2020 the new tax on waste incineration came into force in Sweden. The tax will be charged per tonne of waste and the rate will be increased in line with general price increase from 2023 onwards. In 2021 the tax is SEK 100 per tonne of waste. Biofuels, hazardous waste and animal by-products are not subjected to tax. (The Ministry of Infrastructure, 60) The tax on waste incineration is expected to increase the amount of waste directed to recycling instead of energy recovery.

The waste sector's key policies are ban on landfilling flammable and organic waste, collection of measurement data from dumps, waste tax act, producer's responsibility and municipal waste planning. Ban on dumbing the flammable and organic waste was introduced in 2001 and it includes instructions of collecting and disposing the methane from landfills. In 2000 Waste Tax Act which imposes tax on the waste disposed of in the landfill was introduced. The tax increases gradually and in 2019 it was SEK 520 per tonne of waste and should act as a motivator not to bring the material to the landfills. The purpose of legislation of producer responsibility is to promote the sorting, collecting and recycling of waste but also to reduce it. The environmental Code of Sweden states that every municipality need to have a waste plan for the waste management, and this gives responsibility but also opportunity to organize the system as it suits best for the area. (The Ministry of Infrastructure 2020, 54.)

4.1.3 Fossil free Sweden and Klimatkliv

In addition to the policy instruments Sweden has programs to promote sustainability or renewable sources of energy and as an example here are presented two of them. A roadmap to fossil free heating sector was introduced in 2019 as a part of the Government's Fossil Free Sweden initiative. The roadmap has been developed in collaboration by fifty actors in the heating market with consultant and it presents the actions that the sector is willing to do and gives suggestions to politicians to create the right conditions to reach the goals. The main goals in the roadmap are the heating sector to be fossil free in 2030 and climate-positive in 2045. Heating sector in Sweden is already quite well based on renewables but remaining fossil fuel use should be phased out and cover it with recycled energy like residual heat from industry, businesses or buildings, energy recovery from waste and other renewable fuels. Sorting and recycling of waste needs to be organized so that the fossil content (plastics for example) in the residual waste, that goes to energy recovery, is minimized. Like other sectors, also heating sector is interested in carbon capture and storage to neutralize the emissions from the incineration of fossil-based content of the waste. Important point is also to increase the efficiency of the biofuel boilers to achieve the best use of feedstock from forests. (Fossil Free Sweden. 2019, 49-51). There are several commitments how roadmap instructs actors in achieving the goals but here are mentioned only the most relevant issues that may concern this study and its results.

Since 2015 Sweden has had an initiative “Klimatkliv” where all kinds of organisations (non-EU ETS) have been able to apply for a climate investment, for example charging infrastructure for electric vehicles, biogas plants, switching from fossil oil to biofuel or district heating, the expansion of smaller district heating networks, destruction of nitrous oxide in the healthcare sector, cycle paths and cycling infrastructure. The purpose of the initiative is to reduce emissions and as a basis for receiving the support is estimated reduction in GHG emissions per crown. (The Ministry of Infrastructure, 44).

4.2 Sweden’s waste plan

Sweden’s waste legislation mainly bases on EU regulations and EU directives of waste have been built into the Environmental Code. The regulations that concerns waste management are part of the Environmental Code too, but the Waste Regulation (927/2011) also includes regulations about the Swedish waste management. (Naturvårdsverket. 2021b, 23–24.) In Sweden’s waste plan 2018-2023 the concentration is on circular economy and prevention of waste and reducing the impacts on human health and environment, according to the EU’s waste hierarchy. Plan includes also investing on research and new technologies to promote the circular economy. One of the Governments collaboration programs named in the waste plan is program towards circular, biobased economy and it has named biofuel production as one of the areas of concentration. (Naturvårdsverket. 2021b, 8-9; 93.)

In 2019 half of the household waste was directed to incineration and the target for following years is to improve the sorting in households to separate especially paper and plastics. The analysis shows that 60% of the waste going to incineration could be recycled. Producer responsibility has contributed to collection and recycling of packaging waste, but also cars, tires, electronics, batteries and medicine. The landfilled waste has decreased remarkably while energy recovery of the waste has increased. The reason for decreased landfilling is a ban for dumping of combustible and organic waste under the Ordinance (2001:512) on the Dumping of Waste. For other material there is a tax for disposing the waste on the landfill. (The Ministry of Infrastructure, 54.) However, according to the waste hierarchy, recycling is high on the agenda for future years with the idea to reduce the need of virgin materials in industry and keeping the materials on the loop. (Naturvårdsverket. 2021, 13-14).

In Sweden the responsibility of collecting the waste is divided between municipalities, producers and other waste owners but municipalities are responsible of household waste. Contractors offer services for municipalities and producers to handle the waste for further purposes, but the municipalities mostly own the waste handling facilities like biological treatment and waste-to-energy facilities and landfills. Several recycling companies offer sorting and recycling services for municipalities to treat the residual waste. (Naturvårdsverket. 2021b, 30-33).

4.3 Biomass and wood by-products

Bioenergy is a dominant fuel in district heating in Sweden. By 2015 roughly 60% of the energy in district heating was from biofuels and 15% waste. About 8% was residual heat from forest industry and together all these sources cover 83% of the Sweden’s district heating. (IRENA. 2019, 14).

Bioenergi (2021b) has put together on the map all bioenergy heating networks in Sweden in 2021 using biofuels (wood fuels, pellets, bio-oils, arable fuels etc.), waste or peat to produce district heat. Figure 11 shows all networks and total there are 556 district heat networks that generate bioheat and 279 biggest networks are also named in the map by the owner. Also, residual bio-heat from forest industry is included in the map. The map shows the fuel or fuels that each plant uses and in addition size of the dot tells about the magnitude of the network. The map includes the WtE plants using only waste as a fuel.

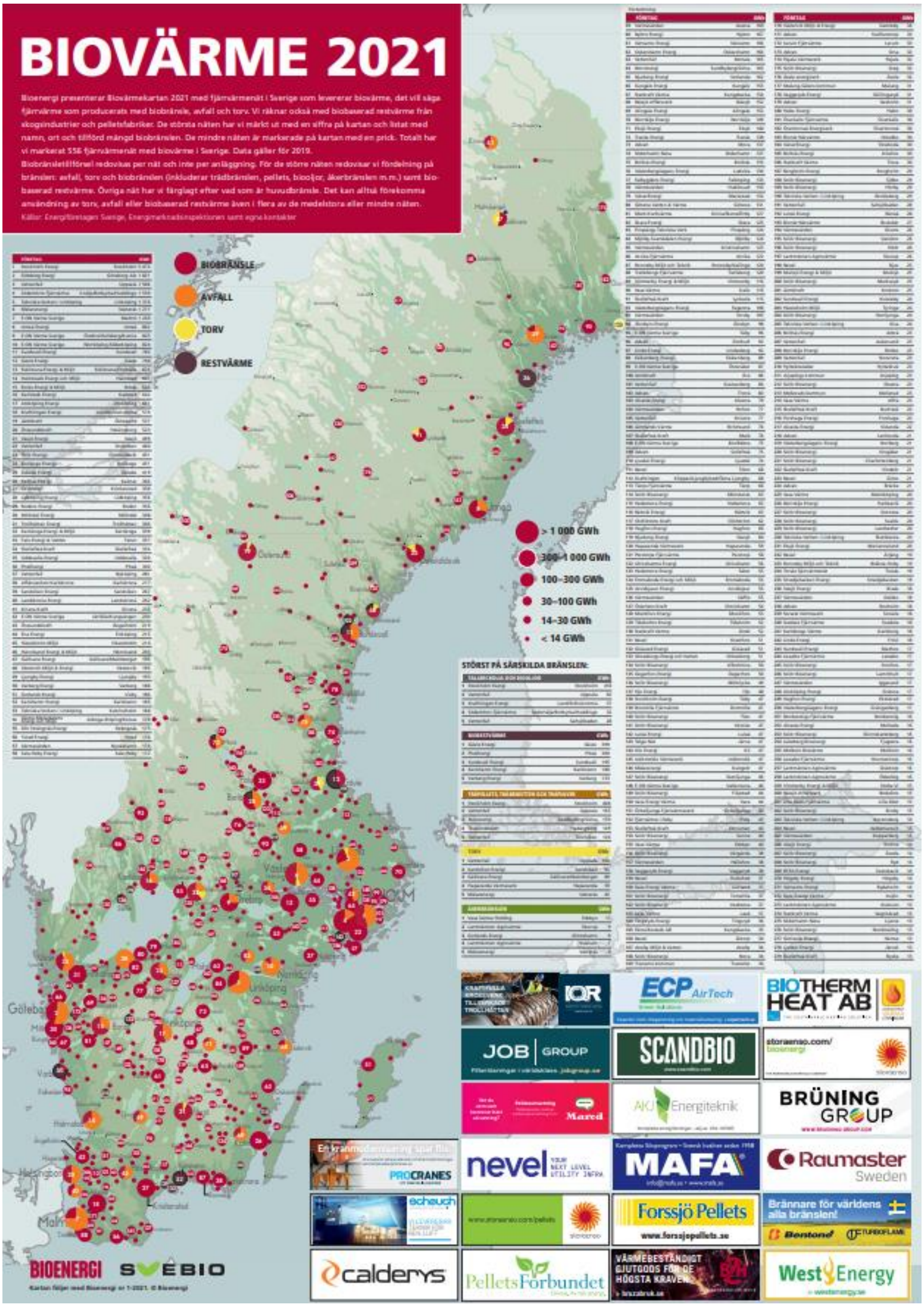

Figure 11. Bioheating networks in Sweden 2021. (Bioenergi. 2021b.)

As mentioned earlier in this study, Sweden has had a carbon tax since 2018 and that tax reform has been the most important factor in advancing the use of renewables and enabling the competition with fossil fuels. The price of heating oil has nearly doubled after the tax but also volumes of biomass and improved harvesting and conversion technology has lowered the costs of biomass and enlarged the price difference between fossils and renewable biomass. This change drives to investments in new boilers and feedstocks in energy production. In addition to the carbon tax, the Swedish Government provides incentives at local level to investments and infrastructure of the heat and CHP plants. (IRENA. 2019, 11-12, 15.)

The priority in biomass use is using it as a material before using it in energy production. The highest value wood is a sawmill product for example wood used in buildings or furniture and the medium value products are pulp, paper and board. The lowest value has the by-products used in energy production, such as residues and waste from lumber and pulp industry and the energy wood from harvesting and thinning. Residues are generated throughout the supply chain, from harvesting to waste management, so feedstock for energy use is available. There is no governmental regulation for wood use, but the markets are driving the allocation. (IRENA. 2019, 24-25.)

In the report of IRENA there is no compiled statistics about biomass used in production of other biofuels like bio-oils. However, there is a potential for a largescale production of other biofuels in Sweden from biomass and forest residues are also important feedstock for Swedish biorefineries. Kumar, A. et al. (2021) writes that Sweden has one of the biggest biorefinery in the Europe using wood as a raw material and producing green products that can be refined to textiles, medicine or food supplies. Besides this one, there are several other biorefinery companies in Sweden converting biomass to different products and fuels, like methanol from wood.

4.4 Waste-to-Energy

6 156 000 tons of waste was incinerated in 2019 of which household waste covered 39% and other waste, mostly industrial waste, 61%. Energy recovery from waste increased

with 6% compared to previous year being 18,5 TWh. 88% of the recovered energy was used in heating and 12% in electricity production. Heat is directed to district heating systems but also 0,1 TWh was used in district cooling. The Figure 12 shows the distribution of collected household waste to different treatment methods between years 2015-2019.

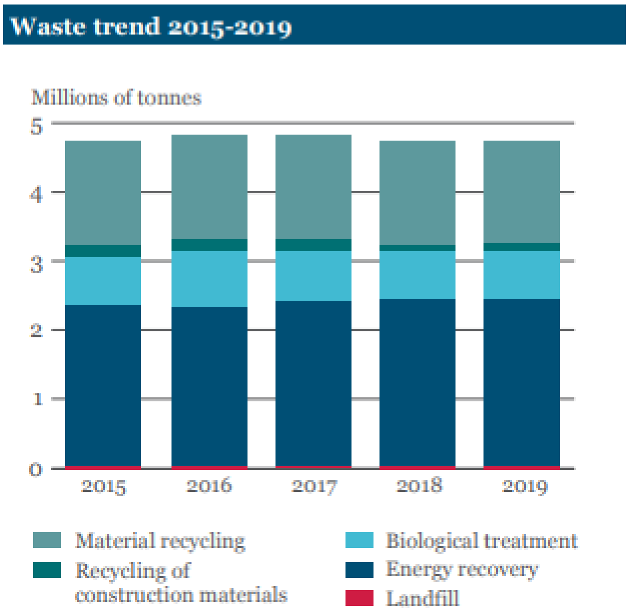

Figure 12. Quantity of household waste in different treatment methods in Sweden in 2015-2019. (Avfall Sverige. 2019b, 7).

Energy recovery is the most used treatment method for household waste and in 2019 half of the household waste was incinerated. 32% of the household waste was recycled, 14% was treated by biological treatment and 0,8% went to landfill in 2019. Of all waste generated only 0,8% ended up to the landfill in 2019. (Avfall Sverige. 2019b, 7.) In industrial sector, the biggest share of the waste generated for example in mining, paper and pulp and metal, waste is treated in the facility where it is generated. For example, sludges or bark from pulp industry goes mostly to energy recovery but there are also landfills at the sites. (Naturvårdsverket. 2021b., 46-47.)

There were 35 incineration plants incinerating household waste in Sweden in 2019. The availability of the combustible waste was lower than capacity of the energy recovery plants and due to this 1,5 million tons of waste was imported from other European countries to be treated in Swedish plants in 2019. (Avfall Sverige. 2019b, 30-33.)

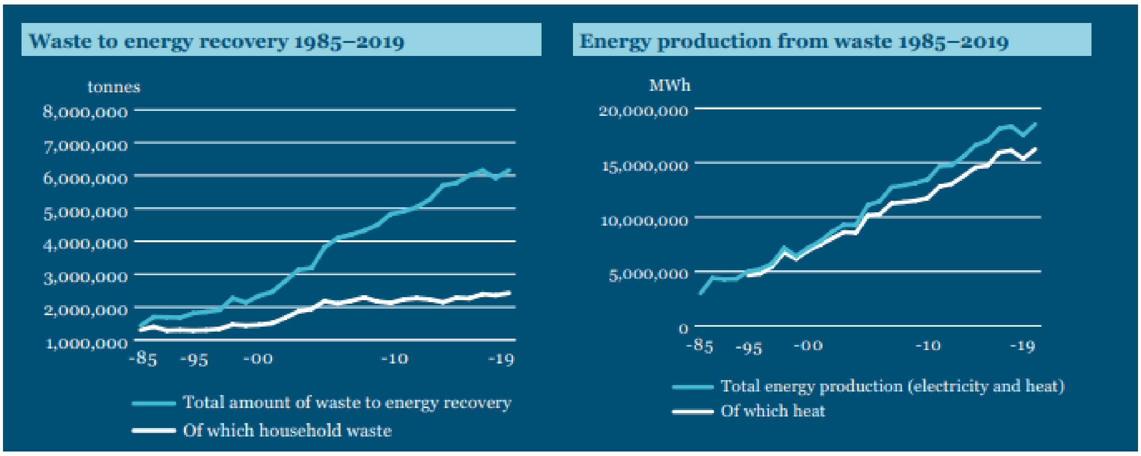

Figure 13. Development of energy recovery from waste in Sweden in 1985-2019. (Avfall Sverige. 2019b, 33.)

The Figure 13 shows the development of the use of waste in energy recovery and the energy production from waste between years 1985-2019. The table includes both household waste and other waste and it shows that energy utilization from waste has been increasing during the period as well as the total amount of used waste. However, the use of household waste has not been increasing as much as the use of other waste. Reasons for that may be the reuse and recycling demands imposed to municipal waste; 65% of the waste needs to be recycled by 2035 including intermediate phases 55% by 2025 and 60% by 2030.

4.4.1 Capacity of energy recovery in future

In 2019 capacity for energy recovery was 6,7 million tons and imported waste covered 1,4 million tons of the capacity. After 2019 there were plans for new investments and in 2020 capacity was estimated to be 6,9 million tons after E.On’s and Stockholm Exergi’s plans to build more WtE capacity. Between the years 2020-2024 it is estimated that 1,1-2,4 million tons imported waste is needed, depending on built capacity and if the recycling targets of municipal and construction waste are achieved. (Avfall Sverige. 2019a, 5.)

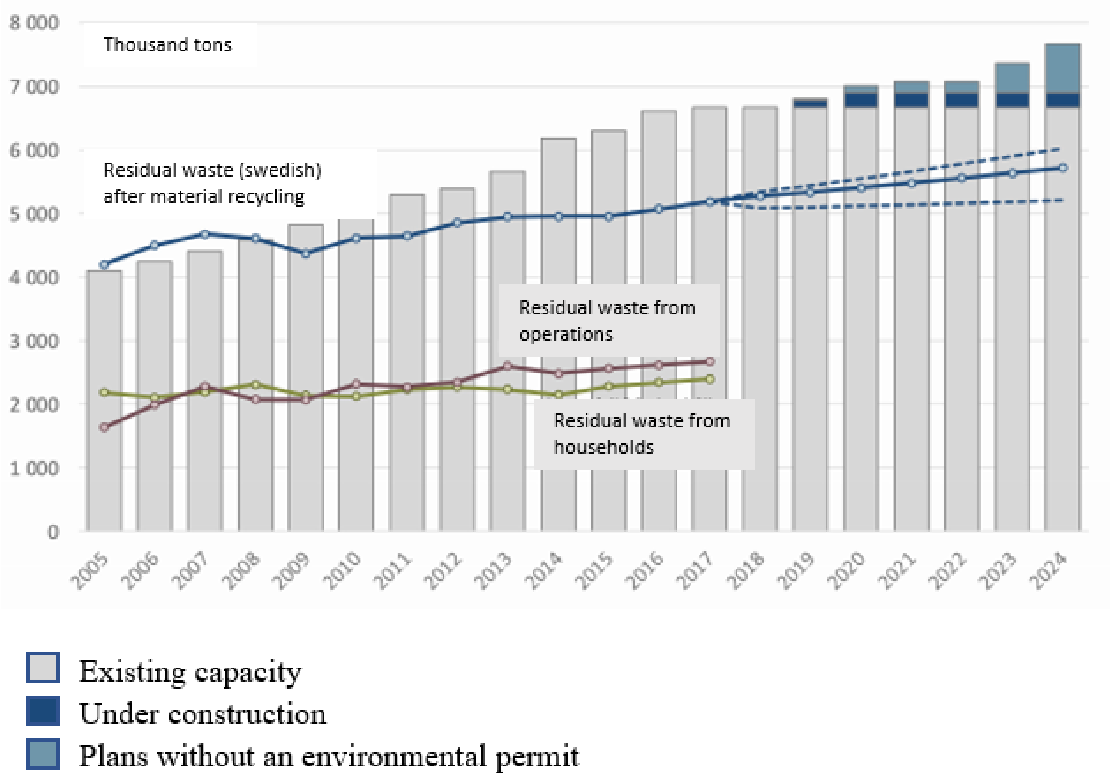

Figure 14. Comparison between forecasted waste amounts and WtE capacity in Sweden. (Avfall Sverige. 2019a, 6.)

Figure 14 describes the estimated growth of WtE capacity and amounts of residue waste (thousand tons) in Sweden until 2024. The capacity marked with grey is existing capacity, darker blue is the capacity that is under construction and light blue indicates the capacity that is planned but doesn't have an environmental permission. Blue line stands for residue waste after material recycling.

