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DECARBONISATION OPTIONS FOR THE DUTCH ASPHALT INDUSTRY

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Colophon

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MIDDEN project coordination and responsibility

The MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) was initiated and is also coordinated and funded by PBL and TNO. The project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. Correspondence regarding the project may be addressed to: D. van Dam (PBL), Dick.vanDam@pbl.nl, or S. Gamboa (TNO), Silvana.Gamboa@tno.nl.

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Accessibility

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Summary

This report describes the current situation of the Dutch asphalt sector, which is composed of 34 industrial sites. In 2020, the total production of asphalt was more than 7 million tonnes.

Based on literature sources, the average energy consumption of the asphalt sector is between 0.28-0.33 GJ/tonne asphalt mix. According to the EU-ETS registration, the CO_2 emissions for this sector were 99 kilotonnes (kt) in 2020. The main energy source for the asphalt manufacturing sites is natural gas, which represents around 84% of the sector's total energy consumption.

The main sources for emissions are the drying and mixing steps. This report explores the options and preconditions for decarbonisation of the asphalt sector in the Netherlands considering a 2050 horizon. The decarbonisation options studied in this report include the following categories: fuel substitution by hydrogen, heating system electrification, alternative feedstock and recycling. All the covered options present benefits and challenges related to its implementation, which are further discussed in this report. Hydrogen can be gradually introduced into the fuel mix without changing the standard equipment configuration (up to 30%vol. of hydrogen in the blend). However, equipment adaptations would be necessary for higher concentrations of hydrogen or full substitution. Furthermore, due to an increased volume flow rate, higher NO_x emissions and higher pressure loss when considering higher concentrations of hydrogen in the mix can occur.

Electrification of the heating system requires reliable renewable electricity supply and significant infrastructural changes on site. One of the fuel substitution options explored is the electrification of the heating systems. For some heating processes, such as bitumen heating, fully electrically heated tanks are already available and used in the market. The challenge arises in the heating processes that demand higher heating power, such as drum heating reclaimed asphalt pavement (RAP) and asphalt mixture. Regarding feedstock substitution, this study focuses on the exploring the opportunities to use a blend of lignin and bitumen. Bitumen is one of the by-products from the refinery sector and it is used as a binding material in the asphalt production. Depending on the sourcing of the lignin, this alternative could reduce the indirect emissions of the sector and the dependence on the refinery sector, which is the supplier of fossil-based bitumen. However, the full replacement of bitumen by lignin has not been proven yet.

Recycling and repurposing is already a common practice in the asphalt sector. Something that could still improve the current process would be increasing the amount of RAP in the asphalt mix. Studies show that this could reach levels of up to 71% in some use cases. However, the asphalt mix can be affected by the amount of RAP included in the recipe.

Several aspects should be considered while evaluating the possible decarbonisation alternatives for this sector. For instance, specific regulation and quality requirements for each type of asphalt mix production site, commodity prices (such as electricity, green hydrogen and biomass) may play a relevant role in the transition of the asphalt sector to a low-emission future.

1 Introduction

This report describes the current situation for the production of asphalt in the Netherlands and the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

Research aim & scope

This research aims to:

1) Provide an overview on the production of asphalt for road pavement in the Netherlands,
2) Inquire the most prevalent method of asphalt production in order to allocate the energy and its corresponding sources of CO_2 emissions,
3) Describe the application and products obtained from the Dutch asphalt industry, and
4) Provide suitable decarbonisation options for the Dutch asphalt industry.

The overall goal of this research is to investigate the decarbonisation options for the Dutch asphalt industry as a whole, and not per company.

The starting point for this research is the production of asphalt for motorways and the direct emissions attributed to it. In order to quantify the reductions of both CO_2 emissions and energy use for the decarbonisation options, the functional unit taken into consideration for the process of asphalt will be one tonne of asphalt mix. The boundary of this report includes only the quantification of the processes and subsequent emissions within the facilities of the asphalt plant, also called “Scope 1”. The indirect processes and material flows involved in the production of asphalt will be only described in Chapter 2. Nonetheless, the production of asphalt with reclaimed asphalt (RA) will be included within the boundary of this research. The emissions attributed to the use of electricity will not be taken into consideration as they fall outside the given boundary.

Reading guide

Chapter 2 introduces asphalt product and the current situation of the Dutch asphalt industry. Chapter 3 describes the asphalt production processes in the Netherlands, and Chapter 4 describes the relevant asphalt mixes of these processes, whilst options for decarbonisation are systematically quantified and evaluated in Chapter 5. The feasibility of and requirements for those decarbonisation options are discussed in Chapter 6.

2 Asphalt production in the Netherlands

Asphalt is a unique commodity in comparison to others, mainly due to the fact that it has a limited processing period but high durability, which makes it fit for use as paving course. Its composition can vary significantly depending on the grading of the aggregates (the skeleton of the concrete asphalt). For this reason, the product's quality is highly dependent on the elements of the asphalt mix. According to the norm EN 13108-1, the selection of composing materials (e.g. raw materials and the share of reclaimed asphalt) is mainly dependent on the contractors (Mohajeri, 2015), thus hindering the standardization of asphalt in both production and composition. Different composition alternatives are possible to meet the specifications set by the contractors in motorways construction, thus, as long as road specifications such as the Type Test requirements are met (EN 13108-20; Mohajeri, 2015), in principle, the product (asphalt mix) is appropriate to be used in roads construction.

There are two main institutions that regulate and provide guidelines in the production of concrete asphalt across Europe. The first one is the European Asphalt Pavement Association (EAPA) that keeps track on the production volumes, and the other one is the European Committee for Standardization (CEN), who provides the norms required in road construction. Additionally, different levels of governance have different requirements based on the type of road and other specifications (e.g. noise diffusion, share of recycled material, etc.). In the case of the Dutch government, Rijkswaterstaat (part of Ministry of Infrastructure and Water Management) is the public authority to which all road construction projects should comply in the Netherlands.

The geographical conditions, weather conditions, norms, availability of resources, desired life span, among other elements, make the production of concrete asphalt unique in every project. As an illustration, in the US, the Department of Transportation (DOT) has different restrictions between the states (Hoppe, Lane, Fitch & Shetty, 2015).

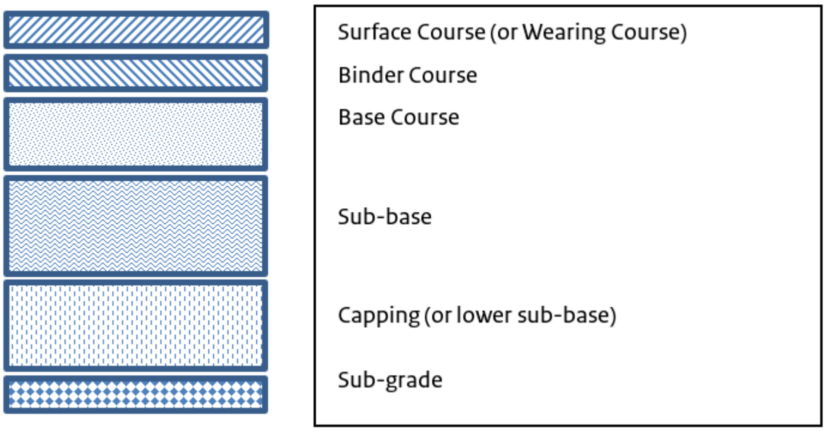
2.1 Asphalt as a paving material

As the prevalent paving material for road construction in multiple countries, there are certain principles that an asphalt mix needs to follow to be used as paving material, which can be summarized as follows (Thom, 2008):

- guard the subgrade layer;
- protect against deformation & break ups;
- guard against environmental threats;
- grant a suitable surface and
- assure maintainability.

Within the paving options, there are multiple configurations possible. However, there is a basic guideline to follow in most paved roads, especially those paved with asphalt. The top or upper course layer (wearing course) is in contact with vehicles and therefore it has to offer resistance against shear and deformation in order to protect the layers below. The binder course, represented in Figure 1, will be taken into consideration as part of the wearing course for this report. The third layer is called base, and its fundamental purpose is to support and distribute the loads applied to the wearing course. Finally, the bottom layer (sub-base) is made of unbound raw material, or else called soil (Thom, 2008; Speight, 2015). In some cases, this layer has to be reinforced with the use of bitumen, cement, lime, or other soil stabilization techniques (Speight, 2015). The structural condition of each layer determines the main characteristics of the pavement. Damages in one layer compromise the properties of the others, and therefore, hinders the integrity of the road. The wearing course (surface and binder) and the base course compose the asphalt. For this reason, this report focuses mainly on these layers.

Figure 1
Pavement Layers Nomenclature (adapted from Thom, 2008)



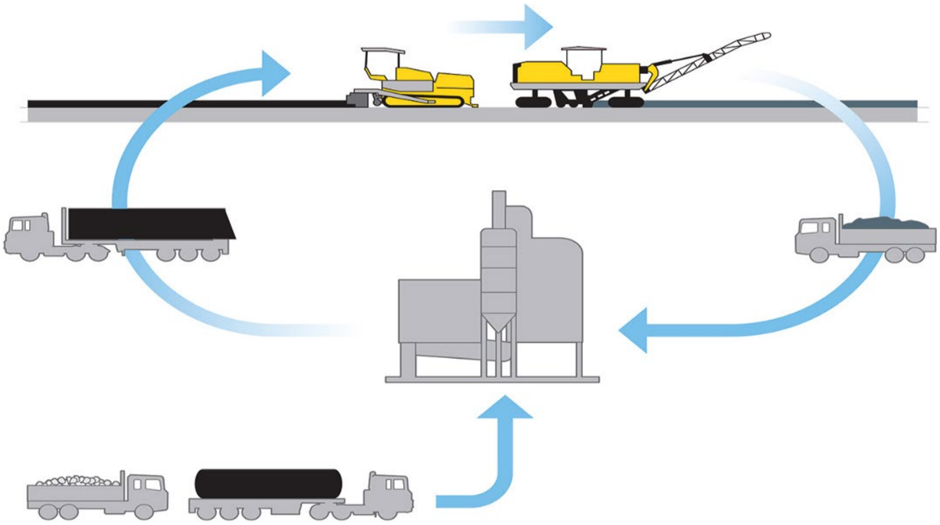
In addition to the distinctness regarding paving materials, and the principles mentioned above, one of the key factors in the selection of paving materials does not notably rely on the engineering performance, but on the product’s life cycle, both environmental and economic (Thom, 2008). Consequently, making the production of paving products such as asphalt, unique.

2.2 Asphalt Lifecycle

Asphalt is a mixture of aggregates, sand, filler, bitumen and, possibly, some extra additives. Aggregates (also known as mineral aggregates) are hard, inert materials (e.g. gravel, crushed stones, slag or rock dust). Fillers are also inert minerals but in the form of dust, they are used to fill voids in coarser aggregates to increase the stability, density and toughness of the conventional paving mixture (Ladis and Csanyi, 1962). Besides the mentioned materials, the production of new asphalt courses also includes the use of recycled asphalt.

Part of the asphalt waste is not allowed to be recycled in the Netherlands due to its carcinogenic content (containing more than 0.1% of tar), this share represents around 18% of the total asphalt waste in the country (Gibb, 2012; European Asphalt Pavement Association [EAPA], 2007; Europese Afvalstoffenlijst [EURAL], 2001). The remaining 82% of asphalt is recycled in the Netherlands into new asphalt mixtures and/or for soil stabilization (EAPA, 2017). Figure 2 illustrates a typical life cycle for asphalt product in which part of the old asphalt removed can be incorporated in a new product mix to be again used for paving purposes.

Figure 2
Asphalt Lifecycle (extracted from Dynapac, 2019)



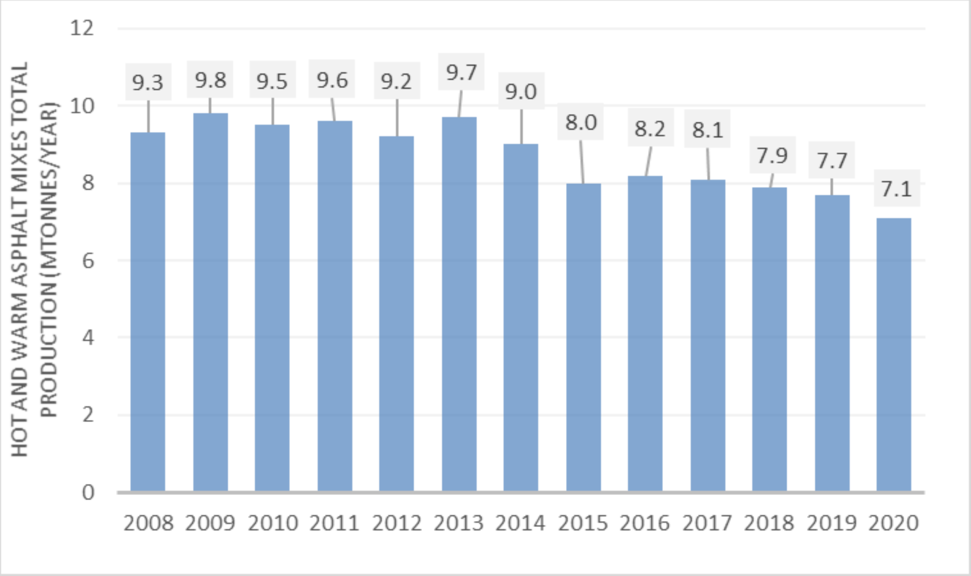
The life span of asphaltic course applied in road construction depends on multiple factors. The life span depends on the way in which it was applied (paved), the traffic loads it withstands and on the lane it was built for (high speed left, low speed right). Surface layers in motorways tend to have a life span between 10 -12 years before maintenance has to be implemented, in comparison to base layers that need to be reinforced between 20-24 years (Keijzer et al., 2015), displaying the durability or stress to what each layer is subjected to. Therefore, the wearing course and base course require periodical maintenance. Because the wearing course protects the base course, the first requires more attention regarding its maintenance. Although the base does not require frequent maintenance as the wearing course does (Keijzer et al., 2015), once the base is compromised, mayor procedures need to be implemented to repair the whole road.

There are three main types of asphalt: hot-mix, warm-mix and cold-mix, besides the composition and physical properties, the difference among them is also the temperature under which the material is submitted in the paving process. Hot mix asphalt (HMA) is normally used for roads, commercial, and residential asphalt pavements. This type of asphalt should be heated (around 150°C) to be poured as pavement. It presents important properties, such as flexibility, resilience, weather resistance, and impermeability. Warm mix asphalt (WMA) is similar to hot mix asphalt; however it requires lower temperature for the paving process. The addition of binders and additives, such as wax and zeolites, allows this material to be poured and spread at a lower temperature. For this reason, warm mix asphalt takes less energy to be produced. The use of warm mix asphalt is similar to hot mix, being often used to pave asphalt roads, driveways, and other types of commercial and residential asphalt pavement. Cold mix asphalt is designed to be used without heating; therefore, it takes longer to harden and cure, it is relatively soft when compared to hot mix, and tends to have a shorter lifespan. This third type of asphalt is normally used as a quick way to fix asphalt cracks and potholes, especially when in temperatures that are too cold to apply hot/warm mixes (Holloway paving, 2020). Further details about each type of asphalt mix are present in Chapter 4 of this report.

2.3 Dutch asphalt sector

The asphalt sector in the Netherlands produced 7.1 million tonnes (Mt) of HMA and WMA in 2020 (EAPA, 2020). This represents three percent of the total HMA and WMA produced in the EU-28 (All the member states of the European Union, 276.9 Mt; EAPA, 2021). In the last ten years, a decrease in the production of HMA and WMA can be noticed (Figure 3), this behaviour could indicate also a decrease on construction of new roads in the Netherlands during the same period. The share of WMA is not even one percent of the total production of asphalt in the Netherlands in the period between 2013-2020 (EAPA, 2020), therefore, the numbers in Figure 3 represent mainly hot mix asphalt production.

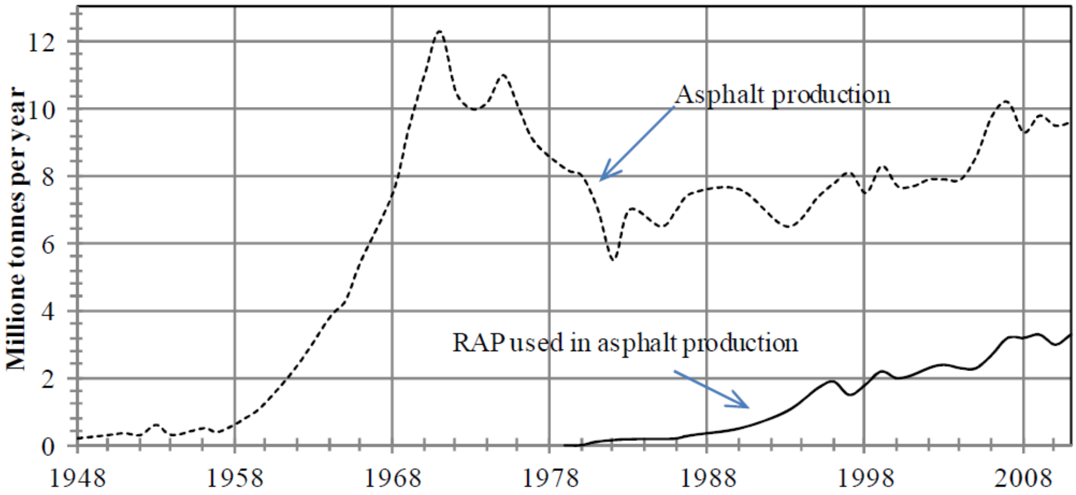
Figure 3
Hot and warm mix asphalt mix production in the Netherlands (EAPA, 2020)



Little data is available for 2020 regarding the asphalt production in the Netherlands, however, in 2017 out of the total 8.1 Mt, the application of the asphalt mix was allocated in this way: 38% Surface Course, 9% Binder Course, and 53% to the Base Course. Moreover, 19% of Asphalt Concrete (EN 13108-1), 10% of Stone Mastic Asphalt (EN 13108-5), and 9% of Porous Asphalt (EN 13108-7), constitute the 39% share of the Surface Course (EAPA, 2017).