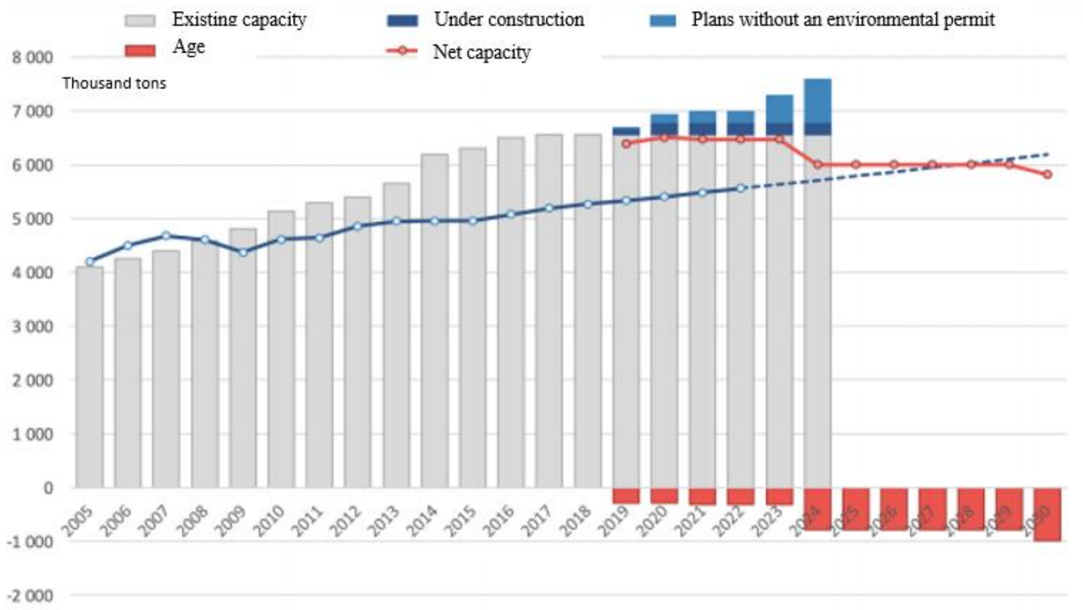

Figure 15. Comparison between forecasted residual waste according to historical values and capacity for energy recovery in Sweden. Age (red bar) describes the capacity of the boilers with the age 30 or more. (Avfall Sverige. 2019a, 7.)

In addition to the previous figure, Figure 15 shows the forecast of residue waste and net capacity until 2030 including the illustration of the boilers with age of 30 years or more. The red bar illustrates the capacity of the oldest boilers and the red line is predicted net capacity of WtE, which results when 30 years old or older boilers are reduced from existing and planned capacity. According to this forecast, the net capacity start decreasing in 2024 due to the larger amount of older boilers. (Avfall Sverige. 2019a, 6-7.)

4.4.2 Sludge

As mentioned earlier in this study, Sweden incinerated only 1,2% of the sludge in 2018. Figure 16 shows Avfall Sverige’s statistics from 2019 and agricultural or forestland remains the main destination for sludge disposal. Sludge was also used in landfill capping (31%) and planting soil (15%). Other methods, in which incineration probably is included, covers 17% of disposal.

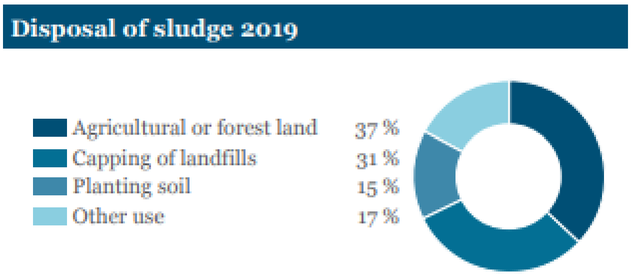

Figure 16. Sludge disposal in Sweden, 2019. (Avfall Sverige. 2019b, 16.)

The sludge management in Sweden has been under long debate and recently there has been an attempt to solve the problem. Stockholm Environment Institute (SEI) (2020, 1; 5) discusses about the situation of sludge management in its report. Swedish Government has delivered several reports for future options on how to dispose the sewage sludge and recover the phosphorus, but political solution is missing. Government has had an ambition that reuse of sludge would be banned in the future. The Governments latest inquiry from 2020 presents two options; first is to restrict the reuse of sludge and second option is to continue the spreading the sludge on the fields but with tighter requirements. SEI presents in its own report that currently the only option for spreading the sludge on the farmland is incineration. Incineration would also fulfil the requirements of recovering phosphorus, because there are emerging technologies available for that. SEI estimates in its report that even if the use of sludge in agriculture would be allowed in the future, incineration is becoming a dominant practice to dispose the sludge.

4.5 Technologies and actors

Earlier there was a map and listing of bioenergy district heating networks in Sweden presented, but there is also similar map and listing of CHP or electricity plants using biofuels in 2020 which is presented in Figure 17. In addition to existing plants, this biopower map includes fifteen planned installations that are not yet operating or will start operating between 2020-2021.

Figure 17. Biopower plants in Sweden 2020. (Bioenergi. 2021a).

Along with the bioheat map, biopower map lists the biggest and the most important actors in Sweden bioenergy sector. The fifteen planned installations are detailed in the following Table 3. According to the biopower map, there are 242 CHP installations that produce heat and electricity mainly by wood fuels, biogas, waste and peat. (Bioenergi. 2021a).

Table 3. Planned installations in Sweden. (Bioenergi. 2021a).

			GWh	MW	Ready
1	Finspångs Tekniska	Completing the existing plant with ORC -turbine	2,25	0,45	2020
2	Ystad Energi	Installation of 2 x 0,25MW ORC -turbine	2,5	0,5	2020
3	Vattenfall, Carpe Futurum, Uppsala	New heating plant prepared to comlete the electricity production	150	30	2021
4	Stockholm Exergi, Högdalen, Stockholm	Builds new boiler 54 MWth to replace P1 and P2			2021
5	Lidköping Energi	Builds new CHP plant for waste	45	10	2021
6	Ystad Energi	Installation of 0,25 MW ORC -turbine	1,25	0,25	2021
7	Metsä Board, Husum	Two old boilers will be replaced to increase the electricity production			2022
8	Stockholm Exergi, Lövsta, Stockholm	Planning for a new CHP plant in northwest Stockholm	250	50	2024
9	Skråmered, Laholm	Planning electricity production with biogas	6		2024
10	Jämtkraft, KVV2, Lugnvik, Östersund	Planned construction of a new CHP plant in the spring 2022			2024
11	E.ON, Malmö	Investigates heating or biopower plant in Östra Hamnen	165	25	2025
12	Göteborg Energi, Rya gaskombikraftverk	Investigating conversion of natural gas to biogas by 2025	400	261	2025
13	Göteborg Energi, Rya biokraftvärmeverk	Planning for a new CHP plant for wood chips and recycled wood	210	40	2027
14	Kraftvärmeverk, nordöstra Stockholmregionen	Need for new base production in northeast Stockholm			
15	Eskilstuna Energi & Miljö, Kjula, Eskilstuna	Waiting for investment			

4.6 Future perspective

Sweden has ambitious targets to lead the world in decarbonizing. Due to geographical location renewable source like hydropower in electricity generation is a natural choice as well as wood-based biofuels in heating due to the strong forest economy. Sweden's Policy instruments that Sweden has set, have been effective. Ban on dumping flammable and organic waste, waste tax and producer responsibility has reduced the share of landfilled waste under 1%. However, the aim of Swedish economy turning to circular economy requires a lot and, in the future, Sweden need to invest in technologies to increase the recycling of waste. This, with waste incineration tax, could mean less waste to incineration and lack of fuel in the plants producing district heat. As heating sector mostly relies on CHP plants combusting solid biofuels and waste as a fuel, the replacing fuel is needed. According to the Roadmap fossil free Sweden's specialists operating in heating sector as well as Sweden's waste plan, there will not be a massive abandonment of waste incineration in the future years. The waste incineration has already needed imported waste to feed the capacity of the incineration plants and to keep the heating network in operation. Aim to direct more waste in recycling may reduce the amount of waste used as a fuel and would mean the need to exceed the amount of imported waste. One option to help the fuel need in incineration plants is depending on Sweden's Governments alignment whether the sludge incineration will become future's main treatment technology for sludge or not. Definitely this will not solve the whole fuel need but surely would increase the use of domestic sources instead of importing. According to the forecast of future capacity of energy recovery, the net capacity will be decreasing, but the decrease by 2040 would be around 500-800 thousand tons compared to 2019 net capacity (6,7 million tons). The concentration in heating and waste incineration will be in improving efficiencies to get more out of the fuel and getting rid of the rest fossil use in district heating. Energy recovery from waste will be one of the technologies also in the future, but recycling of waste will be enhanced and for example plastics (fossil content) should be more carefully separated and used. Also, to minimize the emissions, carbon capture will be essential in the heating sector. Policy instruments has been and will continue to be substantial in increasing the deployment of renewable sources. In electricity sector solar and wind power have had a lot of support and will gain more foothold in the future in electricity generation. Especially wind has a huge potential when nuclear power will be slowly diminished.

5 POLAND

Poland is EU country in Baltic area with 38,39 million inhabitants. The GDP of Poland in 2019 was 595,86 billion USD (The World Bank. 2021b) and per capita 15 692 USD (The World Bank. 2021a). In 2018 CO_2 per capita in Poland was 11 tonnes of CO_2 eq. while the average in EU region in 2018 was 8,6 CO_2 eq. (Eurostat. 2021b). Circular material use rate in Poland in 2019 was 9,8%. (Eurostat. 2021a).

Fossil fuels are dominating the energy supply in Poland. The Figure 18 shows the development of the total energy supply by source from 1990 to 2019. Between the period the total energy supply has decreased 0,5%. In 2019 89,4% of the total energy supply came from fossil sources while in 1990 the share was 97,7% where hydro and biofuels and waste were playing a tiny role of 2,3% in renewables.

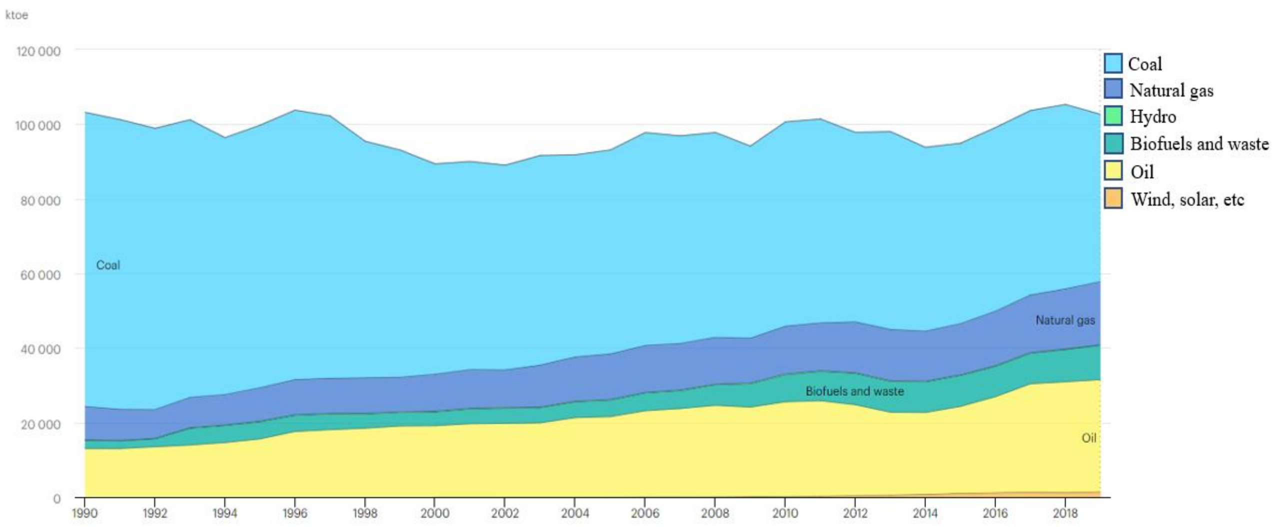

Figure 18. Total energy supply by source in Poland, 1990-2019. (IEA. 2021a.)

As can be seen in the Figure 19, between years 1990 and 2019 the share of the dominant fuel, coal, has been decreasing from 76,4% to 43,6% but meanwhile the use of natural gas and oil has increased. The increase in biofuels has been small in all hydro, biofuels and waste and wind, solar, etc., covering 10,6% of the total energy supply in Poland in 2019. Biofuels and waste were the biggest source of renewables with 9% share. (IEA.2021a.)

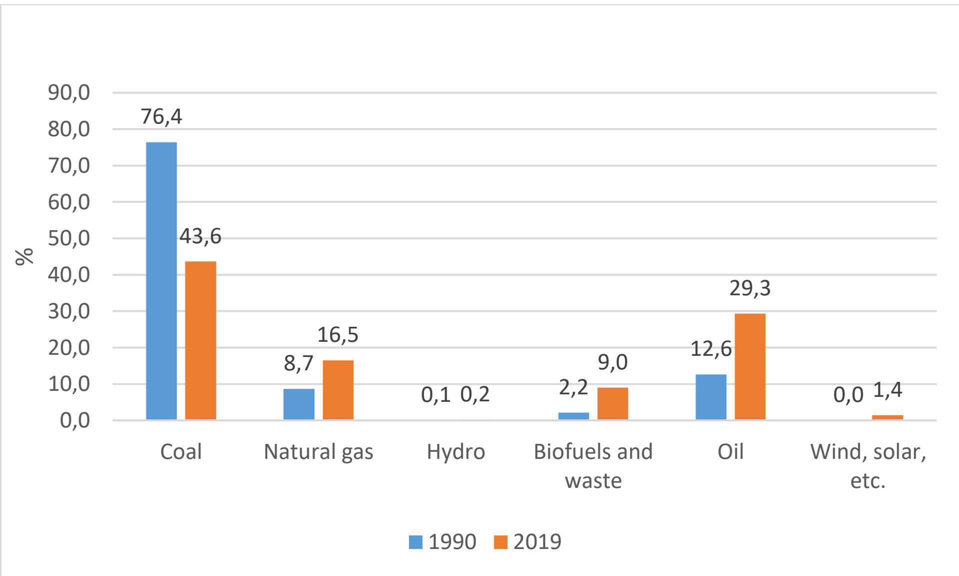

Figure 19. Share of energy supply by source in Poland in 1990 and 2019. (Calculated after IEA.2021a).

In 2019 installed capacity of renewables had a following division; wind 67%, biomass 17%, hydro 11%, biogas 3% and PV 2%. (Olsztyńska, Ilona. 2019, 7.) The Figure 20 presents the situation of renewable energy installations in Poland in 2014.

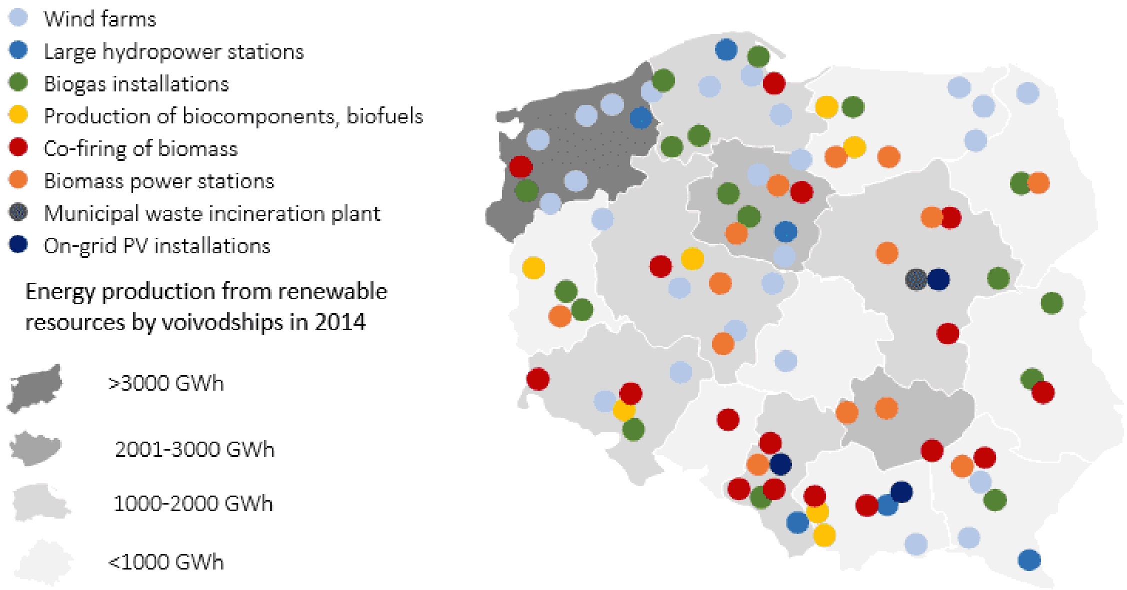

Figure 20. Renewable energy installations in Poland in 2014. (Polish Investment & Trade Agency. 2021).

5.1 Poland's energy and climate plan

Poland's national energy and climate plan, finished in December 2019, involves the period 2021-2030 including the national objectives and targets as well as policies and measures achieving them. The plan bases on the five dimensions of EU Energy Union. Poland has a large energy system being one of the biggest in the EU region and it is very dependent on coal but not just in the meaning of energy, but coal is also huge employer in the mining industry to which the transformation towards renewable energy will effect on. (Ministry of National Assets. 2019c, 6-8.)

EU has set Poland a national GHG reduction target of 7% for the non-ETS sector by 2030 compared to 2005 level. Non-ETS sector (covering mainly transport, agriculture, municipal and domestic sector, waste management and non-ETS industrial sector) is responsible about half of the total GHG emissions in Poland. In addition, Poland has target for 2030 to reduce national GHG to 77,1% compared to 1990. What comes to the dominant fuel coal and lignite, Poland aims to decrease the share of coal and lignite in electricity production to 56-60% and continue with the trend to 2040. In 2019 the share of coal and lignite was around 77%. The implementation of diminishing coal and lignite will take place when old units will be decommissioned gradually, and they are replaced with technologies with higher efficiencies and low or zero-carbon emissions. As a share of renewable energy sources in gross final energy consumption, Poland has set a target of 21-23% by 2030 having a few percent divergence from the EU target of 25%. (Ministry of National Assets. 2019c, 22-31.)

Priority in Poland's energy and climate plan is ensuring energy security which is in accordance with Poland's strategic framework document "The Energy Policy of Poland". The framework defines eight strategic areas in the Poland's energy policy:

- making the optimum use of own energy resources
- expanding electricity production and network infrastructure
- diversifying the supply of natural gas, oil and liquid fuels and expanding the associated network infrastructure
- developing energy markets
- deployment of nuclear power
- developing renewable energy sources
- developing the heating and cogeneration sector
- improving energy efficiency of the economy.

While keeping the coal as a leading source of energy, the purpose is to diversify energy carriers by increasing the share of renewable sources, starting energy production with nuclear in 2033 and increasing the use of natural gas in both electricity and heat production. The development of the district heating system will be pursued inter alia by converting power plants to CHP plants, increasing the use of renewables and gas and increasing the use of waste for energy purposes. In the long run the aim is that district heating is mainly generated by CHP in the future. One of the remarkable energy security actions is the deployment of the nuclear power. Poland will launch six nuclear power units starting with one unit in 2033 and continuing with 2–3-year time span per unit. The total planned capacity would be around 6-9 GW. (Ministry of National Assets. 2019c, 11; 31-32.)

With enhancing the renewable energy sources Poland will diverse the sources of energy as well as increase independency in energy production but also decarbonize the sector. The share of renewable sources in energy mix will be implemented with various technologies. In electricity the sources will mainly be wind power, both off-shore and on-shore, photovoltaics and hydropower and in heating sector biomass, biogas (combined heat and electricity), geothermal and heatpumps. To achieve the target of renewables in heat generation, biomass and waste have the biggest potential due to the availability of the fuel and technical and economic parameters of cogenerations facilities. In addition, the use of waste in energy production contributes well the development of waste management. (Ministry of National Assets. 2019c, 66-68.)