In 2017, more than 80% of reclaimed asphalt (RA) was recycled, with up to 50% content of RA in asphalt mixes (Mohajeri, 2015). However, out of the 4.5 Mt of RA, around 18 % (0.81 Mt) was disposed due to tar content. Tar used to be an element in the composition of asphalt back in the 60's and its use was prohibited in 1991 (Bolk & Van der Zwan, 2000). Therefore, some RA contains this component, limiting how much RA can be mixed into the fresh asphalt mixes. Concentrations of tar higher than 0.1% is considered carcinogenic (Bolk & Van der Zwan, 2000; EAPA, 2007, Europese Afvalstoffenlijst [EURAL]; 2001). The RA containing tar requires special remediation in comparison to the rest of the tar-free asphalt that is being recycled. In 2017, the rest of the reclaimed asphalt (tar-free) was recycled either into HMA or WMA production (71%, 3.15 Mt), or used for cold recycling with bitumen emulsions, foamed bitumen and/or cement (11%, 0.49 Mt; EAPA, 2017). Figure 4 provides the historical data regarding recycling of asphalt in the Netherlands, which grew quite significantly since the 80's.

Figure 4



2.4 CO_2 emissions & energy consumption

The CO_2 emissions reported to the European Union emissions trading system for the Dutch asphalt sector in 2020 were roughly 99 kilo tonnes (NEa, 2021). These emissions correspond to 29 out of the 34 registered Dutch asphalt production sites in the EU-ETS in 2020; 5 registered sites were not active in 2020. These companies and their emissions are summarized in Table 1**.** From the 2020 EAPA's report, only one mobile plant was active in 2020 in the Netherlands and the rest were stationary plants (EAPA, 2020).

Table 1
CO_2 emissions from Asphalt Companies in the Netherlands in 2020 (NEa, 2021)

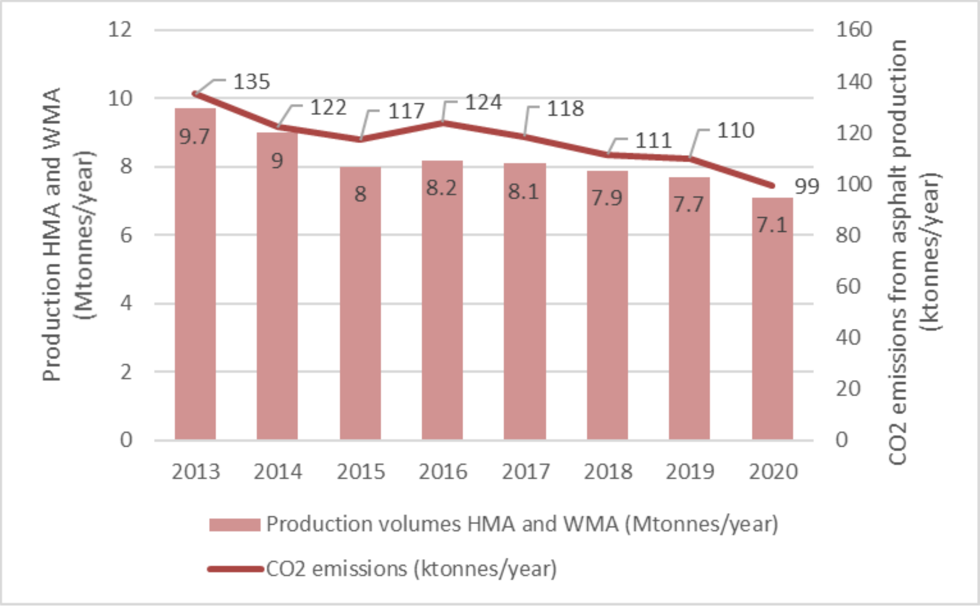
Registration number (NEa)	Site name	Emissions 2020 (kt/year)
NL-201100053	Asfalt Centrale Nijkerk (ACN) B.V.	1.7
NL-201000023	Asfalt Centrale Rotterdam (ACR)	5.5
NL-200800062	Asfalt Productie Amsterdam (APA) B.V.	6.6
NL-201100052	Asfalt Productie De Eem (APE) B.V.	4.5
NL-200800064	Asfalt Productie Doetinchem	1.1
NL-201000113	Asfalt Productie Hoogblokland	6.1
NL-201000116	Asfalt Productie Nijmegen	2.3
NL-201000117	Asfalt Productie Rasenberg Infra B.V.	0.0
NL-200800063	Asfalt Productie Rotterdam Rijnmond (APRR) B.V.	6.2
NL-201000108	Asfalt Productie Tiel B.V.	4.7
NL-201000118	Asfalt Productie Westerbroek b.v.	3.0
NL-201000062	Asfalt Produktie Maatschappij (A.P.M.) B.V.	4.7
NL-200800061	Asfalt-Centrale BAM B.V.	3.7
NL-201400402	Asfaltcentrale Harderwijk	0.7

Registration number (NEa)	Site name	Emissions 2020 (kt/year)
NL-200800071	Asfaltcentrale Heijmans Amsterdam	5.3
NL-200800073	Asfaltcentrale Heijmans 's-Hertogenbosch	5.4
NL-200800075	Asfaltcentrale Heijmans Zwijndrecht	1.3
NL-200800067	Asfalt-Centrale Limburg B.V.	3.8
NL-201000107	AsfaltCentrale Overbetuwe (ACOB) B.V.	2.1
NL-201000061	AsfaltCentrale Stedendriehoek (ACS)	3.8
NL-201000150	Asfaltcentrale Twente B.V.	2.9
NL-201000114	Asfaltproductie Kootstertille (APK)	3.0
NL-200800038	Asfaltproductie Regio Amsterdam BV (ARA)	6.7
NL-201000120	Brabantse Asfalt Centrale B.V. (BAC)	1.4
NL-201000122	Haagse Asfaltcentrale (HAC)	2.4
NL-200800076	Koudasfalt Staphorst BV	3.2
NL-200800077	KWS Infra B.V. Asfaltcentrale Eindhoven	2.9
NL-200800072	KWS Infra B.V. Asfaltcentrale Roosendaal	2.0
NL-201000111	Strabag Asfalt	2.5
	Total emissions	99.4

Figure 5 shows the CO_2 emissions from the Dutch asphalt sector compared to the total production of HMA and WMA between 2013-2020. It is possible to see the interconnection between the two mainly because most of the production of asphalt in the country is related to HMA and WMA. The specific scope 1 emission factor for asphalt did not change much during the mentioned period (0.014-0.015 tonnes CO_2/tonnes asphalt), which could imply that the production process of asphalt in the country has been very similar since 2013.

Figure 5

Hot and warm mix asphalt production in the Netherlands and total CO_2 emissions from the sector in the country (EAPA, 2021; NEa, 2021)



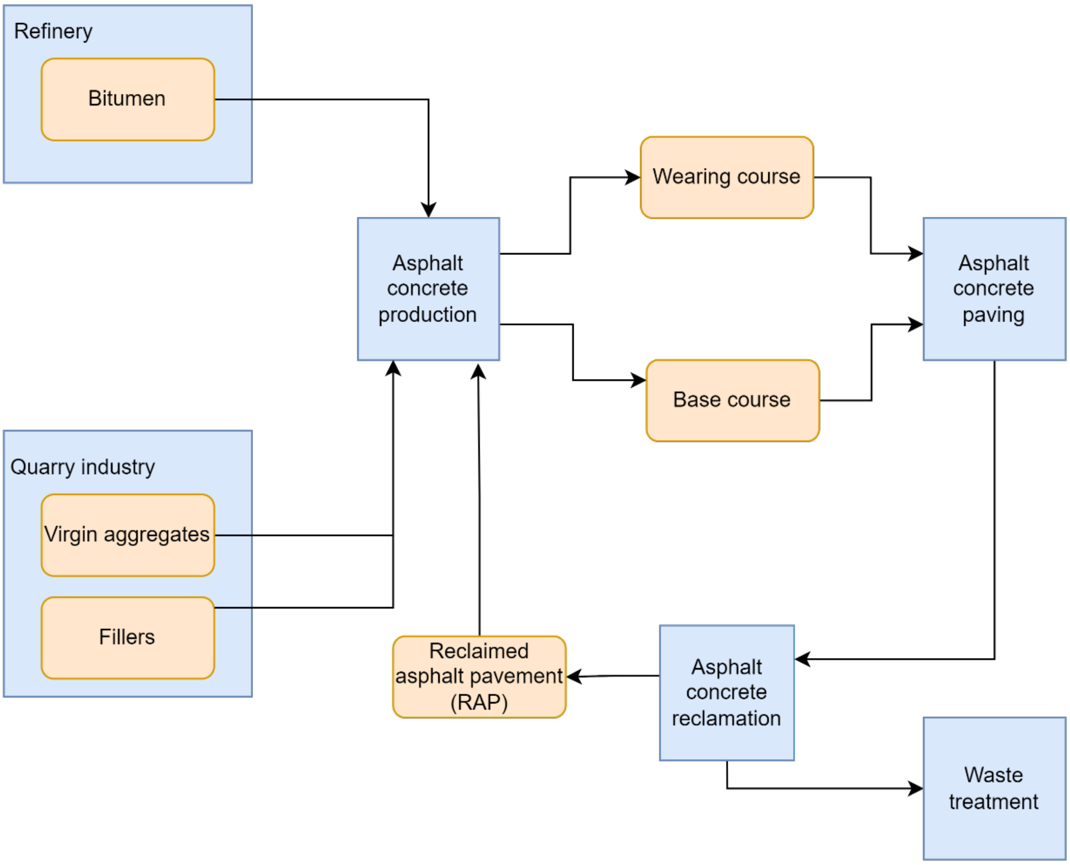
3 Asphalt production processes

This chapter describes the two identified processes for the production of hot/warm mix asphalt: drum mix and batch mix. Batch mix plants are predominant in Europe and are characterized by the use of a special mixer unit (called pug-mill) to prepare the desired asphalt mix. In drum mix plants, the mixing is carried simply by a drum (EAPA, 2007).

3.1 Asphalt production outline

Figure 6 presents an overview of the asphalt value chain. In the picture, three sub systems are represented in light blue: asphalt production, asphalt paving and asphalt reclamation. The main feedstocks for the asphalt production, bitumen and virgin aggregates, are provided by two industrial sectors: oil refinery (Oliveira and Schure, 2020) and quarry industry. The details in the production and processes involved in the asphalt sector are further explained in in the next sub-chapters.

Figure 6



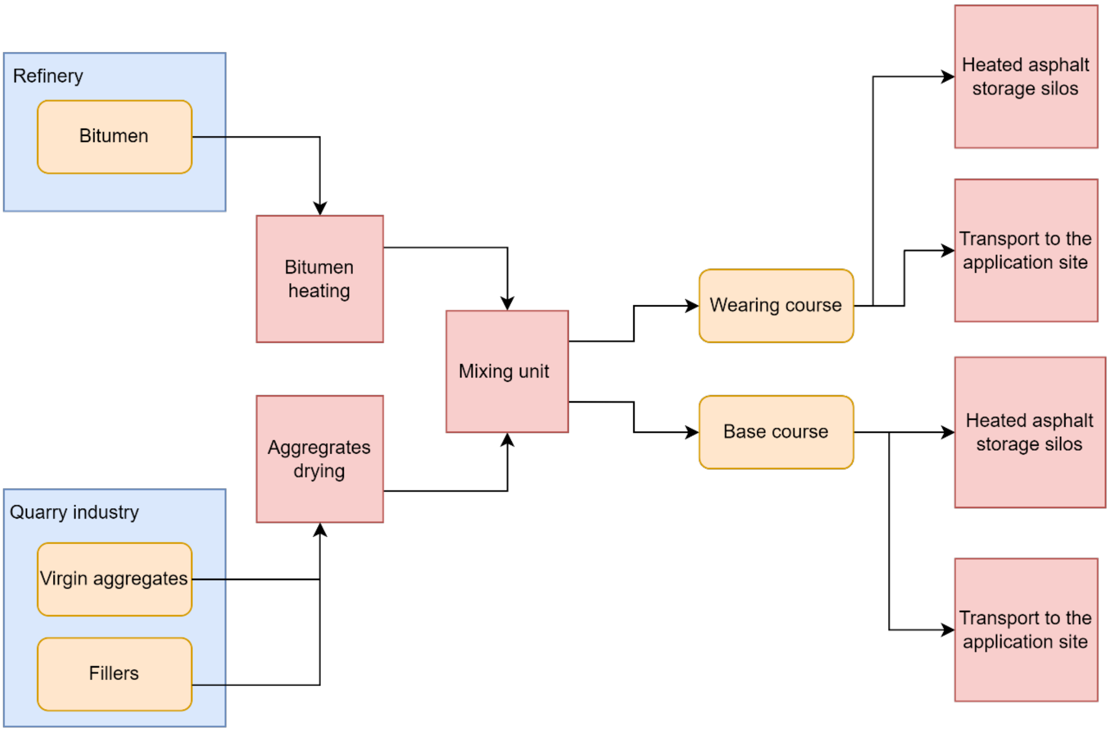
3.2 Batch mix plants

The basis for this process is illustrated by Figure 7 and the following paragraphs describe the main processing steps.

First, different sizes of aggregates are selected, depending on the type of asphalt mixture required, and transported to a rotary drum dryer. The rotary dryer is a steel cylinder with flights inside, these are fin-like structures affixed to the interior of the rotating drum and are responsible for lifting the material from the bed and let it fall down through the hot air stream in the drum. Because the drum is placed with a slight inclination, the aggregates slowly flow forward simultaneously to the drying process. The air is heated in a gas or oil-fired burner, and it flows in opposite direction to the material's flow, the aggregates can reach temperatures around 135-180°C. The angle of inclination, the rotational velocity and flight design influence significantly the efficiency of this step (EAPA, 2007).

After being dried, the hot aggregates can be either directed to the top of the mixing tower or transferred to vibrating screens and separated into different grades in individual hot aggregate storage bins for latter mix. When a specific composition for the asphalt is chosen, the aggregates are processed into the weigh hopper and, from there, they are mixed with bitumen in a pug mill (mixer). The bitumen is normally kept in a heated storage tank and when it is used, it is weighed to the desired amount and injected into the mixer. Mixing time varies between 25 and 90 seconds, depending on plant and mix type. The finished asphalt mix can be either transported directly the job site by trucks or be stored in heated asphalt storage silos (EAPA, 2007).

Figure 7
Batch mix process for hot/warm asphalt mix production (European Asphalt Pavement Association [EAPA], 2007)



As already mentioned, recycling of reclaimed asphalt is a common practice in the sector, therefore, reclaimed asphalt pavement (RAP) is normally feedstock for the mixing unit in batch plants. Essentially, there are three possible techniques to include recycled asphalt in the process: cold, hot and recycling ring methods. The cold technique refers to the addition of RAP directly to the pug mill without pre-heating (Figure 8), it allows recycling percentages of 10-30% depending on the quality requirements. The hot method includes RAP pre-heating previously to the mixer unit, in this case, the recycled material is heated in an extra drum dryer (Figure 9). The recycling rates for the hot technique are normally higher (30-70%). The recycling ring method allows both virgin aggregates and RAP to be dried in the same drum, however, the materials are added in different places in the drum (Figure 10). This process has a recycling range of 30-50%.