5.1.1 Energy and climate policy scenario (ECP)

Energy and climate policy scenario is an analytical annex to Poland’s national energy and climate plan giving an analysis of the impacts of policies and measures and illustrates how those policies will be fulfilled and what kind of impact they will have by 2030 also including an outlook to 2040. Targets that are set for the share of the renewables in gross final energy consumption in 2030 are in electricity 31,8%, district heating and cooling 28,4% and energy in transport 14%. (Ministry of National Assets. 2019a, 5; 33.)

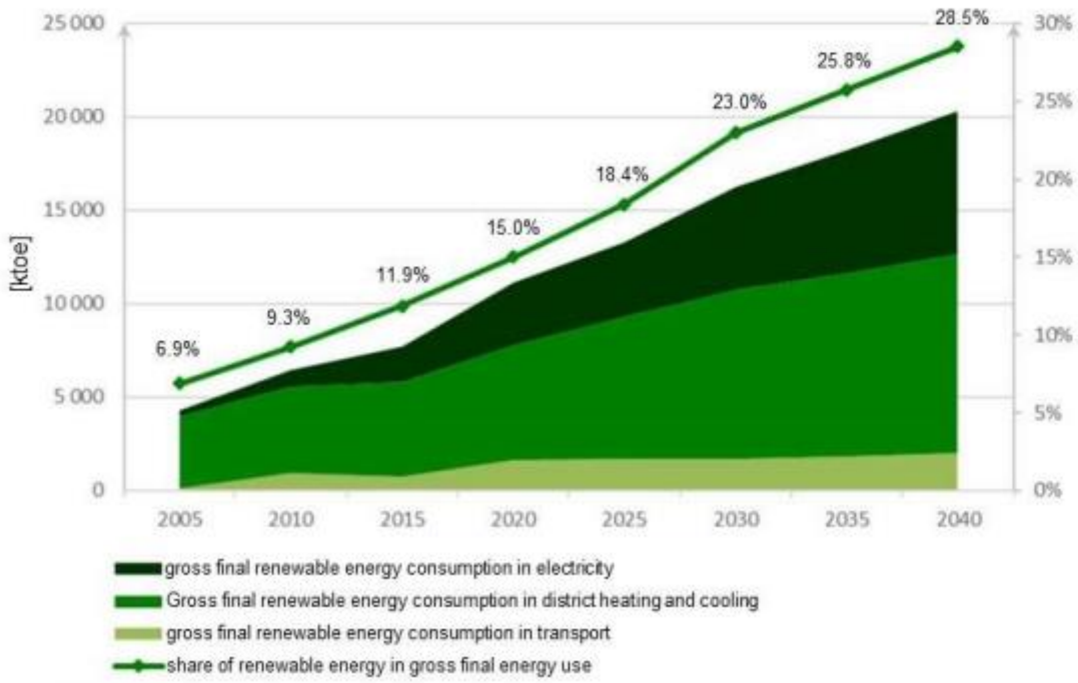

Figure 21. Gross final renewable energy consumption in Poland in the three subsectors [ktoe] and the share of RES in gross final energy consumption [%]. (Ministry of National Assets. 2019a, 33.)

The Figure 21 shows the magnitude of each sector's gross final renewable energy consumption between period 2005-2040 as well as the share of renewable energy in gross final energy use. In 2030 gross final renewable energy consumption is calculated to be 16 000 ktoe of which district heating and cooling 9000 ktoe and electricity 5500 ktoe. Gross final energy consumption is estimated to be 69 300 ktoe in 2030 in Poland. (Ministry of National Assets. 2019a, 5; 33.)

To gain the targets, attention will be in developing especially domestic sources of renewable electricity providing additional volumes by offshore wind farms and large photovoltaics, biomass and biogas installations. Domestic biomass sources are forest biomass (round or cleft wood, root wood and forest residues, tree stands and by-products from industry) and agricultural biomass (crops, by-products from agri-food and agriculture industry and straw). (Ministry of National Assets. 2019c, 27-28.) In the Figure 22 the estimation of the shares of different technologies of renewable energy consumption in the electricity sector for the years 2025-2040 is presented. Year's 2015 materialized figures has been added to the figure to have a contrast and a view of a development that is expected. Wind energy and photovoltaics will play an important role in electricity sector in becoming years and together they will cover 78% of the RES share of the energy consumption in electricity sector. In 2030 there should be a capacity of 4 GW of offshore wind energy plants to fulfil the targets set for electricity sector. Municipal waste has a role of 0,5% of all renewables in electricity.

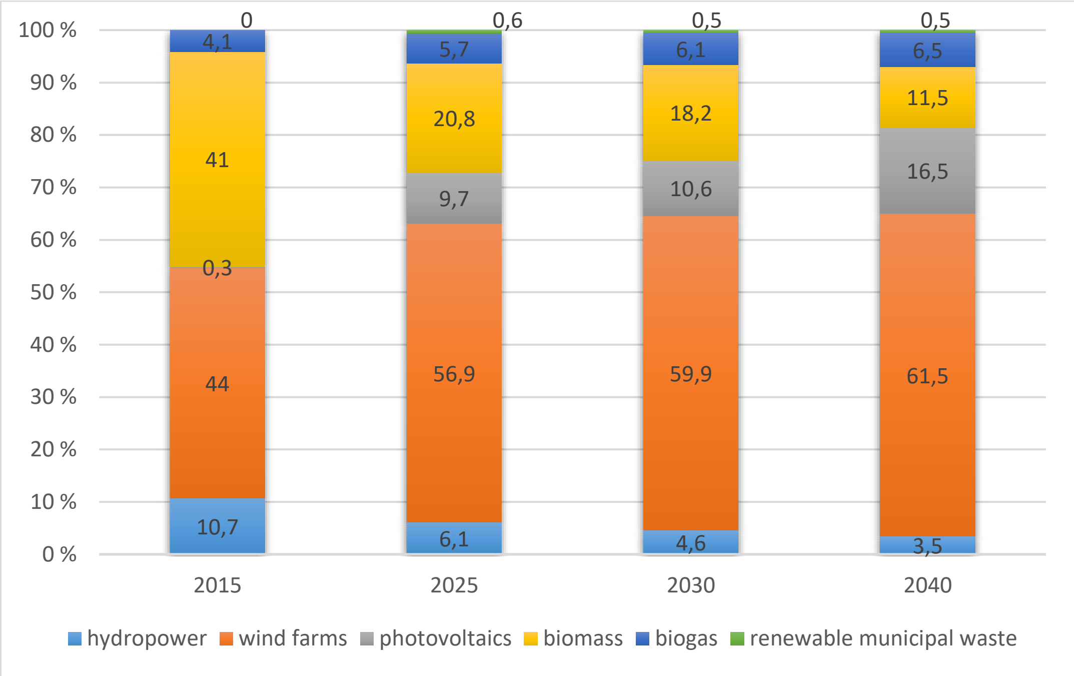

Figure 22. Projected share of technologies in renewable energy consumption in the electricity sector [%], in Poland in 2015-2040. (Ministry of National Assets. 2019a, 34).

In heating sector coal fired boilers are expected to be replaced with biomass boilers and this way biomass' role in heating and in CHP will be increasing. The Figure 23 shows the forecasted development in energy consumption of each renewable source in ktoe and actual figures from year 2015 has been added as a comparison. By 2040 the final renewable energy consumption is estimated to be doubled compared to year 2015. Solid biomass will be a leading source but increase in all technologies is clear. Municipal waste is as well increasing but in forecast the development is quite moderate.

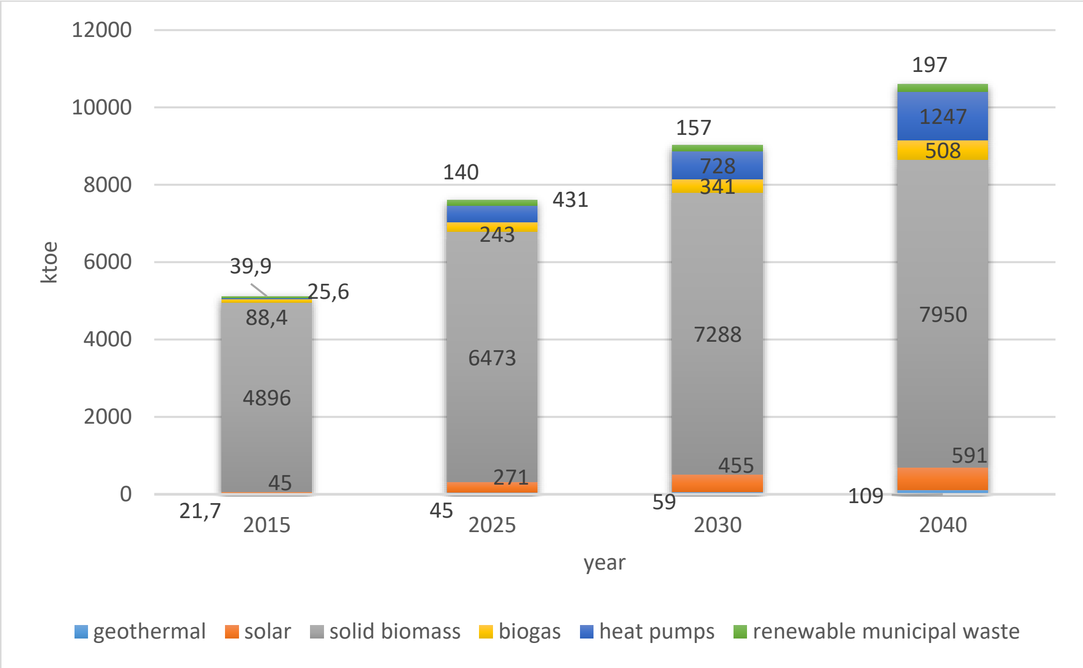

Figure 23. Projected gross final renewable energy consumption in district heating and cooling by sources [ktoe], in Poland in 2015-2040. (Ministry of National Assets. 2019a, 34-35).

Heating sector needs to increase the use of biomass by at least 1,1% per year to be able to gain the target of 28,4% by 2030. In 2019 97% of the heating plants were based on coal and to modernize the existing heating plants in a given timetable requires sufficient financial resources. There are also limiting factors for use of the biomass such as domestic resources, cost of the biomass and sustainable use of biomass that need to be considered. The Figure 24 points out that albeit the increase in use of solid biomass the share is decreasing due to the implementation of other technologies. After solid biomass heatpumps will have a second largest share of RES in 2030 and will increase to 2040 also.

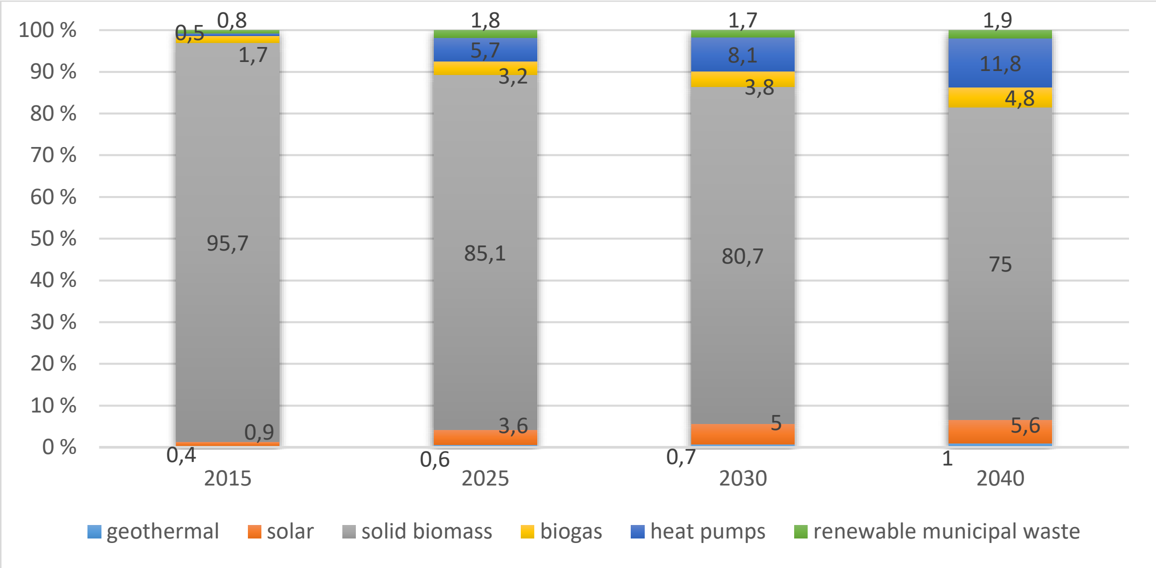

Figure 24. Projected share of technologies in renewable energy consumption in district heating and cooling [%], in Poland in 2015-2040. (Ministry of National Assets. 2019a, 35).

To have a general view on how big role RES will have in heat and electricity generation in the future, input figures for coal, petroleum products, gas and RES, waste and nuclear are presented in the Figure 25 between years 2015-2040. In addition, the input of the fuels is divided to power plants, combined heat and power plants and heat plants and total figures of the use of fuels in all heat and electricity is also added. The numbers are forecasts in the reference scenario and are determined with the model based on the optimal capacity and structure of electricity and heat production.

Most of the coal is consumed in combined heat and power plants and in total figures coal will not have a dramatic decrease until after 2030 when nuclear power is supposed to be started. The price of the carbon allowances, regulatory and the number of the units put out due do not meeting the environmental requirements are the main reasons for the drop in the use of coal and increase in other technologies, mainly gas and renewables. (Ministry of National Assets. 2019a, 54.) The share of RES, waste will increase steadily and is projected to be 14,3% of total fuel input in 2030 and 16,2% in 2040.

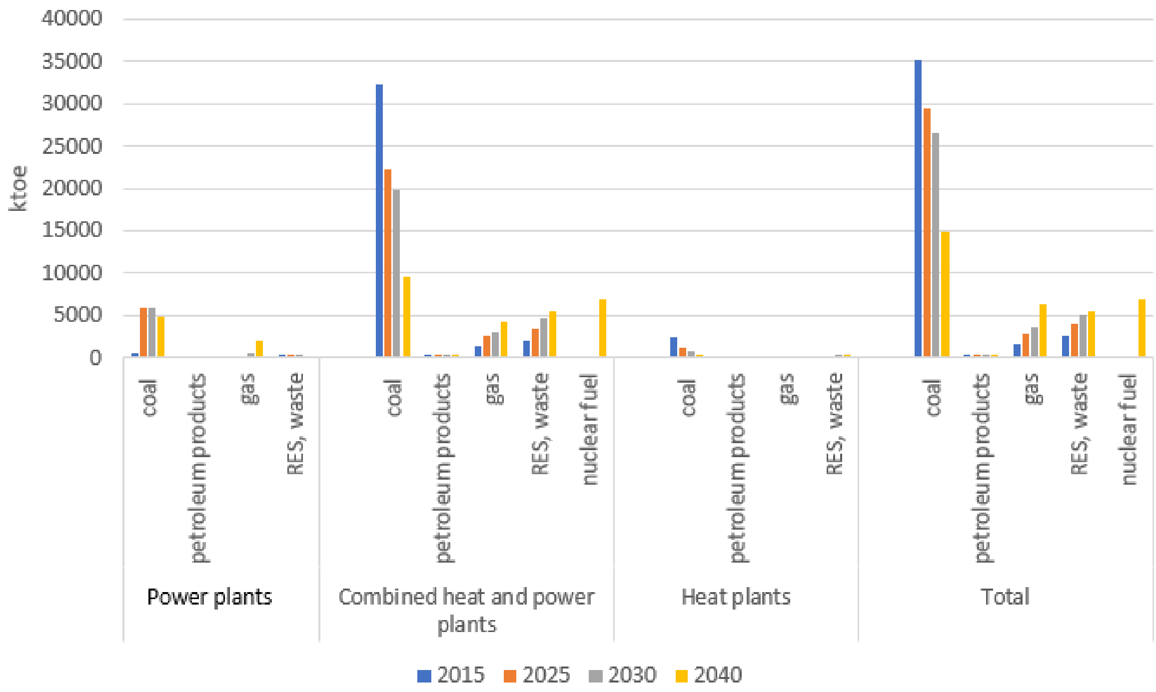

Figure 25. Fuel input for electricity and heat generation in Poland [ktoe]. (Ministry of National Assets. 2019a, 54).

According to the estimates, between years 2016-2040 there will be decommissioning of the generation capacity approximately 26,5 GW in total. The estimates are based on the surveys and annual reports of the power companies and assessment of technical conditions and service hours, but also economic aspect has taken into account when considering the existing machinery and requirements in emission control. The Figure 26 shows the determined and planned shutdowns of the plants, industrial and commercial, by technology. Before 2030 most of the decommissioned plants are coal and lignite fired plants, but after 2031 there will be also wind farms that will come to the end of life. Between years 2031-2035 the largest amount of capacity will be shut down. (Ministry of National Assets. 2019a, 68.)

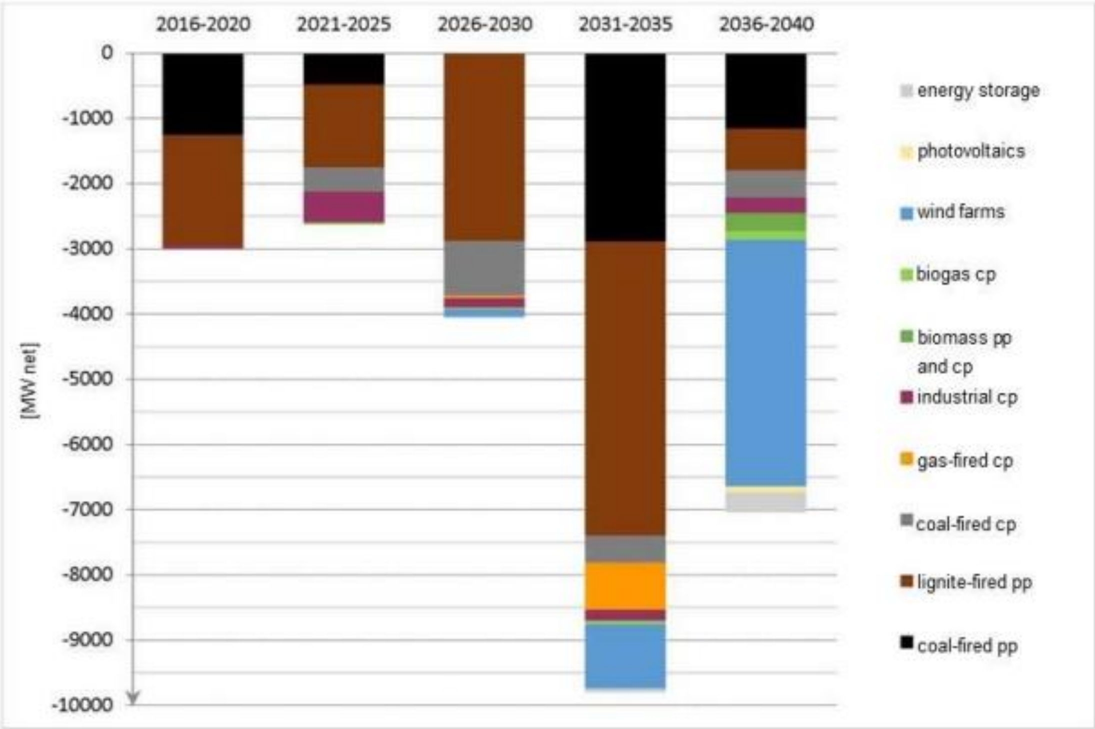

Figure 26. Projected decommissioning of power generation units in Poland. (Ministry of National Assets. 2019a, 68).

5.1.2 Reference scenario (REF)

The reference scenario is an analytical annex of the National energy and climate plan which gives an evaluation about future with the policies implemented before end of year 2017 so it doesn't consider policies and actions after that, including policies in national energy and climate plan. To have a view on how renewable energy sources would develop if policies after 2017 would not be implemented, here are some numbers from reference scenario.

In the Figure 27 shares of technologies in renewable energy consumption in the electricity sector are presented. Most remarkable difference compared to the Energy and Climate Policy scenario (ECP) is that in 2040 use of biomass would have a 24,5% share in a REF (in ECP 11,5%) and on the other hand photovoltaics would cover only 5,1% of the renewables (in ECP 16,5%).

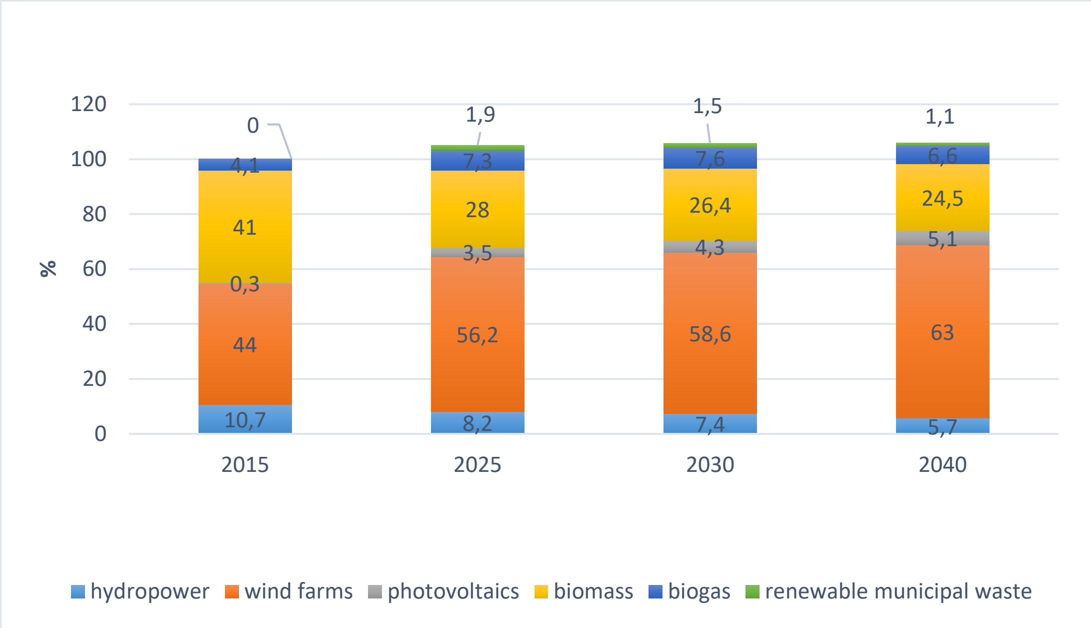

Figure 27. Share of technologies in renewable energy consumption in the electricity sector [%], in Poland in 2015-2040 according to the reference scenario. (Ministry of National Assets. 2019b, 36).

When comparing the district heating and cooling sector and different renewable technologies in the two scenarios, it can be seen that total consumption of renewable technologies is on lower level in REF scenario. In 2040 total consumption of renewable energy in ECP scenario is 10 600 ktoe while in REF it is 7800 ktoe. The biggest differences are with geothermal and heat pumps. The Figure 28 presents gross final renewable consumption in district heating and cooling according to the reference scenario and in Figure 29 forecasted shares of different technologies in renewable energy consumption in heating and cooling 2015-2040.

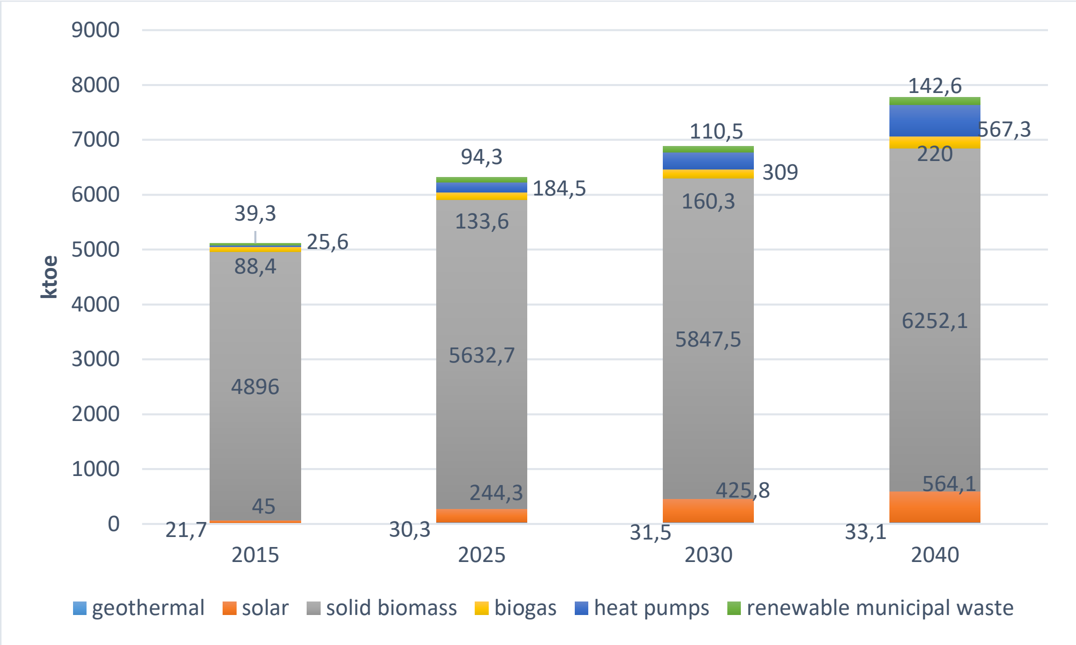

Figure 28. Projected gross final renewable energy consumption in district heating and cooling by source [ktoe], in Poland in 2015-2040, according to the reference scenario. (Ministry of National Assets. 2019b, 36-37).

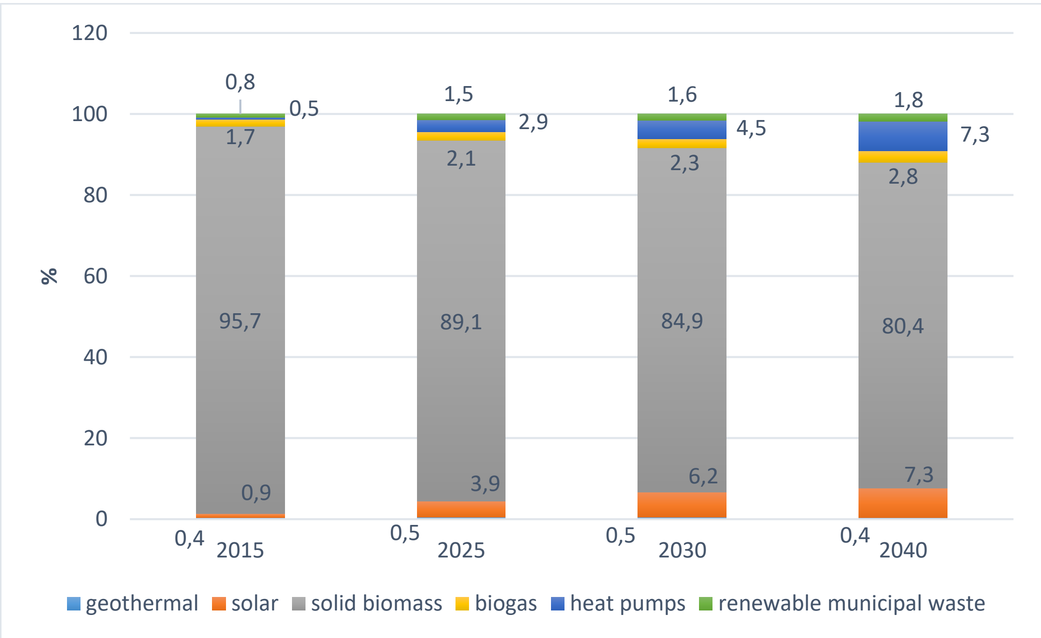

Figure 29. Projected share of technologies in renewable energy consumption in district heating and cooling [%], in Poland in 2015-2040, according to the reference scenario. (Ministry of National Assets. 2019b, 36-37).

5.1.3 Instruments

In addition to the EU policy instruments, like EU ETS, Poland has launched several tools to support the renewable energy sources in Poland. The main incentive in promoting the electricity generation with renewables is the RES auction, presented in the RES Act, where government orders a certain amount of renewable energy and to buy it, the auction is organized. The renewable energy producers that offer the lowest price to produce energy is the winner and the price will be valid for a whole period, normally 15 years giving permanent and stable conditions for investments. Different technologies are divided to five so called baskets according to the fuel or carrier of the plant and categories are divided to “small” (up to 1 MW) and “large” (at least 1MW) installations. It is also notable if the plant is new or existing. First auction took place in December 2016 and after that year there has been some amendments done so the earlier years results are not comparable with each other. Since 2018 the baskets have been the following:

- Basket I: biogas obtained from landfills, sewage treatment plants and other sources, exclusively dedicated biomass combustion installations or hybrid systems, only installations using biomass, biogas, biogas or agricultural biogas incinerated in a dedicated to biomass combustion installations or hybrid systems in high-efficiency cogeneration
- Basket II: hydropower, geothermal energy and offshore wind energy
- Basket III: agricultural biogas installations
- Basket IV: onshore wind, solar PV installations
- Basket V: hybrid installations

Budget and volume of the tenders are defined separately for each auction period and basket. Auctions are scheduled to take place annually, but not always held for every basket. (Bartek-Lesi, M. et al. 2019, 6-8.)

As an example of the auction, Tables 4 and 5 present the characteristics and results of auctions in 2018 for renewable technologies (other than PV and wind). In all cases the auctioned amount was less than 30% of the total amount offered and only in one category there were more than five bids. Also, prices of the auction are close to the ceiling prices. These facts show that auctioned volumes were excessive and there is not much competition. The prices may indicate also poor cost efficiency. (Bartek-Lesi, M. et al. 2019, 17-18).

Table 4. Main characteristics of auctions for new renewable technologies other than PV and wind, 2018, Poland. (Bartek-Lesi, M. et al. 2019, 17).

Technology	Offered amount	Auction budget	Auction with valid bids
Biomass or non-agricultural biogas, more than 1 MW	57 TWh	5.836 billion EUR	Yes
Biomass or non-agricultural biogas, less than 1 MW	13.31 TWh	1.289 billion EUR	No
Hydro, Bioliquids, Geothermal, Offshore Wind, less than 1 MW	3.75 TWh	180 million EUR	No
Agricultural biogas, less than 1 MW	11.7 TWh	1.676 billion EUR	Yes
Hydro, Bioliquids, Geothermal, Offshore Wind, more than 1 MW	5.4 TWh	607 million EUR	Yes
Agricultural biogas, more than 1 MW	3.51 TWh	452 million EUR	Yes

Table 5. Results of effective auctions for new technologies other than PV and Wind, 2018, Poland. (Bartek-Lesi, M. et al. 2019, 18).

Technology	Number of successful bids	Contracted volume (share of offered)	Minimum price	Average price	Maximum price
Biomass or non-agricultural biogas, more than 1 MW	1	0.97 TWh (1.70%)	93.65 EUR/MWh	93.65 EUR/MWh	93.65 EUR/MWh
Agricultural biogas, less than 1 MW	29	3.49 TWh (29.83%)	126.17 EUR/MWh	132.33 EUR/MWh	133.39 EUR/MWh
Hydro, Bioliquids, Geothermal, Offshore Wind more than 1 MW	5	0.82 TWh (15.19%)	98.03 EUR/MWh	108.72 EUR/MWh	112.38 EUR/MWh
Agricultural biogas more than 1 MW	3	0.72 TWh (20.51%)	116.13 EUR/MWh	118.28 EUR/MWh	121.05 EUR/MWh

The Figure 30 presents estimates that The Climate Ministry of Poland has for the 2021 auctions and it contributes about 2500 MW of new capacity mainly to wind and PV installations but also biomass has an estimate of 100 MW of new capacity. Auctions in 2021 are held in June. Total volume of energy sold during auctions 2021 is estimated to be 70 TWh. (PWEA. 2021, 10-11.)

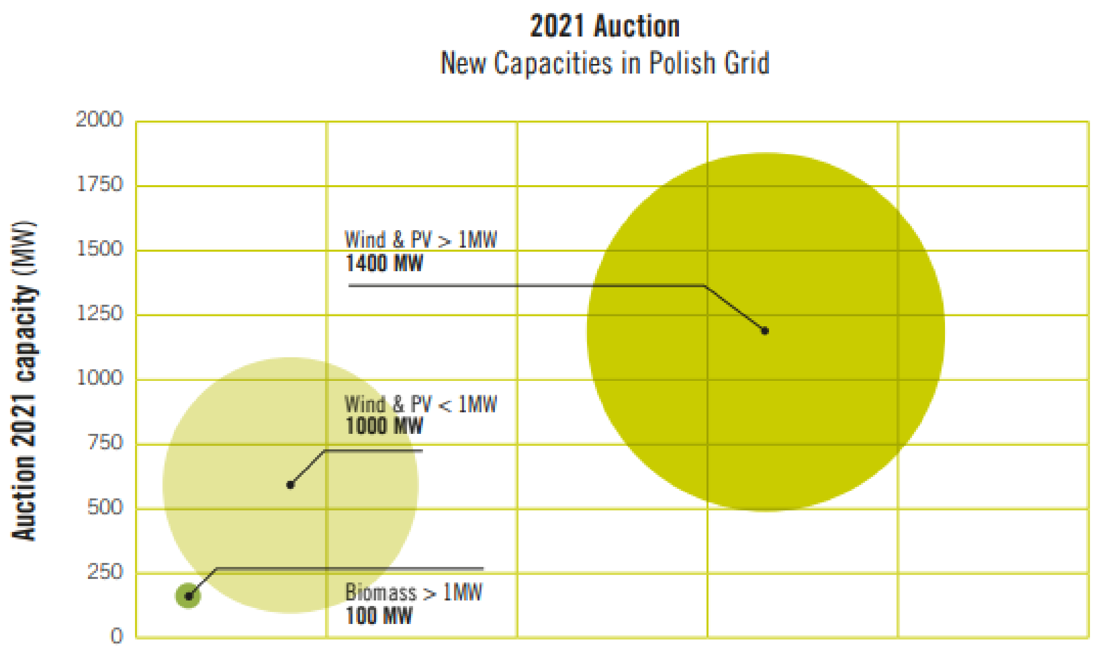

Figure 30. Polish RES auction capacity in 2021. (PWEA. 2021).

Auctions make it possible to direct the support in the certain areas and sectors and this way helps to optimize the right sources of energy. The priorities of the mechanism are to assure maximum availability with the lowest cost and satisfy the local energy requirements but also waste management requirements and utilize the local potential. (Ministry of National Assets. 2019c, 64-65).

There are different kind of supports for renewable energy in Poland and it depends on the size and type of the source, but region has an impact on the support as well. The mechanism includes supports like; priority access to network (at first to all RES installations and it will be modified later), feed-in tariff system and feed-in premium system, grants and repayable aid (depends on local needs), guarantees of origin and aid mechanism targeted on special technologies (for solutions that have no competition on the market, emerging technologies). There are also different funds established for example to increase the number of micro installations of photovoltaics among prosumers, different projects that aim to reduce the negative impact on environment and support to increase the use of geothermal resources in Poland. (Ministry of National Assets. 2019c, 65-66.)

Taxation of energy and carbon in Poland are levied within the framework of EU Energy Tax directive from year 2003. Coal and coke products, fuel oil, diesel and natural gas are taxed but in industrial processes there is a possibility for non-taxation too if the conditions mentioned in the directive are fulfilled. Biofuels and fuels used in CHP plants are not taxed as well as non-renewable waste. (OECD. 2019a, 1; 5.)

5.2 National Waste Management Plan

Poland's National Waste Management Plan 2022 has been released in 2016 and it bases on the Act on Waste. The plan is founded on the EU waste hierarchy and includes also other EU waste management regulations and requirements. The plan covers years 2016-2022, prospectively to 2030 and it bases on statistics from year 2014.

Since 2012 municipalities have been in responsible in organizing the collection and management of municipal waste in municipalities including garbage collection and separate collection biodegradable waste and recyclable materials like metals, glass, paper and plastic. The directive that aims in decreasing the amount of biodegradable waste in the landfills (under 35% compared to 1995 by 16 July 2020) as well as required recycling levels has assisted the implementation of municipal waste treatment plants in municipalities. Recycling and preparing for reuse rate of paper, metals, plastic and glass is set to be 50% by the end of the year 2020. However, there are identified problems in Polish waste management that might hinder achieving the targets. Discovered problems are for example too low share of source separation, low quality of collected waste due to missing national standards, insufficient amount of municipal waste collection centers, insufficient system of collection fees of landfilled waste, lack of education on waste management due to low involvement of municipalities, lack of awareness and knowledge on waste management in society and amount of illegal landfills (at the end of year 2014 there were 2371 illegal landfills in Poland). (National Waste Management Plan 2022. 2016, 18-22.)

The National Waste Management plan includes the forecast of changes in waste management and there are two hypotheses for future generation of municipal waste: high and low. The forecast of generated municipal waste in 2030 varies between 11,68 and 12,28 million tons meaning that other management operations than recycling covers about 4,09-4,30 million tons, 35% of received and collected municipal waste. Other management options for waste treatment in this connection are biological treatment or waste incineration in waste incineration plants or co-incineration plants like cement kilns. (National Waste Management Plan 2022. 2016, 64-67.)

The Table 6 presents the estimated generation of municipal waste in Poland in 2030 divided to each voivodeship (administrative divisions of Poland, columns 2 and 3). The table forecasts amount, for both hypotheses, of waste to be recycled (columns 4 and 5, considering the 65% recycling target) and availability of waste to other treatment methods (columns 6 and 7). Table also shows the total capacity of municipal waste thermal treatment plant (MWTTP) (column 8, existing and newly constructed capacity). Columns 9 and 10 describe the balance of waste to other operations than recycling after the capacity of thermal treatment plants has been reduced. In the table unit Mg is used and Mg stands for 1000 kg and 1 ton, which is used in this text.

Table 6. Estimated balance of the availability of municipal waste in Poland in 2030 including the MWTTP capacity (existing and newly constructed installations). (National Waste Management Plan 2022. 2016, 66).