Figure 8

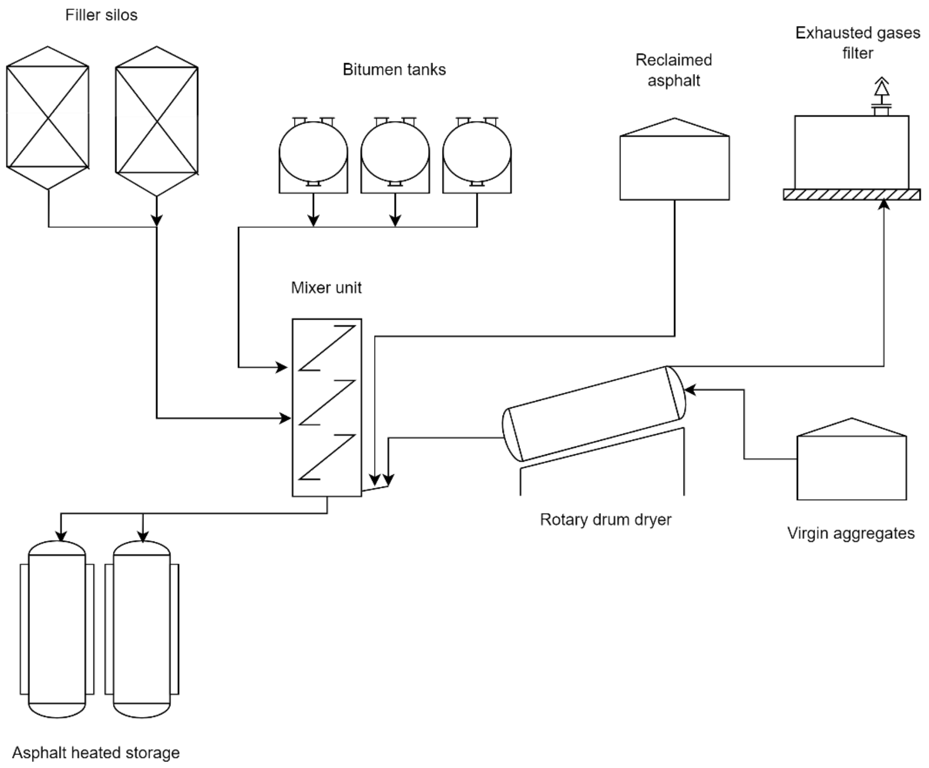


Figure 9

Hot method for use of RAP in batch mixers plants (EAPA, 2007)

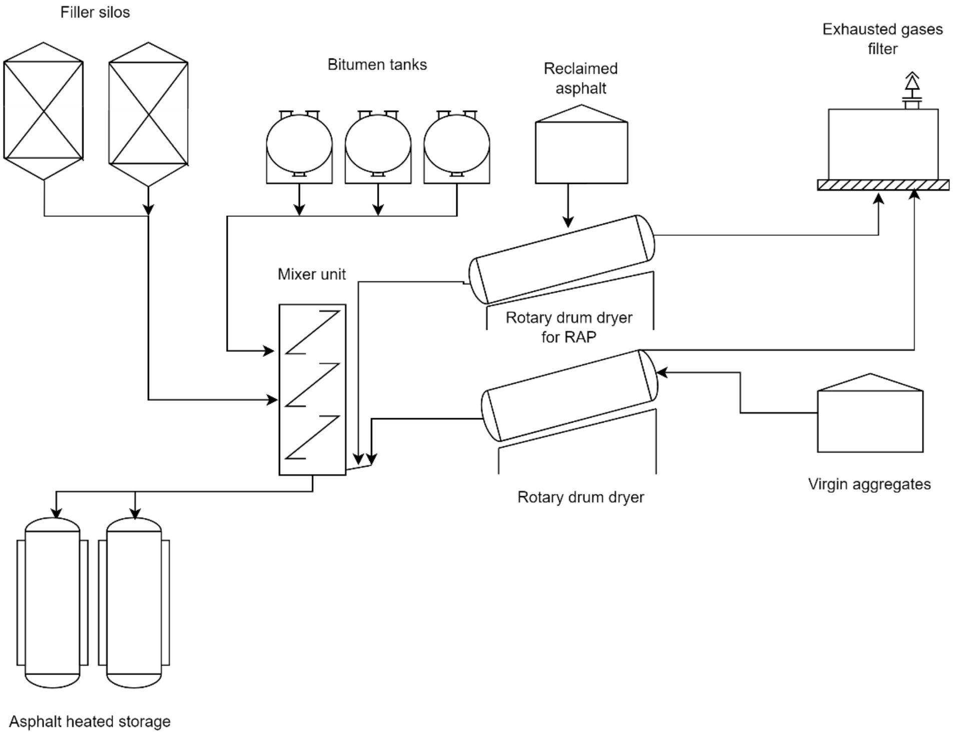
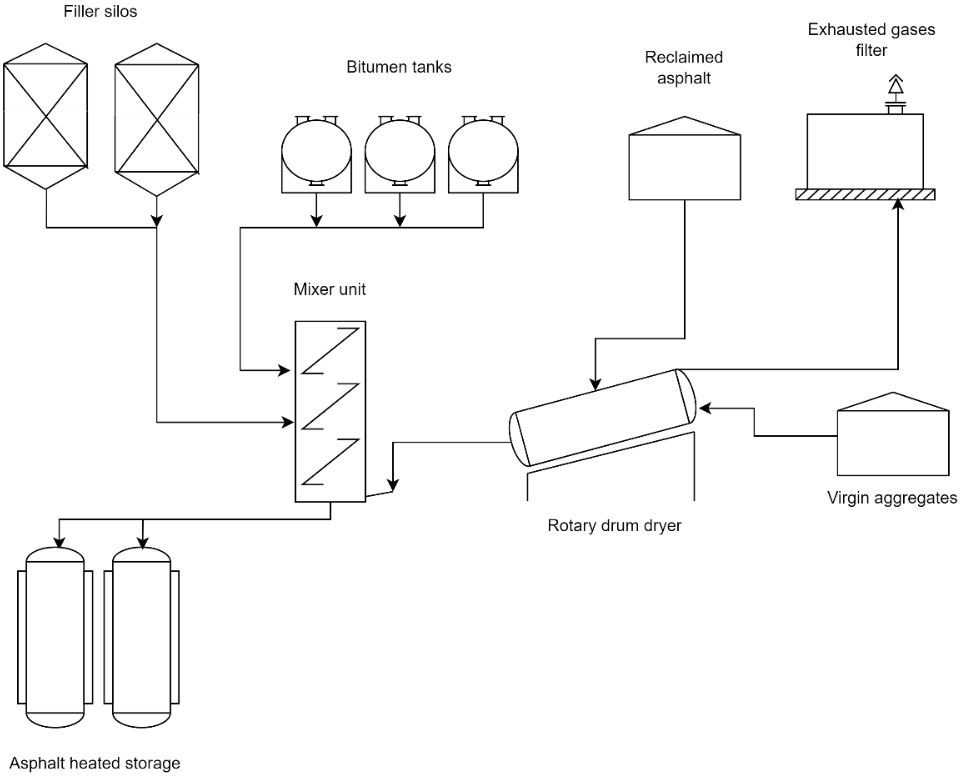


Figure 10

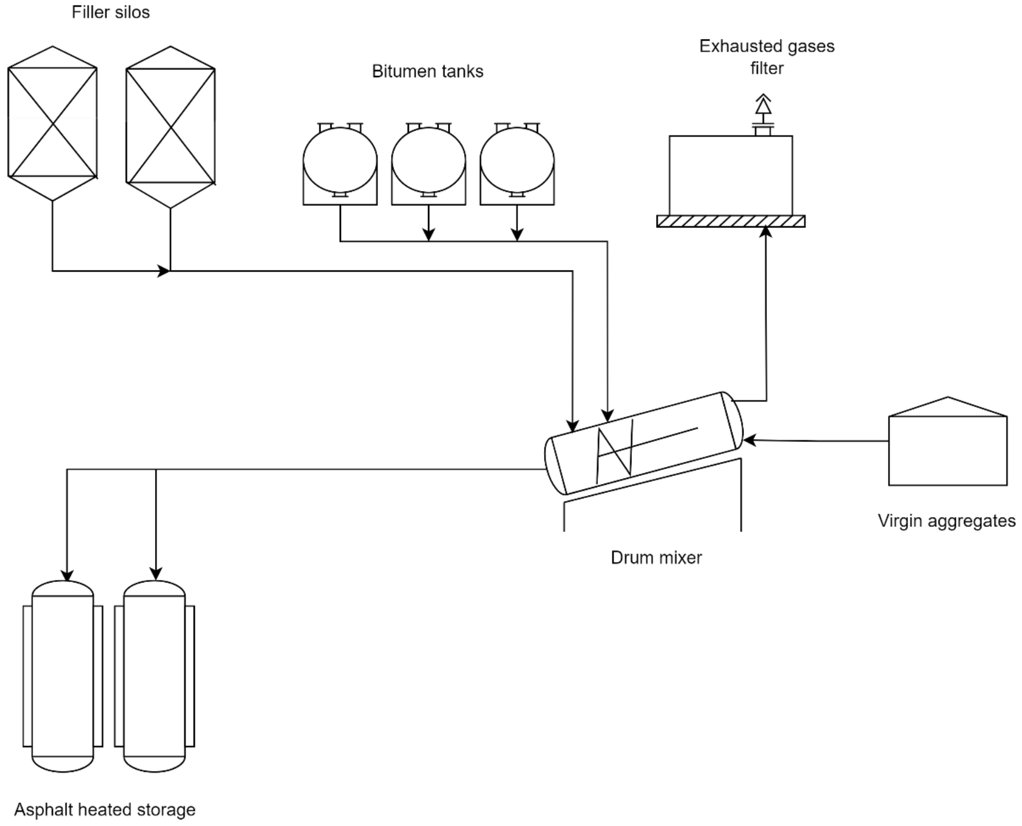


3.3 Drum mixer plants

In this process configuration, the heating, drying and mixing of aggregates, fillers and bitumen take place in a single drum mixer. In some plants, the heating and drying happen in a separated drum from the mixing drum. Normally, drum mixing plants are less flexible in terms of changing between different mixes recipes. That is one of the reasons why batch plants are more common in Europe.