Voivodeship	Forecast of the weight of generated municipal waste in 2030 – high hypothesis [Mg]	Forecast of the weight of generated municipal waste in 2030 – low hypothesis [Mg]	Required levels of recycling of MW (65% in 2030) – high hypothesis [Mg]	Required levels of recycling of MW (65% in 2030) – low hypothesis [Mg]	Balance of the availability of waste to be managed in operations other than recycling – (columns 2-4) high hypothesis [Mg]	Balance of the availability of waste to be managed in operations other than recycling – (columns 3-5) low hypothesis [Mg]	Total of the MWTTP capacity (existing and newly constructed installations) [Mg/year]	Balance of the availability of waste taking into account the MWTTP capacity (existing and newly constructed installations) (columns 6-8) high hypothesis [Mg]	Balance of the availability of waste taking into account the MWTTP capacity (existing and newly constructed installations) (columns 7-8) low hypothesis [Mg
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Dolnośląskie	1,070,085.07	1,017,223.44	695,555.30	661,195.24	374,529.77	356,028.20	0	374,529.77	356,028.20
Kujawsko-Pomorskie	677,193.09	640,649.39	440,175.51	416,422.10	237,017.58	224,227.29	180,000	57,017.58	44,227.29
Lubelskie	470,876.39	451,956.83	306,069.65	293,771.94	164,806.74	158,184.89	0	164,806.74	158,184.89
Lubuskie	368,818.12	348,356.23	239,731.78	226,431.55	129,086.34	121,924.68	0	129,086.34	121,924.68
Łódzkie	693,165.26	664,252.92	450,557.42	431,764.40	242,607.84	232,488.52	0	242,607.84	232,488.52
Małopolskie	988,647.09	921,321.40	642,620.61	598,858.91	346,026.48	322,462.49	220,000	126,026.48	102,462.49
Mazowieckie	1,815,243.47	1,686,770.04	1,179,908.26	1,096,400.53	635,335.21	590,369.51	60,000	575,335.21	530,369.51
Opolskie	324,168.05	319,253.96	210,709.23	207,515.07	113,458.82	111,738.89	0	113,458.82	111,738.89
Podkarpackie	426,715.33	406,280.76	277,364.96	264,082.49	149,350.37	142,198.27	0	149,350.37	142,198.27
Podlaskie	296,486.51	293,927.53	192,716.23	191,052.89	103,770.28	102,874.64	120,000	-16,229.72	-17,125.36
Pomorskie	836,287.10	778,217.37	543,586.62	505,841.29	292,700.49	272,376.08	0	292,700.49	272,376.08
Śląskie	1,714,481.62	1,674,892.65	1,114,413.05	1,088,680.22	600,068.57	586,212.43	0	600,068.57	586,212.43
Świętokrzyskie	227,291.86	222,405.32	147,739.71	144,563.46	79,552.15	77,841.86	0	79,552.15	77,841.86
Warmińsko-Mazurskie	435,172.13	419,015.76	282,861.88	272,360.24	152,310.25	146,655.52	0	152,310.25	146,655.52
Wielkopolskie	1,284,358.75	1,212,308.90	834,833.19	788,000.79	449,525.56	424,308.12	304,000	145,525.56	120,308.12
Zachodniopomorskie	651,382.38	625,189.06	423,398.55	406,372.89	227,983.83	218,816.17	150,000	77,983.83	68,816.17
Poland	**12,280,372.22**	**11,682,021.56**	**7,982,241.94**	**7,593,314.01**	**4,298,130.28**	**4,088,707.55**	**1,034,000**	**3,264,130.28**	**3,054,707.55**

According to the Table 6, in 2030 the capacity of thermal treatment is estimated to be 1 034 000 tons. It is also worth noticing that thermal treatment plant capacity is missing from ten out of sixteen voivodeships, but existing plants may service regions from other voivodeships too. After recycling and incineration capacity has been reduced, there is still 3,1-3,3 million tons of waste left to other treatment options. Voivodeships have their own waste management plans and also individual decisions regarding waste management are done. In Poland cement kilns use RDF made from municipal solid waste as a fuel and voivodeships may also consider including cement kilns as a part of the waste management system. However, according to the National waste Plan incineration as a treatment method shouldn't account more than 30% of the generated MSW. (National Waste Management Plan 2022. 2016, 64-68.)

The objectives Poland has set for the municipal waste management are named in the National plan. The objectives include EU policies like waste management according to the waste hierarchy and recycling rate targets for different waste fractions but first listed is the aim to reduce the waste generation and increasing the public awareness about the waste issues. To make the recycling more efficient the amount of selectively collected waste needs to be increased and in order to enable that, standard of selective municipal waste collection will be introduced by the end of the year 2021. There are also objectives for landfilling like reducing the illegal dumping of municipal waste but also ending the landfilling of separately collected biodegradable waste and untreated municipal waste. The system to monitor the municipal waste management is named as a one objective. (National Waste Management Plan 2022. 2016, 75.)

5.3 Biomass and wood by-products

Production of energy from solid biofuels (firewood, forest residue, briquettes, pellets, wood chips, sawdust, black liquor, energy crops, agricultural waste and charcoal) in 2019 was 260 000 TJ (total primary energy production 2 484 000 TJ) and solid biofuels was clearly the most used and important renewable source in Poland with 65,6% share of all renewables, covering also 10,4% of total primary energy production. (Statistics Poland. 2020a, 39). Development of energy production from solid biofuels can be seen in the Figure 31 and the numbers show that there has been decrease since 2015 to 2018 but slight increase in 2019. Electricity from biomass was generated 6 400 GWh and heat 16 000 TJ in 2019.

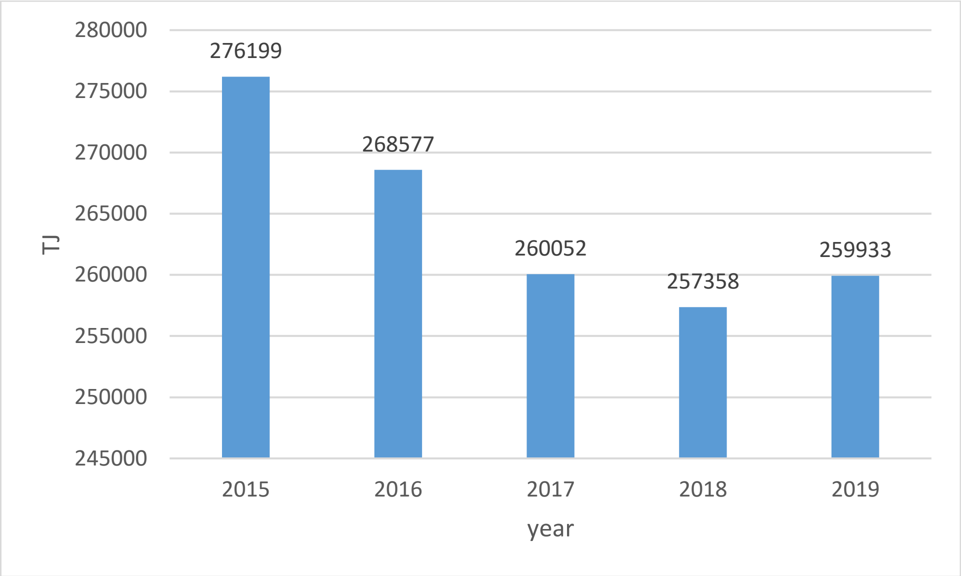

Figure 31. Energy from solid biofuels in Poland, 2015-2019. (Statistics Poland. 2020a, 72).

In 2014 there were 24 production units combusting biomass and these units had a capacity of 629 MW in total. (Olsztyńska, Ilona. 2019, 7).

There are several reasons for the decrease of biomass use but the main reason may be the decrease in coal price which in 2016 was lower than price of biomass. The plants that were co-firing biomass with coal decided to burn only coal. Other factors effecting on the favor of coal were homogeneity and high calorific value and easiness with storing and documenting (related to need to confirm the origin of the biomass). Also drop in prices of green-certificates due to oversupply was effecting the decrease in use of biomass. On the other hand in 2018 prices of CO_2 allowances were increasing and this seems to have an effect on the growth on the demand of biomass again. (Olsztyńska, Ilona. 2019, 9.)

As mentioned earlier in this study, biomass has an increasing role in future heating in Poland due to the efforts to make the district heating network more efficient so the trend in use of biomass should continue upwards. According to ECP scenario, solid biomass production in Poland between 2015-2030 will grow 56% from 6 268 ktoe to 9 986 ktoe. (Ministry of National Assets. 2019a, 58.) National Waste Management Plan presents that forecasted annual increase in the amount of waste from wood processing and from other production of panels, furniture, pulp and paper and cardboard would be 1,5-2,5% compared to 2013 level (3 906 000 ton) which is related to socio-economic growth and increase in use of paper and cardboard. (National Waste Management Plan 2022. 2016, 72.)

Despite the potential and forecasts, the development of biomass use in power and heating has been quite slow resulting from inadequate financial resources allocated to modernization of existing heating plants but also above-mentioned price variations with coal and collapse with supporting certificate system. On the other hand, increase in prices of CO_2 allowances, co-financing programs by EU and new EU guidelines that require increasing the role of RES and legal requirements by EU would help to increase the use of biomass in the future. (Olsztyńska, Ilona. 2019, 17-18.)

ZE PAK SA is the largest private energy group in Poland. It currently has two power plants of which Konin power plant has been operating with biomass since 2012 and there will be an investment of another biomass unit in the near future. Contract made in March 2020 with Valmet Technologies Oy includes design and conversion of old boiler to fluidized bed boiler. The investment means that Konin will be the first coal plant converted to biomass in Poland and city of Konin has 100% renewable heat. (Zepak. 2020.)

5.4 Waste-to-Energy

Environment 2020 (Statistics Poland. 2020b) study presents analysis of environment state and environmental protection in Poland and it also provides information of municipal waste treatment in 2019. In 2019 almost 127 million tons of waste was generated in Poland of which 10,1% was municipal waste (waste from property owners and separately collected municipal solid waste), meaning that 332 kg municipal waste was generated per person. There are big variations in generation of waste per person between the voivodeships. (Statistics Poland. 2020b, 12; 149). Poland also imported and exported waste in 2019; about 550 000 tons of waste was imported and 100 000 tons was exported. The biggest importer to Poland was Germany. (Waste Management World. 2021).

In 2019 12,7 million tons of municipal waste was collected, of which 85% from households, and there was an increase of 3% compared to previous year. Figure 32 shows the shares of the four treatment methods that were used to treat municipal waste. Biggest share, 43% (5,5 million tons) of the total amount was landfilled and 22,9% (2,9 million tons) was incinerated. Other methods were composting and fermentation 9% (1,2 million tons) and recycling 25% (3,2 million tons).

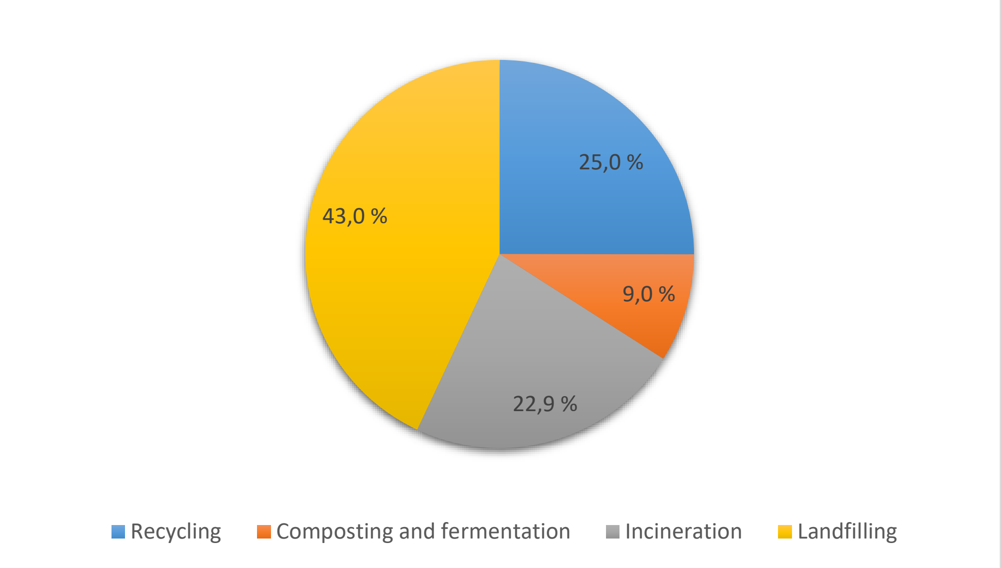

Figure 32. Municipal waste treatment methods in 2019 [%]. (Calculated based on Statistics Poland. 2020b, 157).

There were 278 landfills in 2019 for municipal waste and the amount is systematically decreasing. However, there are numerous illegal landfills in Poland and in 2019, there were 11 000 illegal landfills with 26 000 tons of waste were closed. Separately collected waste has increased remarkably since 2010 covering 31% of the municipal waste collected in 2019. In 2010 separately collected waste was 0,9 million tons and in 2019 almost 4 million tons. (Statistics Poland. 2020b, 152-158). Development in separately collected waste has been fast.

In 2019 energy production from municipal waste was 4 300 TJ while the total primary energy production was 2 500 000 TJ. Electricity generated from municipal waste in 2019 was 105 GWh and heat 730 TJ. The Figure 33 shows the development in energy production from municipal waste since 2015 to 2019 and utilization of waste in energy production has been growing. Albeit the increase in energy utilization of waste it is not playing a significant role in total energy production in Poland. In 2019 municipal waste covered 1,1% of energy production from renewable sources (396 498 TJ). (Statistics Poland. 2020a, 37–39).

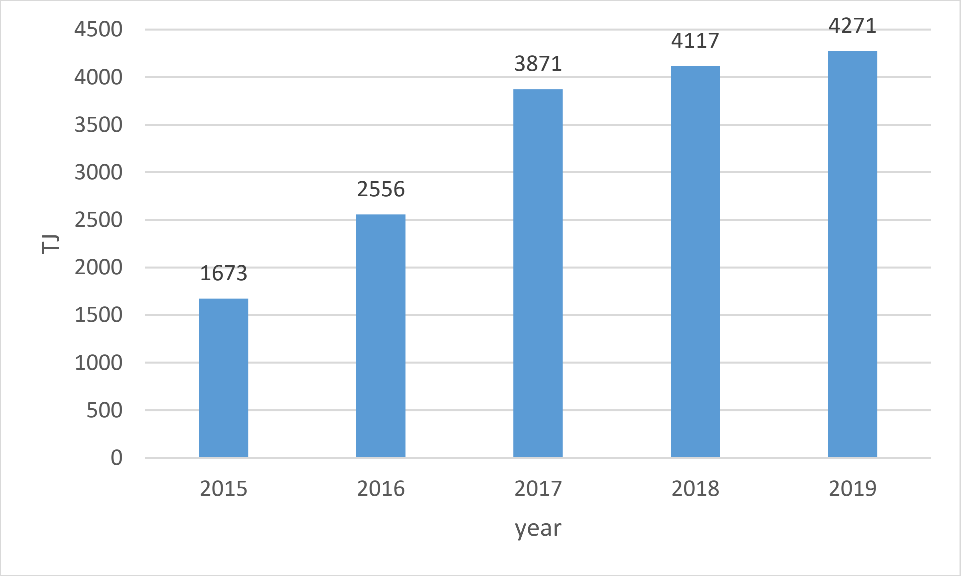

Figure 33. Energy production from municipal waste in Poland in 2015-2019. (Statistics Poland. 2020a, 84).

According to Kępys & Jaszczura (2020, 47-48) there were eight incineration plants for municipal solid waste in Poland in 2018, presented in Table 7, with capacity of 1,1 million tons per year, 190 MW thermal power and 61 MW electric power. All installations have recovery system for electricity and heat, and installations are able to use MSW and RDF. Most used technology is grate combustion. In 2018 there was also one co-incineration plant with capacity of 225 MW started which uses RDF, coal and biomass and produces both heat and electricity. Together with heat and power plants, biggest consumer of RDF are cement plants producing clinker, where RDF is burnt substituting the main fuel, coal. Also biomass is used as a co-fuel in cement kilns. In Poland there were ten cement plants that were using about 1,4 million tons of alternative fuel in 2015 of which 1,1 million tons RDF and it is estimated that in 2020 the number would be 1,8 million tons of which 1,5 million tons combustible fraction of MSW.

Table 7. WtE plants in Poland in 2018. (Kępys & Jaszczura.2020, 48).

No.	Installation location in Poland	Capacity [Mg/year]	Calorific value of waste [MJ/kg]	Thermal power [MW_t]	Electric power [Mw_e]
1	Kraków	220 000	8.8	35	10.7
2	Bydgoszcz	180 000	8.5	27.7	9.2
3	Konin	94 000	7.8	15.5	4.4
4	Poznań	210 000	8.4	34	15
5	Szczecin	150 000	10.5	32	9.4
6	Białystok	120 000	7.5	17.5	6.1
7	Warszawa	40 000	10.1	9.1	1.4
8	Rzeszów	100 000	8.0	16.5	4.6
	Total	1 114 000	-	187.3	60.8

WtE plant in Krakow was started in 2016 with capacity of 220 000 tons of treated municipal waste in a year. The plant has been constructed according to best available techniques (BAT) generating both heat and electricity. Technology used includes moving grate furnace integrated to drum-type heat recovery steam generator with natural circulation. The construction, design and operation were done by Krakowski Holding Komunalny S.A. (Ekospalarnia Krakow. 2021.)

The Bydgoszcz Waste Incineration Plant in Bydgoszcz has a capacity of 180 000 tons municipal waste per year, and it started operation in 2015. The plant has two production lines, and it produces heat and electricity to the surrounding area. The general designer of the architectural and construction stages of the project was AECOM. (AECOM. 2021.)

Poznań WtE plant started operation in 2016 and it treats thermally 210 000 tons of non-recyclable municipal waste per year producing heat and electricity. The technology used is grate combustion. The project was carried out in public-private partnership and SUEZ Zielona signed a 25-year design, build, finance and operation contract with city of Poznań. (Suez Group. 2021.)

Communal Waste Disposal Plant in Białystok started operating in 2016 and it generates both heat and electricity. The capacity of the installation is 120 000 tons of municipal waste a year. European Union was partly funding the project. (Budimex. 2016.)

The Szczecin waste-to-energy plant has a capacity of 150 000 tons per year and it uses moving grate as a technology. It has two lines generating both heat and electricity. The project was implemented between years 2007-2013 and it was funded by EU. (European Commission. 2014.)

In addition to the existing plants, there are projects ongoing to build new plants incinerating residuals of sorted MSW. One will be built in Gdańsk with capacity of 160 000 tons of municipal waste per year. The facility will be high-efficiency cogeneration plant that supplies energy to district heating system and to national electricity grid. Project is implemented in partnership of municipal and private actors; municipal company Port Czystej Energii owns the plant while private partner is responsible of construction and operation of the facility as well as production of heat and electricity. Planned duration of the project is 10/2019-12/2022 and EU is funding the project. (European Commission. 2020b.)

Waste-to-energy plant with capacity of 110 000 tons/year will be built in Olsztyn in the area of Warmińsko-Mazurskie to provide heat and improve the regional waste management. The technology used is a grate boiler. The plant is constructed by district heating company MPEC and Dobra Energia dla Olsztyna is responsible of design, building, financing and operating the plant for 25 years. EU is funding the project that has a duration between 11/2019-10/2022. (European Commission. 2020c.) The plant will be delivered by Doosan Heavy Industries & Construction who is partnering with its German subsidiary Doosan Lentjes. (Power Engineering International. 2020.)

Also Warsaw in Poland will have a new, rebuilt waste-to-energy plant as South-Korean POSCO Engineering & Construction has contracted, with supplier Doosan Lentjes, to build two lined WtE plant treating 265 200 tons municipal waste per year. When constructed by 2024 the installation will be Poland’s largest WtE plant. Doosan Lentje will provide air-cooled reciprocating grate and a horizontal-type steam generator to the plant. (Power Engineering International. 2021.)

Besides these ongoing projects waste-to-energy plant is also planned to be built in Włocławek and city of Rzeszów is considering a second plant to be built. Veolia is also planning a WtE plant to the city of Łódż, but the decision about the permissions has not yet been decided. (Waste Management World. 2021.)

5.4.1 Sludge

Objectives set for sewage sludge management is to prevent the landfilling and instead increasing the treatment of sludge and the amount of sludge directed to incineration aiming to maximize the use of nutrients in the sludge. (National Waste Management Plan 2022. 2016, 79-80). There has appeared a need to clarify the legislation in the field of wastewater but also waste management regarding the treatment of sewage sludge. National Programme for Municipal Waste Water Treatment will be updated to include a wider reference to the treatment of municipal sewage sludge that hasn’t had a status of waste. It should be defined when the sludge is a part of wastewater system and when it becomes a waste so it could be treated under correct legislation. (National Waste Management Plan 2022. 2016, 87-88.)

In 2019 195 700 tons (dry solid) of sewage sludge was incinerated in Poland which is 18,7% of the total amount of sewage sludge generated both in industrial and municipal wastewater treatment plants. Industrial treatment plants treated thermally 26,5% of the sewage sludge while municipal treatment plants thermally transformed 12,2% of sludge in 2019. The total amount of incinerated sludge has been increasing since year 2000, but in 2019 there was a drop compared to previous year. Measured in tons, incineration is the most popular method for sewage sludge treatment. (Statistics Poland. 2020b, 67-70). The most used technology in thermal treatment of sewage sludge is fluidized bed boiler but also combustion in grate boiler is used. In 2019 there were eleven incineration plants that were using only sewage sludge as a fuel having a capacity of 162 500 tons/year (dry mass). Seven of these plants have fluidized bed boiler and four installations mechanical grate. (Kępys & Jaszczura. 2020, 49.) The Poland's National Waste Management Plan 2022 (2016, 72) forecasts that annual increase in the amount of municipal sewage sludge would be around 2-3% (dry weight).

5.5 Technologies and actors

IEA (2016, 78) lists the largest energy companies that dominate the energy production in Poland. PGE is the biggest company having a 38% share in the generation sector in 2014 following companies like TAURON Group (11%), ENEA (9%), EDF Group (9%), PAK (7%), GDF Suez (6%) and ENERGA (3,3%). The three largest companies owned a bit over 50% of all capacity in Poland. The largest companies PGE's and Tauron Group's strategies doesn't reveal any concentration on biomass or waste but instead to wind, solar and hydro power. In 2019 3,74% of the generated electricity sold by Tauron was from biomass. (Tauron. 2019.) PGE plans to invest in providing heat in district heating network and to modernize coal fired units mainly to gas units and this way providing the lowest cost heat to customers. (PGE Capital Group. 2019.)

5.6 Future perspective

Poland is continuing to keep the coal as the main source of energy. Poland has energy policy that concentrates on eight strategic areas of which all are important from the waste and biofuels' point of view. Optimal use of own energy resources as a one of the strategic areas should increase the meaning of biofuels and waste as an energy source especially in heating sector. Also, fundamentals problems that are identified in waste management are about to increase the interest of waste incineration as a part of the solutions when developing the waste management system. Developing the heating and cogeneration sector as well as the effort to enlarge the district heating network will increase demand of biofuels and waste when coal-based plants will be turned to biofuel plants and new biofuel plants and waste incineration plants are about to be built. Trend for utilizing waste in cogeneration can be seen in the ongoing and upcoming waste incineration plant projects. National Waste Management Plan of Poland however defines that not more than 30% of the generated MSW should be incinerated. When looking at the figures from 2019 nearly one million ton of waste could have been incinerated more to reach the suggested limit. From this perspective there is still room for several plants, depending on the capacities, but also several projects are ongoing or planned. Will this 30% be realistic when considering the state of waste management in Poland? At least it will follow the waste hierarchy trying to direct the waste to other treatment methods. The waste hierarchy defines the reuse and recycling as priorities before energy utilization, but lack of insufficient waste management is hindering the progress of recycling. Turning to circular economy is a target and requires a lot more recycling and other treatment plants to reach the recycling targets. Landfilling is still one of the main treatment methods in Poland and there is lot to do to direct the waste to other treatment methods and more efficient political tools to prevent landfilling and illegal landfilling is needed. Poland is dependent on financial support on building a low carbon infrastructure in energy generation and EU has been financing for example several new waste-to-energy plants in recent years. To decarbonize Poland waste management and energy sector are very important factors and investments in this sector are lifeline but also possibility.

6 UK

UK is an island country that comprises of Great Britain, including England, Wales and Scotland, and the northern part of Ireland. UK is no longer a member of European Union since it resigned EU in 2020. However, in this report most of the statistics are from year 2019 when all UK countries were members of EU. UK has 66,84 million inhabitants and the GDP of the UK in 2019 was 2 829,108 billion USD (The World Bank. 2021b) and per capita 42 330 USD (The World Bank. 2021a.) In 2019 CO_2 per capita in UK was 7,5 tonnes of CO_2 equivalent which was slightly under the EU average. (Eurostat. 2021b). Circular material use rate in UK in 2019 was 16,4%, which after Italia and Belgium was the third highest rate. (Eurostat. 2021a.)

UK has succeeded in climate actions that has been done so far. Early policy actions with increased competition and innovation has resulted 43% decrease in emissions between years 1990-2018 and meanwhile the GDP rose 75%. Also, the capacity of renewables connected to grid has had a substantial increase from 8 GW to 48 GW between years

2009-2020. (HM Government. 2020, 8.) As can be seen in the Figure 34, the use of coal has decreased a lot since 1990 and meanwhile alternative fuels have taken a foothold. In 2019 natural gas (67 300 ktoe) was the biggest source of the total energy supply in UK covering 39,7% of the total energy supply (169 500 ktoe) and after gas came oil with 34,8 % share (59 000 ktoe). Biofuels and waste have had an increasing share since the beginning of 2000s and in 2019 they covered 9,2% (15 700 ktoe) of the total energy supply. (IEA. 2021c.) When added together, in 2019 share of all renewables in total energy supply was 13,5%. (IEA. 2021c.)

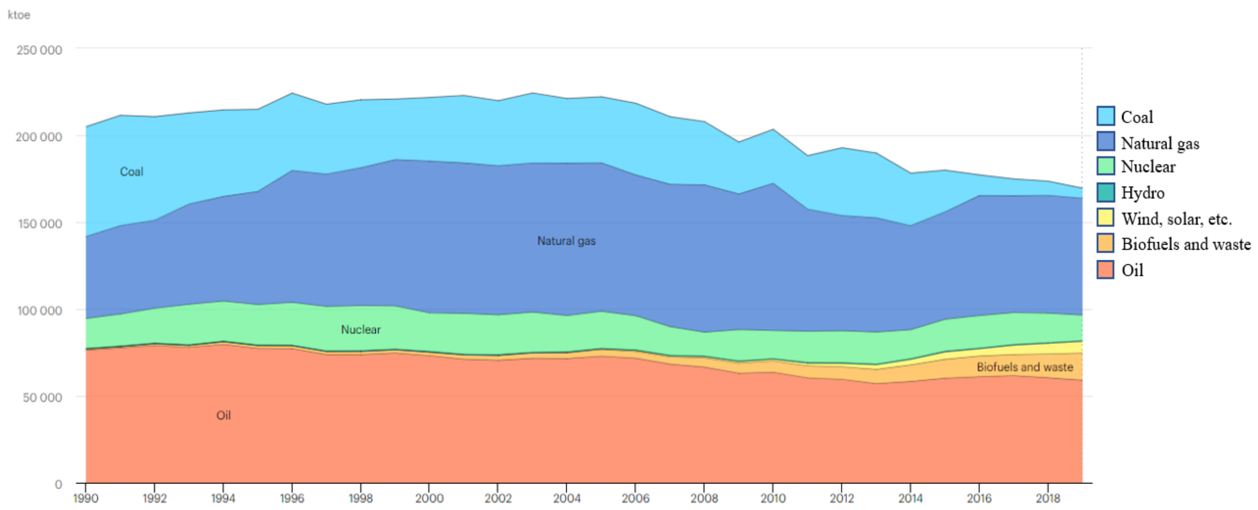

Figure 34. Total energy supply by source in UK in 1990-2019. (IEA. 2021c).

The Figure 35 describes the change in fuel use in energy supply in 1990 and in 2019. The most dramatic change can be seen with use of coal that has decreased from 30,8% to 3,4%. In 2019 wind and solar energy had a higher share in energy supply than coal. Nuclear and hydro seems to have quite stable role in energy supply through the reference period.

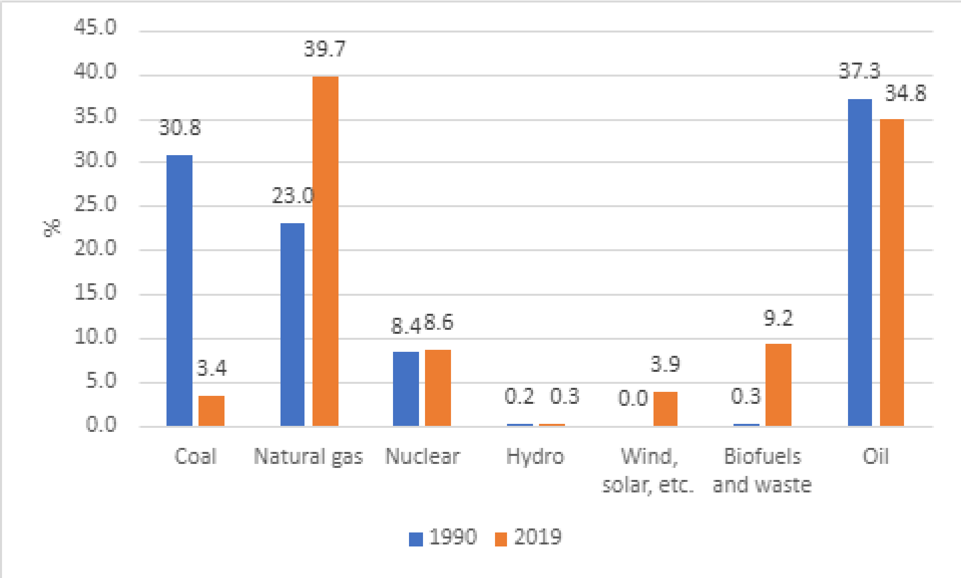

Figure 35. Share of energy supply by source in UK in 1990 and 2019. (Retold after IEA.2021c).

What comes to renewables, in 2019 the dominant renewable fuel was bioenergy (66,2% of total renewable fuels), wind had a share of 22,8%, solar was 4,8%, heat pumps accounted 4,1% and hydro 2,1%.

6.1 National Energy and Climate plan

UK's integrated National Energy and Climate Plan (NECP) was published on January 31st, 2020. That is the same date that UK left European Union and from that date on UK is no longer contributing the energy and climate targets of EU but is sending the NECP according to Withdrawal Agreement. The content of the report is exact until 31st January 2020 but after that policy announcements and publications are not included in NECP and NECP doesn't replace announcements done domestically. (Department for Business, Energy & Industrial Strategy. 2020b, 5.)

The Climate Change Act 2008 sets UK's national approach to respond on climate change. In 2018 amendment in the Act was made as government set a target of net zero GHG emissions by 2050 across the UK economy. While EU climate targets are not binding UK anymore there is still Withdrawal Agreement that requires commitment to NECP and due to that NECP presents same targets that is required from EU members, the report however is not that comprehensive. UK gives an estimation to reach 22%-29% share of renewable energy in final energy consumption in 2030. That target is divided to the sectors and two different pathways, and estimated shares are in electricity 50% (pathway 1) and 75% (pathway 2), heating and cooling 13% and 17 % and transport 16% in both pathways. This would mean that heating and cooling sector is the most difficult to decarbonise mainly due to dependency of natural gas, that accounts 70% of all heat use. UK Government is preparing a Heat and Buildings Strategy to set the actions to reduce emissions from buildings. Possible solutions for future heating are heat pumps, low carbon gases (like hydrogen via existing gas grid) and district heating network but large-scale transformation is needed to energy systems in UK to decarbonize the sector. Biomass is an important fuel in both heat and electricity production. Other renewable technologies that are used in UK are wind, solar, photovoltaics, hydro and shoreline wave and tidal. (Department for Business, Energy & Industrial Strategy. 2020b, 30-32; 41.)

Scenario for future energy consumption is presented in NECP referring to the year 2032 with existing policies. Existing policies are from 2016 presented in Energy and Emissions Projections. The scenario assumes that there will be a decrease of 14% in total final energy consumption and the share of bioenergy will be increasing with 29% being 159 TWh and covering about half of the total capacity of electricity. If planned policies will be considered in the scheme, there would be 185 TWh of electricity from renewable sources, about 60% of all generation.

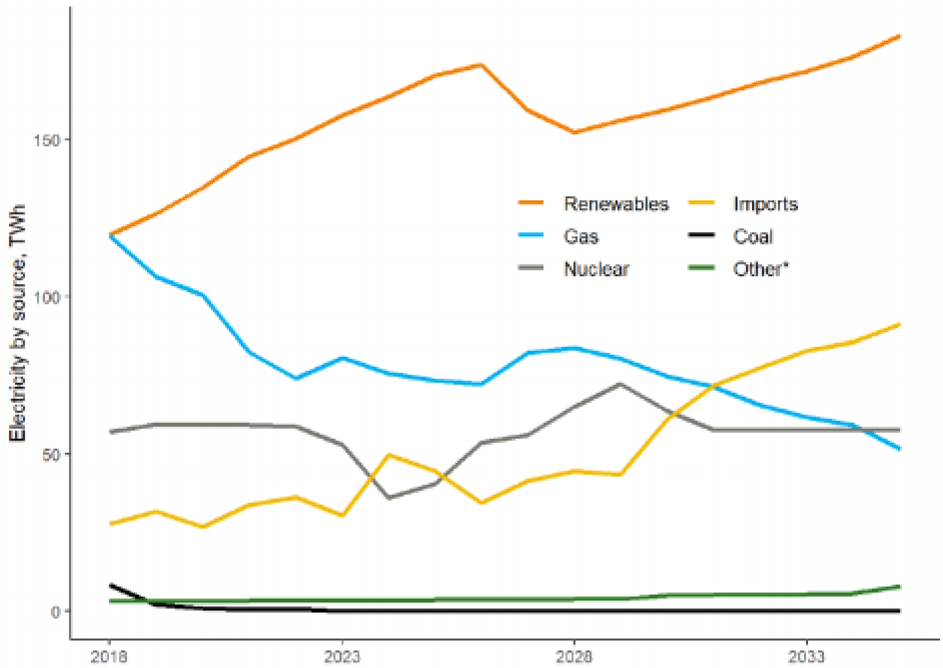

Figure 36. UK electricity by source technology [TWh], 2018-2035. (Department for Business, Energy & Industrial Strategy. 2020b, 162).

Figure 36 presents projections of electricity generation by source technology from 2018 to 2035. It shows how renewables take place while gas is decreasing, and coal has reached a level near to zero. Source “others” include electricity generation from coal or gas with Carbon Capture and Storage, oil, generation from other thermal plants and electricity storage. The share of “others” will be slowly increasing between 2028-2035. (Department for Business, Energy & Industrial Strategy. 2020b, 161-162; 165.)

In 2018 a review from Government was released that presented options for the UK how to reach emission reduction targets in heating sector by 2050. The conclusion was that there is no clear consensus what the best approach to decarbonizing would be and how it should be implemented. As the policies concerning heat generation are uncertain the NCEP doesn’t present any further projections of how future heat generation is executed. (Department for Business, Energy & Industrial Strategy. 2020b, 32; 162.)

Energy White Paper published in 2020 is a document that addresses the transformation of UK’s energy system and economic growth leading to net-zero emissions by 2050. It bases on Prime Minister’s Ten Point Plan and National Infrastructure Strategy. Energy

White Paper (HM Government. 2020, 16) presents following policies and commitments concerning energy transition:

- target of 40 GW offshore wind by 2030, including 1 GW floating wind, alongside the expansion of other low-cost renewable technologies
- supporting the deployment of CCUS (Carbon Capture, Usage and Storage) in four industrial clusters
- establishing the new UK Emission Trading System
- at least one large scale nuclear project to the point of Final Investment Decision (by the end of current parliament)
- consult the possibility to end gas grid connections to new homes from 2025 in favor of clean energy alternatives
- growing the installations of electric heat pumps from 30 000 per year to 600 000 per year by 2028
- building world leading digital infrastructure for the energy system.

Electricity is seen as a key enabler in energy transformation and Government is investing £1 billion in UK's energy innovation programme developing technologies like hydrogen and advanced nuclear. The paper presents two forecasts (A and B) of future electricity mix compared to current electricity mix with the assumption that demand of electricity could double by 2050. The Figure 37 shows the situation from 2019 in UK and both projections of future electricity mix.

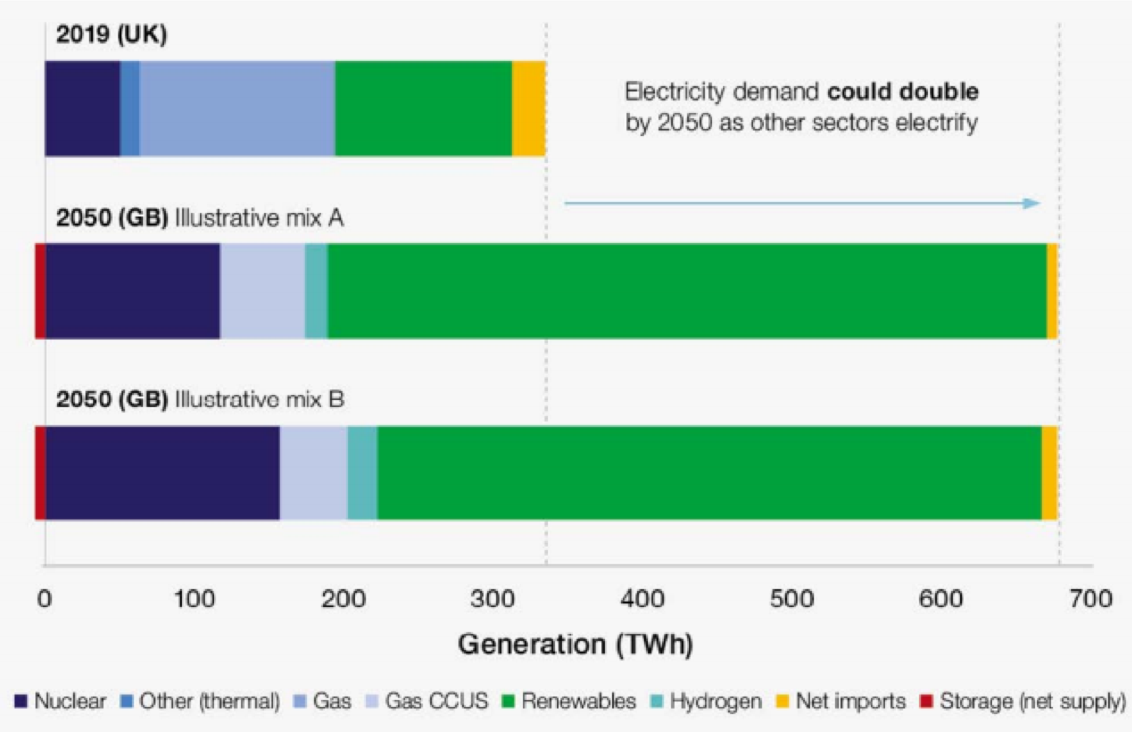

Figure 37. Electricity mix today and illustrative 2050 mixes in UK. (HM Government. 2020, 44).

In both future scenarios renewables have a major role and within renewables, onshore and offshore wind and solar power will be essential sources. In the option B nuclear with hydrogen has a bigger role which results less renewables and gas as a source of electricity. Currently nuclear accounts about 16% of the UK's energy need and in addition new nuclear plant is about to be commissioned around 2025 and that plant would deliver 7% of the current electricity need. Nuclear fits to UK's low-cost and low-emission energy plan and additional nuclear capacity may be needed more in the future as the old capacity will retire during the next decade. It is assumed that by 2050 electricity could cover over 50% of the final energy demand replacing petrol and diesel in cars but also gas in heating. (HM Government. 2020, 44-48; 66.)