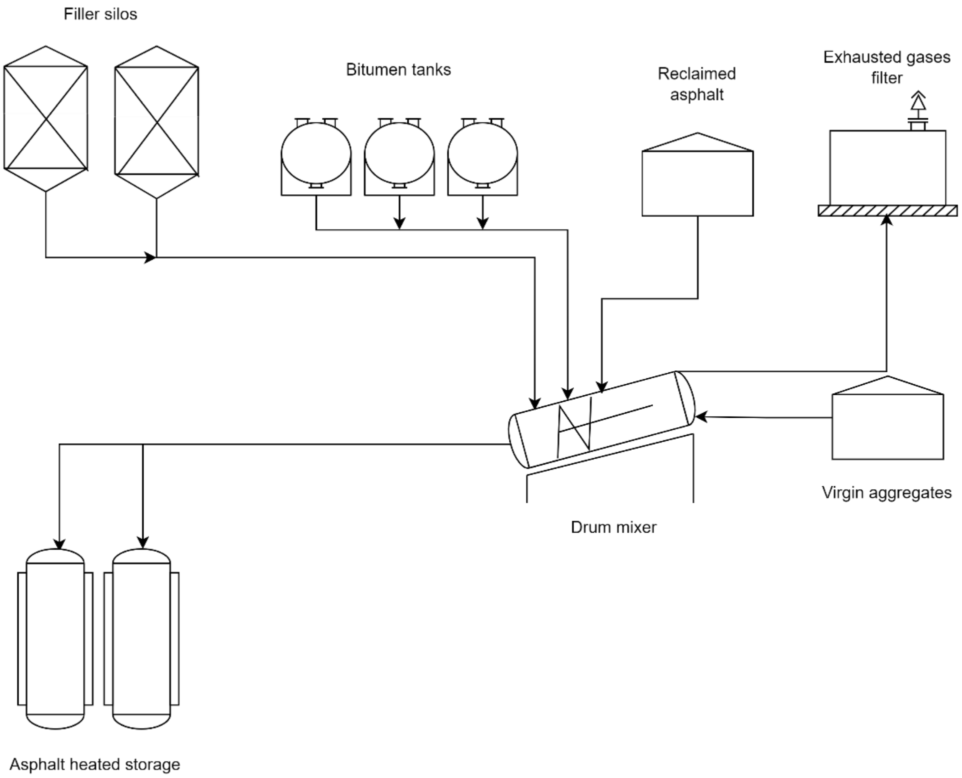
Figure 11 illustrates a typical drum mixer plant, the process can be described as follows: aggregates are introduced into the revolving drum, where both heating and drying occur by hot burner gases in the drying zone of the drum. Filler and liquid bitumen are added to the aggregates around halfway the drum, at this point the mixing process starts. Flights inside the rotating drum allow proper drying and mixing inside the drum. Similar to the batch process, the finished asphalt is discharged to a conveyer, and it can be either transported directly to the paving site or stored in heating bins.

Figure 11
Drum mixer unit overview (EAPA, 2007)



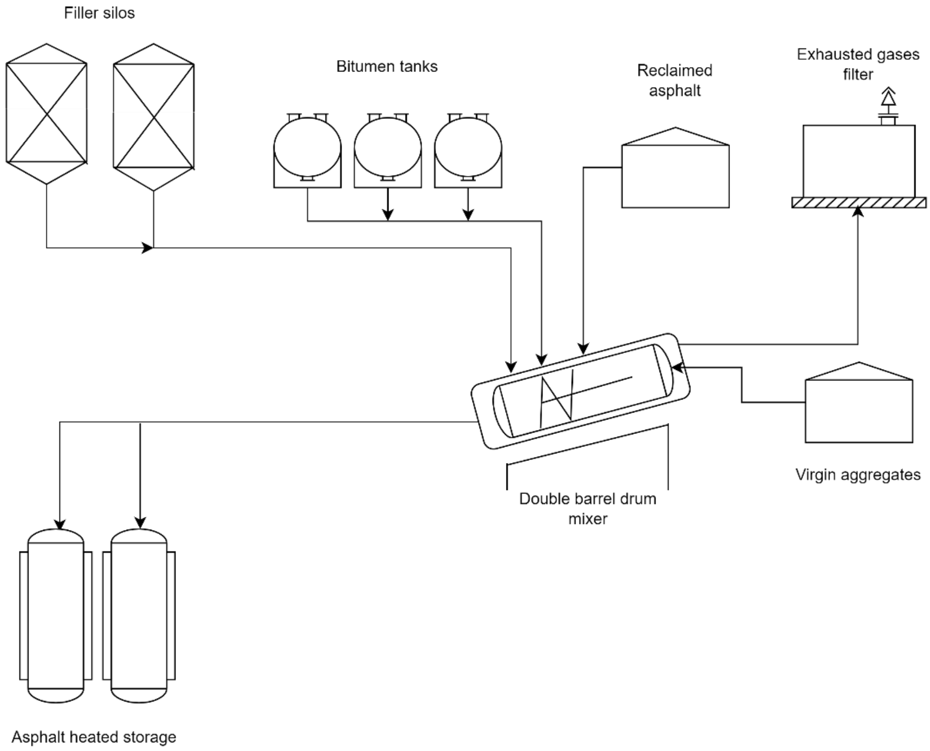
The use of recycled asphalt as feedstock is also possible in drum mixer plants, which normally takes place combining two methods: direct flame heating and heated aggregate. The reclaimed asphalt can be fed to the drum in the midpoint, allowing the material to be heated by the hot virgin aggregates and the hot burner gases, this technique is named split feed drum mixer (see Figure 12).

Figure 12
Use of RAP in a split feed drum mixer plant (EAPA, 2007)



Another possible configuration is the double barrel drum mixer plant, where the recycled material is introduced in the outer shell of the mixing drum, outside the hot gas stream (see Figure 13). The virgin aggregates are dried and heated in the inner drum and access the outer shell by falling through openings in the inner drum. The heated aggregates flow through the outer shell in opposite direction to RAP and bitumen, where all these components are mixed. Therefore, the mixing process happens in the space between the two drums with the support of blending blades placed on the exterior shell of the inner drum.

Figure 13
Use of RAP in a drum mixer plant with a double barrel mixer (EAPA, 2007)



The third process configuration for the use of RAP in drum mixer plants is the counterflow mixer system. The virgin aggregates are fed to the end of the drum opposite to the burner and the recycled asphalt enters the drum halfway. The drum is designed in such way that allows preheating of recycled material to happen behind the flame before entering the mixing zone. For this reason, neither bitumen nor the recycled material are in direct contact with the flame and heated gases. Therefore, the counterflow principle enables a reduction of temperature of the hot gases and improved environmental performance through less heating of the recycled asphalt. Submitted to optimal conditions, this process allows up to 50% recycling.

Regarding the process conditions, bitumen usually has to be kept between 130-160 °C to remain in a semi liquid state for mixing with aggregates. Aside from mixing, it has to remain above 107°C in the asphalt mixture to be properly applied, and higher than 80°C before its compaction as paving on the road site before its solidification (Speight, 2015). Depending on the process, type of plant, and others, the temperature of the aggregates may range from 160 to 450 °C (Mohajeri, 2015).

3.4 Mass & energy balances

The mass and energy flows in an asphalt production site depend very much on the recipe chosen for the asphalt mix. TNO together with Ecochain, a Dutch consultancy company, prepared an LCA (life cycle analysis) study focused on the Dutch Asphalt sector (TNO and Ecochain, 2020). Ecochain provided the energy consumption for 17 different types of hot asphalt mixes produced in the Netherlands, 13 being suitable for surface layer and the remaining four for base course. Among the mixes provided, the consumption of natural gas ranges between 6.12-9.41 m^3 /tonne asphalt mix and the electricity consumption between 11.9-16.4 kWh/tonne. In order to simplify the mass and energy balances description, the 17 types of asphalt in the study were grouped in 4 different mixes: asphalt concrete (AC) with reclaimed asphalt (RAP), asphalt concrete (AC) without RAP, stone mastic asphalt (SMA) and very open concrete asphalt (Zeer Open Asfaltbeton, ZOAB) mix. The stone mastic asphalt mix contains a high content of coarse aggregates, high bitumen and the voids are filled with binding material. Due to its composition, it has good wear resistance and it is waterproof (Planete TP, 2008). In contrast, the ZOAB mix presents high percentage of hollow spaces (around 20%), characteristic that helps to reduce noise compared to other pavement mixture and to prevent splashing of water (Rijkswaterstaat, 2022).