The problematic decarbonizing sector in UK, heating, is mostly implemented by fossil fuels. Nearly 90% of homes in UK is heated with fossils and about 85 % of the homes is connected to the gas grid using natural gas while the rest use oil, liquified propane gas, electricity or are connected to heating network. Also the efficiency in the buildings is poor which losses a lot of energy and not just in private homes but also in public buildings and Government has invested £9.2 billion in energy efficiency initiatives. It is also foreseen that the Future Home Standard will be implemented in the near future, and it requires 75-80% lower carbon emissions from new built homes than homes that are built with current standards. (HM Government. 2020, 99-). Also Heat and Buildings Strategy is expected to be published soon. There are some expectations what it is about to be included, like a ban for gas boilers in existing homes, more information about the Heat Clean Grant (scheme replacing the Renewable Heat Incentive), and about which technologies for heating are eligible as well as the actions to reach installation of 600 000 heat pumps by 2028. Speculations of feeding hydrogen to the gas grid has also appeared but the cost is a concern in that solution. (Homebuilding & Renovating. 2021.)

6.1.1 Instruments

After year 2020 UK has no longer been part of the EU ETS system and to keep reducing emissions in power sector, aviation and energy intensive industries carbon pricing would be needed. For this UK has established UK ETS in January 2021 to replace EU ETS and ensuring that investments in low-carbon technologies are about to continue. (GOV.UK. 2021b.)

One of the main support mechanisms for large-scale renewable electricity projects in UK is The Renewables Obligation (RO) while smaller scale generation is supported in feed-in-tariffs. The aim of the mechanism is to increase the share of electricity generated from renewable sources. Electricity suppliers are obligated to precent certain amount of renewable obligations in respect to each MWh of supplied energy during an obligation year. The suppliers buy the certificates from renewable producers. The system has been closed for new generating capacity since March 2017 but stations already in the system will continue to receive support until 2027 or until the final closer in 2037. (Department for Business, Energy & Industrial Strategy. 2020a, 122-123.)

Another main mechanism is Contracts for Difference which is a scheme that support projects aiming to renewable electricity production. The purpose is to offer long term contracts for low carbon technologies and this way avoid uncertainties that are related to markets. The mechanism offers a fixed “strike price” that is secure for electricity generators and if the market price is lower than strike price the generators receive a top-up payment for each sold unit. If the market price is higher than strike price, producers pay back the difference. The mechanism is executed via auction. (Department for Business, Energy & Industrial Strategy. 2020a, 123). Allocation round in 2019 led to 5,5 GW of offshore wind and 275 MW of remote island wind. The auctions will take place every second year and the next one is planned for end of 2021 open to onshore and offshore wind, photovoltaics and other established technologies deploying about 12 GW renewable generation. (HM Government. 2020, 45.)

Feed-in tariff system is meant for technologies like solar PV, wind, CHP, hydro and anaerobic digestion with the capacity up to 5MW (CHP 2 MW). Feed-in tariff system was closed to new applicants in April 2019 but is available for existing generation. It is meant for small scale production for organisations, businesses, communities and individuals to support investments in small-scale renewable and low-carbon electricity generation. (Department for Business, Energy & Industrial Strategy. 2020a, 123-124.)

Since 2016 UK government has financially supported implementation of low-carbon heat technologies like heat pumps, biomass boilers and solar water heaters in homes and businesses. (Department for Business, Energy & Industrial Strategy. 2020b, 93).

6.2 Waste Management Plan

The Waste Management Plan of England, published in January 2021, with the associated documents together with local authorities' waste local plans and plans by administrators in Scotland, Wales and Northern Ireland and Gibraltar ensures that waste management plans are in use in the whole UK. England being responsible of 85% of the UK's waste, the concentration in this chapter is in England's waste plan. The Waste Management Plan for England focuses on waste generation and management while The Resources and Waste Strategy from year 2018 sets out the vision and policies to move to a more circular economy. (Department for Environment Food & Rural Affairs. 2021, 3.)

Like in EU, also UK has a target to move from linear economy to the circular economy. There are five ambitious targets that The Resources and Waste Strategy (HM Government. 2018, 17) identifies:

- To work towards all plastic packaging placed on the market being recyclable, reusable or compostable by 2025
- To work towards eliminating food waste to landfill by 2030
- To eliminate avoidable plastic waste over the lifetime of the 25 Year Environment Plan
- To double resource productivity by 2050
- To eliminate avoidable waste of all kinds by 2050.

UK government has set a legally binding target of net zero GHG emissions across the UK economy by 2050 and waste sector acts a remarkable role in achieving it. The emissions from waste sector has decreased 69% between years 1990 and 2018, but to achieve MSW re-use and recycling rate of 65% and landfilled MSW 10% or less of MSW generated by 2035, there is still job to do. (Department for Environment Food & Rural Affairs. 2021, 6; 11-12.)

There are three main ways that municipal residual waste is treated in England: energy recovery, exporting waste as RDF and landfilling. The government supports energy recovery from residual waste that can’t be utilized otherwise considering it as a best management option in terms of environmental impact. As a part of the actions to improve waste management, England wants to recover more heat from EfW plants and encourages companies to utilize heat that their EfW plants are currently wasting. Most of the EfW plants in England are generating only electric power but also using the heat that the efficiency of the installation would increase. There is Heat Networks Investment Project with the capital of £320 million ongoing that aims to help utilize EfW plants as a source of heat for district heating networks and it is also under investigation how to ensure that future plants would be located near the potential heat customers. The shift would decrease the use of gas as a fuel in heating. (HM Government. 2018, 76-77.) By January 2021 there has been funding for six EfW plants counting over 150 GWh of waste heat annually. (Department for Environment Food & Rural Affairs. 2021, 13).

UK is exporting RDF for energy recovery mainly to northern continental Europe and Scandinavia. The amount of exported RDF was 3,5 million tonnes in 2018 and has been increasing since 2012 when exported amount was 961 000 tonnes. (Department for Environment Food & Rural Affairs. 2021, 24). However, in 2019 there was a drop in total exported waste amounts. RDF exports fell 15,7%, but SRF exports were increasing with 4,1%. Largest markets for UK export markets are Netherlands, Sweden, Germany, Norway and Denmark. One reason for decreased exports is Netherlands' tax for imported waste but also uncertainty of Brexit had an impact on exports. Increasing costs is the one reason why UK is more interested in processing waste itself but also improving the waste management with new EfW facilities is a one reason for that. (Resource. 2020b.)

The Landfill tax rates were increased in April 2021 to encourage minimizing the generated waste and other waste management options (applies only in England and Northern Ireland). The tax is charged of material disposed at landfill or unauthorized waste site. Landfill tax was originally introduced in 1996. Tax credits is possible to achieve if the waste is sent to recycling, incineration or reuse. (GOV.UK. 2021a.)

6.3 Biomass and wood by-products

As biomass accounted 66,2% of all renewable use in UK in 2019, two-thirds of it was used in electricity production. In the Figure 38 biomass is divided further to sources and figure shows also how the sources are used in heat and electricity production. The most used biomass is plant biomass, and it is mostly used in electricity production. Wood biomass on the other hand is only used in heat generation and is the most popular source used in heating but also waste wood accounts a small portion in heat generation. (Department for Business, Energy & Industrial Strategy. 2020a, 109.)

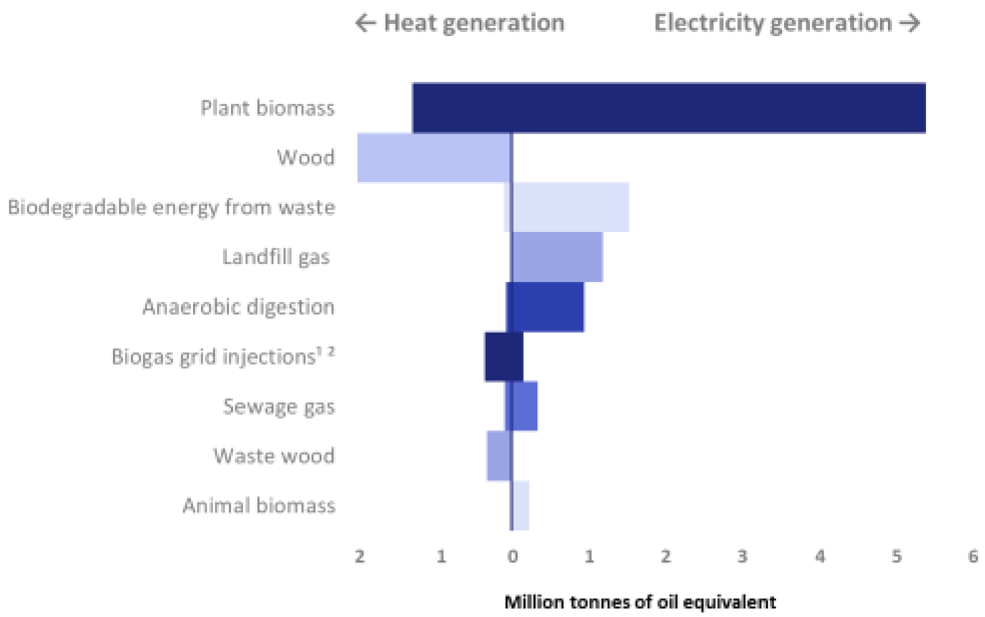

Figure 38. Biomass by source in heat and electricity generation in UK in 2019, [ktoe]. (Department for Business, Energy & Industrial Strategy. 2020a, 109).

In the UK the feedstocks of biomass are biomass wastes (food, sewage, biomass portion of mixed black waste), wood/dry biomass residues (forestry residues, by-products from agriculture or timber), energy crops (domestic fast-growing trees, grasses) and other crops (food crops domestically or internationally produced.). UK Government considers biomass as one of the most valuable tool for reaching the net zero emissions. Bioenergy could support decarbonisation in buildings that are dependent in fossils and The Renewable Heat Incentive is supporting use of biomass as well as biogas technologies in heating until 2021. (Department for Business, Energy & Industrial Strategy. 2020b, 33-34.) A new Biomass Strategy will be published in 2022 including the results of available sustainable biomass and how this resource could be best utilized to achieve the net zero GHG target by 2050. One important aspect in the report will be the role of Bioenergy with Carbon Capture and Storage (BECCS) that could deliver negative emissions from processes like combusting or gasification. There are various applications for BECCS in UK like hydrogen production, power generation, waste management and heat in industrial processed. (HM Government. 2020, 53.)

Committee on Climate Change has released a report "Biomass in low-carbon economy" in 2018 that assesses the role of biomass in UK and how the use of biomass could be low-carbon and sustainable prioritizing the most valuable end use. The findings of the report tells that biomass could have a remarkable role in decarbonizing, but governance should be improved to make this happen. Sustainable way to manage the biomass stocks is important to ensure that carbon absorption is continuing and this way helping the decrease of carbon in atmosphere. UK’s land use scenario has presented that there is a possibility to increase the carbon stock like woodland or restoring peatlands and this way increase also supply of sustainably harvested biomass. There is an estimation that by 2050 there could be 27 million tons (dry) of forest and agricultural residues and energy crops available and with projected imports it would mean that bioenergy could have a portion of 5-15% of UK’s energy demand. Currently biomass covers around 7% of the demand. However, the prioritizing the biomass stock use is important, and the report presents that current uses of biomass should be changed and direct it to the sectors like construction and BECCS. Current use for example in surface transport, heating or power generation without carbon capture and sequestration do not bind carbon and have also other low-carbon alternatives so the use of biomass should be directed elsewhere over time. That is where Government policies is needed to make that transition. The report presents hierarchy for best use of sustainable biomass by 2050:

- Bioeconomy
    - wood in construction, potentially other long-lived bio-based products (within circular economy)
- Buildings
    - Only very limited additional use for buildings heat: niche uses in e.g. district heat and hybrid heat pumps
- Industry
    - BECCS in industry alongside other low-carbon solutions
- Power
    - Biomass used for hydrogen production or power with CCS
- Transport
    - Up to 10% aviation biofuel production with CCS.

(Committee on Climate Change. 2018, 8-13.)

6.4 Waste-to-Energy

UK Statistics on Waste -report differs from other countries reports by using the data from year 2018 so annual waste statistics presented here are from 2018 but some data origins also from 2016.

In 2016 UK generated 221 million tonnes of waste of which household waste was 12%, commercial and industrial sector 18%, construction, demolition and excavation 62% and other waste 8%. England was responsible of 85% of the total amount of UK waste. In 2018 the total waste derived from households was 26,4 million tonnes having a small decrease of 1,8% compared to 2017. 8,7 million tonnes of municipal waste was directed to landfill in 2018. When concidering all waste generated, recycling and recovery was the most typical (48,5%, of which around two thirds from construction, demolition and excavation) treatment method in 2016 and landfilling came second (24,4%). (Department for Environment Food & Rural Affairs. 2020, 5-6; 11-14.)

Tolvik Consulting (2021) has released a seventh annual report on UK Energy from Waste (EfW) in co-operation with the Environment Agency, Environment Services Association and indicidual EfW operators and the figures are from year 2020. The term “residual waste” discussed in the report includes non-hazardous, solid and combustable mixed waste that remains after recycling operations.

In 2020 13,96 million tonnes of residual waste was treated in UK EfW facilities and there was increase of 10,5% from the previous year. Annual thermally processed waste amount accounted 52% of the overall residual waste market in UK in 2020. 79,9% of the input waste in 2020 were from Residual Local Authority Collected waste and the rest was commercial and industrial waste. Power generation from waste to energy process is presented in Figure 39. The amount of generated power has been increasing since 2016, except the year 2018, and in 2020 net power generated was 7 762 GWh_e. Energy recovered from EfW facilities is mostly electric power but in addition to the power figures also heat has been generated 1 651 GWh_{th} in 2020. (Tolvik Consulting. 2021, 5-8.)

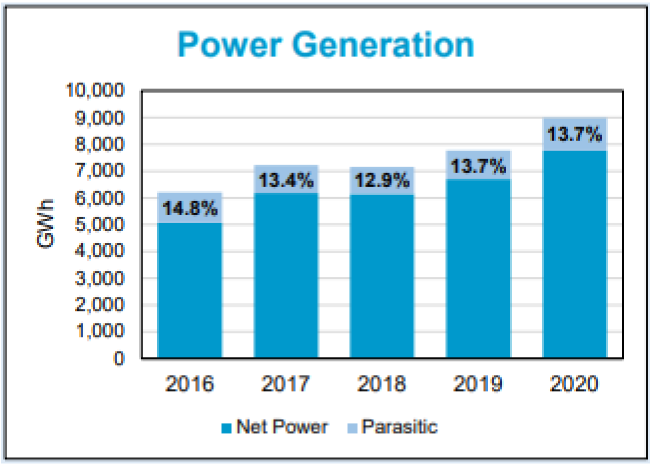

Figure 39. Power generation from EfW facilities in UK in 2016-2020. (Tolvik Consulting. 2021, 7).

In 2020 there were 54 plants producing energy from waste in UK with 105 lines. As can be seen in the Figure 40 the total amount of facilities has been increasing steadily since 2016.

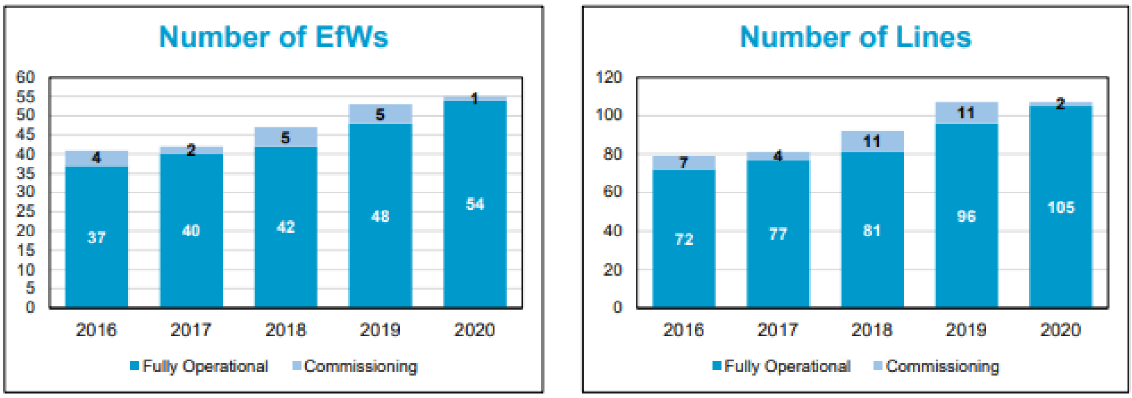

Figure 40. Number of EfW facilities and lines in 2020 in UK. (Tolvik Consulting. 2021, 4.)

Weighted average age of UK's EfW plants in 2020 was 10,4 years and has maintained at 9-10 years over the last four years as new facilities has been established. In the time average age will start rising since the amount of new facilities will be deminished. However, it is forecasted in the report that in 2025 the operational capacity would be 18,2 million tons of waste which is a small increase compared to 2020 figures. (Tolvik Consulting. 2021, 4; 17.)

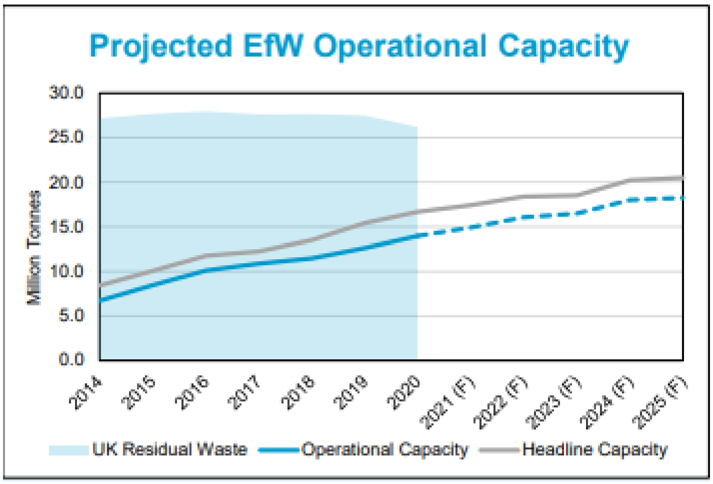

Figure 41. Projected EfW capacity in UK in 2020-2025. (Tolvik Consulting. 2021, 17.)

As the Figure 41 shows, the capacity of EfWs is forecasted to be increased at least until the year 2024 after which the increase of capacity seems to stop. The amount of additional capacity in the future is dependent on number of permissions for EfW projects. The Figure 41 also includes the historic data of residual waste amount in UK and preliminary estimate for year 2020. According to the figure, the amount of residual waste has been decreasing since about 2018. The Figure 42 on the other hand shows how the Residual Waste Market in UK has been divided to different treatment methods. The Figure reveals that share of thermal treatment exceeded share of landfilling as a treatment method of residual waste first time in 2019. The curves tell that since 2010 share of landfilling has come down from around 85% to below 40% in 2020 and EfW has increased from around 12% (2010) to 52% (2020). UK is a big exporter of the waste and in the peak years about 15% of the residual waste was exported. The estimation for year 2020 is that exports are decreasing, even 31% compared to year 2019. (Tolvik Consulting. 2021, 4-5.)

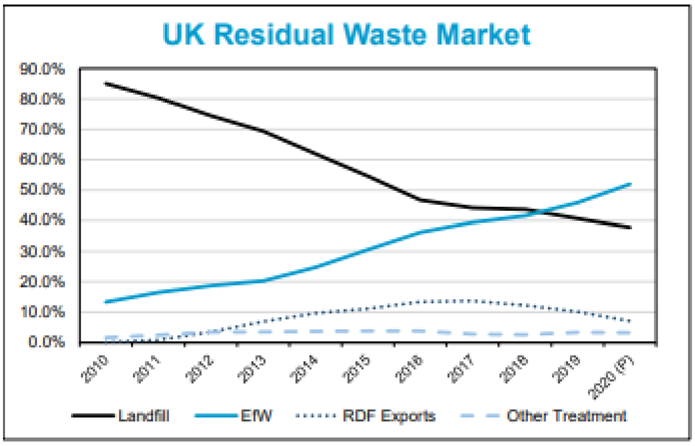

Figure 42. UK Residual Waste Market. (Tolvik Consulting. 2021, 5).

In the Figure 43 energy from waste facilities, that are included in the Tolvik Consulting's report, are detailed by location on the map. Plants operating are marked with blue, plants commissioning are orange and plants under construction are marked with green spots.

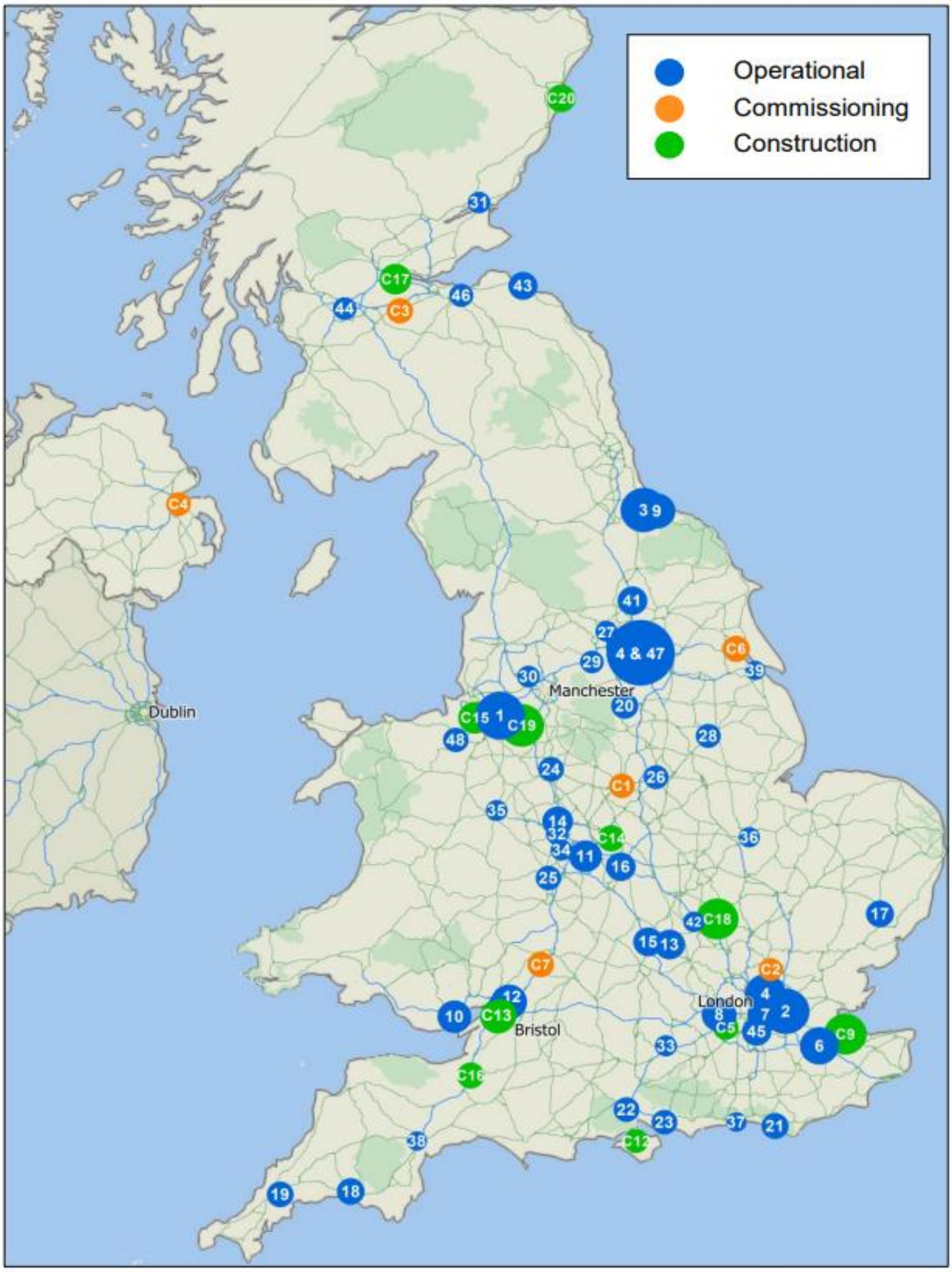

Figure 43. EfW facilities in UK included in the Tolvik Consulting's report. (Tolvik Consulting. 2020, 17.)

The biggest operators in the field of EfW in UK are Viridor (having a 21,8% share of input tonnages in 2020), Veolia (16,7%) and Suez (15,5%) dominating together over half of the market share. Other operators are: WTI (13%), FCC (10,5%), Council (6,3%), Cory

(5,2%) and others (10,9%; MESE, MVV and Amey each having less than 3% share). (Tolvik Consulting. 2021, 6.) Detailed lists of EfW facilities operating, commissioning and under construction are found in Tables 8, 9 and 10.

Table 8. EfW facilities operating in UK in 2020. (Tolvik Consulting. 2020, 18.)

Operational EfWs

	Permitted Name	Known As	Location	Operator	Capacity (ktpa)	Processed (ktpa) 2018	Processed (ktpa) 2019
1	Runcorn EfW Facility	Runcorn	Halton	Viridor	1,100	884	962
2	Riverside Resource Recovery Facility	Riverside	Bexley	Cory	785	740	743
3	Tees Valley - EfW Facility	Tees Valley	Stockton-on-Tees	Suez	756	637	651
4	Ferrybridge Multifuel 1	Ferrybridge FM1	Wakefield	MFE	725	647	667
47	Ferrybridge Multifuel 2	Ferrybridge FM2	Wakefield	MFE/WTI	675	0	129
5	EcoPark Energy Centre	Edmonton	Enfield	Council	620	518	498
6	Allington Waste Management Facility	Allington	Kent	FCC	560	492	488
9	Wilton 11 EfW	Wilton 11	Middlesborough	Suez	500	467	448
7	SELCHP ERF	SELCHP	Lewisham	Veolia	464	441	439
8	Lakeside EfW	Lakeside	Slough	Lakeside	450	431	427
10	Cardiff Energy Recovery Facility	Trident Park	Cardiff	Viridor	425	376	366
11	Tyseley ERF	Tyseley	Birmingham	Veolia	400	343	343
12	Severnside Energy Recovery Centre	Severnside	S.Gloucestershire	Suez	400	377	397
13	Greatmoor EfW	Greatmoor	Buckinghamshire	FCC	345	308	295
14	Staffordshire ERF	Four Ashes	Staffordshire	Veolia	340	336	337
15	Ardley EfW Facility	Ardley	Oxfordshire	Viridor	326	290	280
41	Allerton Waste Recovery Park	Allerton Park	North Yorkshire	Amey	320	244	255
16	CSWDC Waste to Energy Plant	Coventry	Coventry	Council	315	289	299
45	Beddington Energy Recovery Facility	Beddington Lane	Croydon	Viridor	303	80	279
43	Dunbar Energy Recovery Facility	Dunbar	East Lothian	Viridor	300	40	251
17	SUEZ Suffolk - EfW Facility	Great Blakenham	Suffolk	Suez	295	264	267
18	Devonport EfW CHP Facility	Devonport	Plymouth	MVV	265	255	265
20	Sheffield ERF	Sheffield	Sheffield	Veolia	245	234	230
21	Newhaven ERF	Newhaven	East Sussex	Veolia	242	224	223
19	Cornwall Energy Recovery Centre	Cornwall	Cornwall	Suez	240	221	243
25	EnviRecover EfW Facility	Hartlebury	Worcestershire	Severn	230	200	201
22	Integra South West ERF	Marchwood	Southampton	Veolia	220	199	211
23	Integra South East ERF	Portsmouth	Portsmouth	Veolia	210	207	195
24	Stoke EfW Facility	Hanford	Stoke-on-Trent	MESE	210	186	179
26	Eastcroft EfW Facility	Eastcroft	Nottingham	FCC	200	177	188
48	Parc Adfer ERF	Parc Adfer	Deeside	WTI	200	0	58
28	Lincolnshire EfW Facility	North Hykeham	Lincolnshire	FCC	190	171	175
46	Millerhill Recycling and ERC	Millerhill	Edinburgh	FCC	190	16	142
27	Leeds Recycling and ERF	Leeds	Leeds	Veolia	180	187	174
44	Glasgow RREC	Polmadie ACT	Glasgow	Viridor	150	7	83
29	Kirklees EfW Facility	Kirklees	Huddersfield	Suez	150	124	134
30	Bolton ERF	Bolton	Gtr Manchester	Suez	120	29	76
31	Baldovie Waste To Energy Plant	Baldovie	Dundee	MVV	120	93	96
32	Wolverhampton EfW Facility	Wolverhampton	Wolverhampton	MESE	118	110	114
33	Integra North ERF	Chineham	Hampshire	Veolia	110	93	94
34	Dudley EfW Facility	Dudley	Dudley	MESE	105	94	96
35	Battlefield EfW Facility	Battlefield	Shropshire	Veolia	102	96	99
42	Milton Keynes Waste Recovery Park	Milton Keynes ACT	Milton Keynes	Amey	94	27	58
36	Peterborough EfW Facility	Peterborough	Peterborough	Viridor	85	81	80
37	Enviropower Ltd, Lancing	Lancing	West Sussex	Enviropower	75	60	55
38	Exeter ERF	Exeter	Devon	Viridor	60	58	58
39	Integrated Waste Management Facility	NewLincs	NE Lincolnshire	Tiru	56	51	51
40	Energy Recovery Plant	Gremista	Shetland Islands	Council	26	23	21
	Other EfWs in Commissioning but not achieved Takeover in 2019					57	205
			Totals		**14,596**	**11,488**	**12,626**

Table 9. EfW facilities commissioning in UK in 2020. (Tolvik Consulting. 2020, 19.)

EfWs in Commissioning

	Permitted Name	Known As	Location	Operator	Start Date	Headline Capacity (ktpa)	Net Input 2019 (ktpa)
C1	Sinfin IWTC	Sinfin Road ACT	Derby	Mothballed	Q3 2014	0	49
C2	Hoddesdon EfW Plant	Hoddesdon ACT	Hertfordshire	Bouygues	Q2 2014	90	13
C3	Levenseat Renewable Energy	Levenseat ACT	West Lothian	Outotec	Q2 2015	180	20
C4	Full Circle Generation EfW	Belfast ACT	Belfast	Bouygues	Q3 2015	120	34
C7	Javelin Park ERF	Javelin Park	Gloucestershire	UBB	Q3 2016	190	68
C6	Hull Energy Works	Energy Works ACT	Hull	Engie	Q1 2016	227	21 (est)
				Total		**807**	**205**

Table 10. EfW facilities in construction in UK in 2020. (Tolvik Consulting. 2020, 19.)

EfWs In Construction

	Permitted Name	Known As	Location	Developer	Start Date	Capacity (ktpa)
C5	Charlton Lane Eco Park	Eco Park ACT	Surrey	Suez	Q2 2016	60
C9	Kemsley Park EfW	Kemsley	Kent	WTI	Q3 2016	550
C12	Isle of Wight EfW	Isle of Wight	Isle of Wight	Amey	Q2 2017	30
C13	Severn Road RRC	Avonmouth	Bristol	Viridor	Q1 2017	350
C14	Baddersley EfW	Baddersley	Warwickshire	Equitix	Q1 2018	100
C31	Baldovie Waste To Energy Plant (New)	Baldovie	Dundee	MVV	Q1 2018	110
C15	Hooton Park Sustainable Energy	Hooton Park ACT	Merseyside	BWSC/Cogen	Q4 2018	266
C16	Bridgwater Resource Recovery	Bridgwater	Somerset	Equitix/Iona	Q4 2018	100
C17	Earls Gate Energy Centre	Earls Gate	Falkirk	Earls Gate	Q4 2018	237
C18	Rookery South ERF	Rookery South	C Bedfordshire	Covanta/GIG	Q1 2019	545
C19	Lostock Sustainable Energy Plant	Lostock	Cheshire West	FCC	Q1 2019	600
C20	NESS EfW Facility	Ness	Aberdeenshire	Indaver/Acconia	Q3 2019	150
				Total		**3,098**

There are ongoing projects for new EfW plants as well in the UK. At the moment Newhurst Energy Recovery Facility is under construction near Shepshed and the plant is planned to be completed in 2023. Hitachi Zosen Inova is the principal contractor, and the facility is being developed by Biffa, Covanta and Green investment Group. The capacity of the new facility will be 350 000 tons of residual waste annually generating up to 42 MW of energy. (Covanta. 2021.)

New EfW plant will be constructed to Drakelow with capacity of 169 000 tonnes of RDF per year generating 18 MW of electricity. Energy company Vital Energi has designed the plant and will supervise the construction and operation of the plant. The energy company E.ON. has a 30 year concession on the land and the agreement of supply of the fuel is done with Beauparc Group. The plant is scheduled to be completed in 2023. (Resource. 2020a.)

6.4.1 Sludge

2019 UK Energy Statistics divides sewage sludge as one of the biomass sources, sewage gas from anaerobic digestion. As presented earlier in this study, Figure 38 shows the role of sewage gas in heat and electricity generation. Majority of the sewage gas is used in electricity production, about 0,3 ktoe in 2019, while in heating about 0,1 ktoe. There were 194 sites that were generating electricity from sewage sludge in 2019. (Department for Business, Energy & Industrial Strategy. 2020a, 125.)

6.5 Technologies and actors

Operators on the field of WtE are presented earlier in section 6.4. What comes to whole electricity markets in UK, it is dominated by the former gas and electricity monopoly suppliers the “Big Six” (Centrica, Électricité de France (EDF) Energy, Uniper, RWE Npower, SSE, and Scottish Power) who operate on the field of generation, supply and/or retail of electricity and gas but their share has come down by the time. When looking at the generation, in 2016 the biggest actors by installed capacity were RWE Npower (share of 10,1% of the installed capacity), British Energy (9,1%), SSE (7,0%), Uniper (6,6%), EDF Energy (5,5%), Drax (4,1%) and ENGIE (4,1%). (IEA. 2019, 143.)

6.6 Future perspective

UK has succeeded in decreasing the use of coal, but other fossils, oil and natural gas, are dominative fuels in energy supply. Electricity has a big role in energy transition in UK and renewables, especially wind, are taking place in electricity generation in the following years. What comes to more complex sector, heating, there are more modest expectations for transition to renewables. Gas is a leading fuel in heating but there are alternatives such as heating pumps becoming more common, and the Government has ambitious target to increase the amount of installations. UK is waiting for two important documents, that have effect on nations energy solutions, to be published; Heat and Buildings Strategy, that will include introduction of new heating technologies among other things, and new Biomass strategy, that specifies the priority to utilize the biomass resources. While biomass has been one of the biggest renewable sources in heating so far it is expected to be a valuable in the future in decarbonizing the heating sector. Use of biomass will continue but as a technology BECCS will be strong with biomass in energy use purposes to reach negative emissions. UK is very interested in CCUS and it is not only attached to strategy of biomass burning but it is expected to be solution in other industries too. Government is, as well, supporting energy recovery from waste and with CCUS technology it would have lower environmental impact and energy recovery is considered as a best treatment option for residue waste. Plans to increase the district heating network especially with heat from WtE plants also speak in favor of the strong role of waste incineration in the future. It is expected to have more residual waste in the upcoming years because waste is to be treated more domestically and exports are expected to decrease due to higher costs. In the latest forecasts the capacity of the WtE plants was projected to slightly increase at least to 2024 but it will be seen whether the new Heat and Building strategy will include new guidelines for waste incineration and will that have impact on capacity too.

7 SUMMARY

This study aims to investigate the role of the energy recovery from waste and solid biomass and sludge in energy production and what kind of future these fuels and technologies would have in selected countries Sweden, Poland and UK. As all the countries are or recently were EU members, EU policies for energy and climate as well as for waste are presented in the study. Fuels and technologies for their utilization are also gone through to show the possibilities of each fuel.

EU has several policies and programs that aim in renewing the energy system and decarbonizing the energy sector, such as EU Green Deal, European Climate Law, Energy Union and EU ETS. EU defines the targets and schedules for the share of renewable energy sources that member states need to achieve for EU to stay in course in the fight against GHG emissions and global warming. Waste sector is bound to energy sector in the form of energy recovery and energy recovery is essential part of the waste management in several European countries using the residual waste in energy generation.

One important factor to consider when thinking about the waste-to-energy technology is waste hierarchy according to which energy recovery is the second last option in waste treatment. EU is aiming to circular economy and prioritizes reuse and recycling in waste management and trying to avoid landfilling. Energy recovery has benefits in reducing volume of the waste and getting energy out of it, but EU is willing to diminish the use of the technology prioritizing recycling. Biomass is currently a vital fuel in EU region and in the future, it is assumed to have a big potential in energy production as well. There are several end use possibilities with biomass and in the future prioritizing and political decisions are also needed to get the best value out of the feedstock.

All studied countries have applied EU policies in climate and energy issues until January 2020 but after that UK is carrying out its own policies. Each country has their own characteristics in energy sector due to their geographical location or economics and they all are in different phases in energy transition. All examined countries however are interested in implementing more renewable technologies and one in common future direction is wind power, as well as PV, in electricity generation. Also heating pumps and carbon capture and sequestration are technologies with high interests in every country's agenda.

Sweden is a forerunner in the use of renewable energy sources and especially in heating sector, waste and biofuels are fuels with great importance producing 75% of the energy to district heating (in 2015). There were 35 incineration plants for household waste in 2019 and energy recovery from waste in 2019 was 18,5 TWh while capacity of plants was 6,7 million tons of waste annually. Currently Sweden is dependent on imported waste (1,5 million tons in 2019) due to the overcapacity in the waste-to-energy plants. According to the forecast, future capacity of waste-to-energy installations will be decreasing with about 500-800 thousand tons by 2040 compared to 2019 level so Sweden is not abandoning waste-to-energy in the following twenty years.

Poland still relies on fossil fuels having nearly 90% of the total energy supply from fossil sources in 2019 and the transition to renewables has been slower than in other countries studied. Biofuels and waste comprised the biggest renewable source (9% of the total energy supply) in 2019 and both fuels will have a role in future especially in heating sector when Poland aims in enlarging its district heating network. According to scenarios, in district heating and cooling solid biomass will have a magnitude of 6200-7900 ktoe in 2040 and municipal waste 140-200 ktoe by 2040. Solid biomass will be an important factor when old coal plants are turned to using biofuels and to gain the renewable targets set to Poland, biomass use should be increased at least 1,1% annually. 2,9 million tons of municipal waste was incinerated in 2019 in Poland and energy generation from that waste was 4300 TJ. WtE has been increasing in recent years and in 2018 there were eight incineration plants for municipal solid waste. There are several projects for new waste-to-energy plants in Poland ongoing but also planned ones waiting for permissions. Poland's National Waste Plan defines that no more than 30% of the generated MSW could be incinerated and when looking at the figures from 2019 there is about one million ton of waste that could be incinerated.

The dominative fuels in UK in energy supply are oil and natural gas, which is commonly used in heating. UK's challenge in decarbonizing the nation is to find renewable solutions to the heating sector substituting gas and waste-to-energy is seen as a one possibility in the form of local district heating networks. UK has a lot of waste-to-energy plants existing, 54 plants and 105 lines in 2020 and nearly 14 million tonnes of waste was incinerated in the plants generating about 7800 GWh power, mostly electric power. Utilizing the heat from the WtE process would be one opportunity to replace natural gas in heating sector. UK is planning to increase the district heating network and WtE plants are important part of that plan. Forecast until 2025 show that the capacity of waste-to-energy facilities is increasing slowly but the fact that UK intends to increase the amount of domestically treated waste in the future will contribute to strengthening the perception that waste incineration will continue to be strong. Currently biomass is the biggest renewable energy source in heating and of all renewable use, share of biomass covered nearly 70% in 2019. Biomass is considered as valuable source of energy also in the future, especially with CCUS with which negative emissions could be reached. It is estimated that in 2050 biomass could cover 5-15% of the UK's energy demand when it currently is about 7%.

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