Table 2 summarizes the average values estimated for natural gas consumption of each process step per group of asphalt mixes. Table 3 shows the electricity consumption for each group. The estimated numbers are calculated based on the background report related to the LCA study from TNO and Ecochain (TNO and Ecochain, 2020). These numbers refer to 2019 and the "average recipes" present in the study were compiled by the Permanent Committee Sustainability of the Department of Bituminous Works (VBW), therefore, they are considered to represent the Dutch asphalt sector.

Table 2
Average natural gas consumption (m^3/tonne asphalt mix) per type of asphalt mix (based on TNO and Ecochain, 2020)

Process step	AC without RAP	AC with RAP	SMA mix	ZOAB
Rotary drum heating and drying	8.10	6.25	7.28	6.69
Rotary drum heating and drying for RAP	0	2.31	0	0
Recipe changes	0.47	0.47	0.47	0.47
Starts and stops	0.25	0.25	0.25	0.25
Total natural gas	8.83	9.29	8.00	7.42

AC = asphalt concrete, RAP = reclaimed asphalt pavement, SMA = stone mastic asphalt, ZOAB = Zeer Open Asfaltbeton.

Table 3
Average electricity consumption (kWh/tonne asphalt mix) per type of asphalt mix (based on TNO and Ecochain, 2020)

Process step	AC without RAP	AC with RAP	SMA	ZOAB
Bitumen heating - electricity	2.69	1.38	5.13	2.26
Heated asphalt mix storage[1)]	10.78	10.51	11.27	10.69
Total electricity consumption	13.47	11.89	16.40	12.95

[1)] *In the reference used, this amount of electricity consumed is called Other electricity use. The consumption was allocated to the heated storage.*

AC = asphalt concrete, RAP = reclaimed asphalt pavement, SMA = stone mastic asphalt, ZOAB = Zeer Open Asfaltbeton.

The material flows are presented by Table 4 and are also based on the 17 asphalt mixtures provided by Ecochain. The amount of recycled asphalt varies between 0.29-0.50 tonne/tonne asphalt in the mix group called AC with RAP.

Table 4
Average material flows (tonne/tonne asphalt mix) per type of asphalt mix (based on TNO and Ecochain, 2020)

Material flows	AC without RAP	AC with RAP	SMA	ZOAB
RAP	0	0.36	0	0
Bitumen	0.06	0.04	0.11	0.05
Aggregates	0.89	0.58	0.82	0.90
Filler	0.05	0.02	0.08	0.05
Total	**1**	**1**	**1**	**1**

AC = asphalt concrete, RAP = reclaimed asphalt pavement, SMA = stone mastic asphalt, ZOAB = Zeer Open Asfaltbeton.

3.5 CO_2 emissions

The CO_2 emissions corresponding to the combustion of natural gas are estimated based on an energy content of 31.65 MJ/m^3 (RVO, 2020)and an emission factor of 56.4 kgCO_2/MJ (RVO, 2020). The emissions per type of asphalt mix are estimated and presented in Table 5. As can be noticed from the data in Table 2, the process steps drying and drum mixing are responsible for around 90% of the total fuel consumption, therefore, these units can be considered the main sources of CO_2 emissions in an asphalt manufacturing site.

Table 5
Estimated CO_2 emissions per tonne of asphalt mix

Asphalt mix group	kg CO_2/tonne asphalt mix
AC without RAP	15.8
AC with RAP	16.6
SMA	14.3
ZOAB	13.2

AC = asphalt concrete, RAP = reclaimed asphalt pavement, SMA = stone mastic asphalt, ZOAB = Zeer Open Asfaltbeton.

A graphical representation of the material and energy flows for the production of asphalt mix without and with recycled asphalt are represented by Figure 14 and Figure 15. The ranges present in Figure 14 cover the flows for the asphalt mixes AC without RAP, SMA and ZOAB.

Figure 14
Energy and material flows of asphalt production process without RAP use

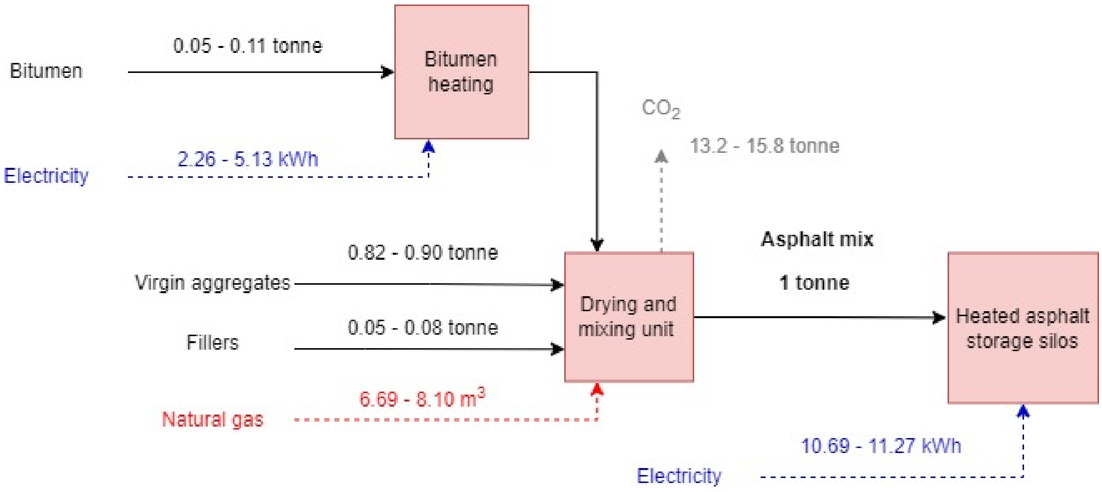
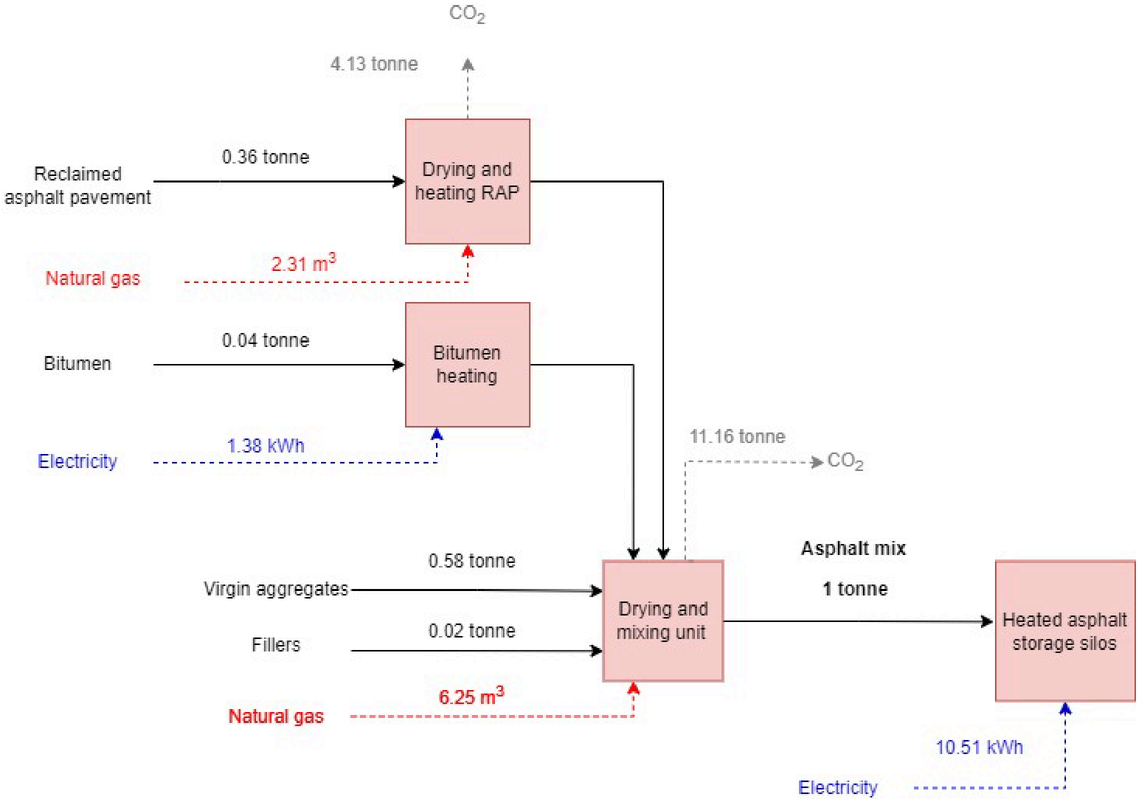


Figure 15
Energy and material flows of asphalt production process with RAP use



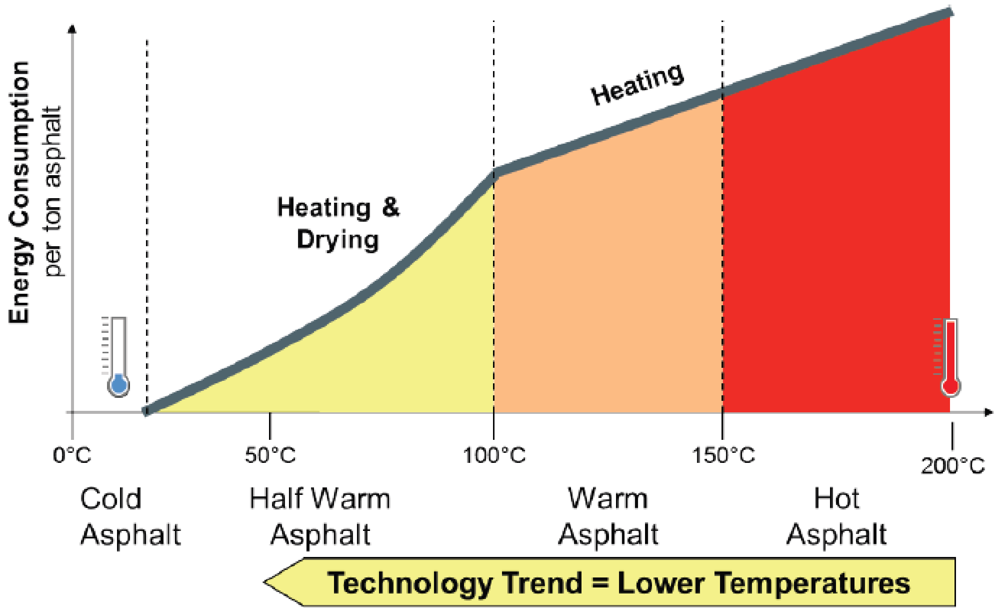
3.6 Operating conditions

In terms of temperature conditions in the asphalt production process, there are four possible types of asphalt mixes: cold, half warm, warm and hot mix asphalt. As the nomenclature indicates, the temperature in which these mixes are produced and handled differ and for this to be possible, different techniques and technologies have been developed or are still under development.

Since the mid-1990s, a number of approaches have been developed to minimize the mixing and laying temperatures, as well as the amount of energy used in the production of Hot Mix Asphalt (HMA). For these new techniques, less energy is used, and the temperature of the mix during paving operations is lower, resulting in lower emissions, reduced exposure, and improved working conditions (EAPA, 2015).

The HMA production temperature depend on the properties of the bitumen used in the recipe and it ranges between 120-190°C. For half warm and warm mix asphalt the temperatures can be 70-100°C and 100-150°C, respectively. For cold mixes, the process temperature is below 50°C. Figure 16 relates the energy consumption intensity to the operating temperature range used by each mix type (EAPA, 2015).

Figure 16
Temperature ranges for different types of asphalt mixes extracted from (EAPA, 2015)



3.6.1 Cold techniques

The most common technique for cold asphalt production is via bitumen emulsion. Bitumen is mixed with water and an emulsifier, which is responsible for stabilizing the mixture, the emulsion is used as a binder in the mixture with sand and aggregates. The structure strength develops over time due to the expulsion of water from the aggregates matrix and the coalescence and subsequent cohesion of the bitumen particles. Another known cold asphalt technique production is via injection of foamed bitumen into the mixer, together with aggregates and water. The foam method allows the use of cold asphalt mix in thick layers (40-50 mm) as surface layer (EAPA, 2007).

3.6.2 Half warm and warm techniques

There are many different technologies that have been developed to produce WMA, some relate to plant modifications and others consist on adding additives to the mix and/or to the asphalt binder (Virginia Asphalt Association, 2020). The most common techniques are: foaming process, addition to organic additives and addition of chemical additives. The main goal of these techniques is to reduce the effective viscosity of the binder to allow full coating and compressibility at lower temperatures.

The foaming method focuses on introducing small amounts of water into the hot bitumen. When water becomes steam, the bitumen volume increases, reducing its viscosity. This volume expansion permits the aggregates to be added in lower temperatures compared to HMA, also, the residual moisture enables the compaction of the asphalt mix during paving (EAPA, 2015).

The inclusion of organic additives also reduce the bitumen viscosity and normally the additives used are waxes or fatty amides. Chemical additives interfere on the interface between aggregates and bitumen, they reduce the frictional forces at the interface. For this reason, the addition of these chemicals allow the mix of bitumen and aggregates to be compacted at lower temperatures. The temperature reduction potential is similar among all the mentioned WMA techniques, being between 20-40^{0}C (EAPA, 2015).

Although the temperature reduction presents benefits regarding safety and environmental impact, the final product should still meet quality requirements and attend local regulations, which might make it challenging to replace completely hot mix asphalt. At the moment in the Netherlands, regulation do not support fully the use of WMA and Cold asphalt due to quality requirements. The products' properties and regulations will be further discussed in Chapter 4 of this report.

4 Asphalt products and applications

As previously mentioned, asphalt is normally a mixture of aggregates, bitumen and fillers. Some additives can be added to influence the product performance, some additives options are adhesion agents, modifiers and fibres (EAPA, 2007). Bitumen, a key element in asphalt production and the residuum from oil processing, provides a cementing-waterproof property that offers durability by combining both flexibility and strength traits (Speight, 2015). This, in turn, provides ideal rheological properties for using it as a paving material in road construction. Due to these characteristics, asphalt mix is the predominant material used for paving in Europe, the United States of America (USA), India, and others (EAPA, 2007).

Since the 19th century, the usage of bitumen became a common material for road construction (paving), with the first asphalt plant developed in Paris in the year 1854. This asphalt plant would take up to four hours to produce a single batch by mixing bitumen and aggregates (Mohajeri, 2015) in comparison to present plants that can produce up to 800 tonnes per hour (EAPA, 2007). Nevertheless, it was until 1870 that the first hot mix asphalt plant was established in the USA. This asphalt plant was invented by the Warren Brothers and it established the fundamental outline of components that asphalt plants follow nowadays (Mohajeri, 2015).

In 1870, Edmund J. DeSmedt applied the first asphalt pavement in New Jersey, thus successfully introducing asphalt into the paving industry and developing methods for paving that would become popular (brick and granite paving) (Speight, 2015). Making the late 19th century very relevant for asphalt production and paving activities.

4.1 Asphalt raw materials

4.1.1 Aggregates

The selection of aggregates depends mainly on the traffic load, weather and the life span of the desired road. The round cubic shape on the aggregate is usually desired due to its high compatibility properties. In contrast, the use of “needle shape” aggregates create voids and reduces the strength of the asphalt mixture, which makes it less desirable (Speight, 2015). The main sources of aggregates are usually sifted products such as limestone, sand, slag, and secondary aggregates (crushed asphalt, concrete, bricks) (Speight, 2015). Additionally, since the 90’s, reclaimed asphalt pavement (RAP) was incorporated as an acceptable source of raw material in the construction sector, playing an important role as a source of aggregates in the asphalt industry (Mohajeri, 2015).

4.1.2 Bitumen

Bitumen is used as a binder in the asphalt mixture and its composition varies significantly due to the different crude oils used in the refinery sector. The variations on carbon content (79-88%), hydrogen (7-13%), sulphur (8%), oxygen (2-8%), and nitrogen amount are responsible for the composition difference (Koenders et al., 2000; Speight, 2015; Sweeney, 2005). The bitumen used for the asphalt mixture should be a paving grade bitumen (CEN, 2006). Additionally, the quality of the binder is usually determined by its penetration and viscosity (Sweeney, 2005). As already mentioned in Chapter 3, at room temperature, bitumen is in a semi-solid form, therefore, in order to maintain it in a liquid form with low viscosity, it should be kept hot (130-160 °C). In addition, to properly mix the bitumen with the aggregates at the asphalt plant, the bitumen should travel along pipes and scattered through nozzles, which can only be accomplished while it is still in its liquid form (hot).

4.1.3 Filler

Filler is sometimes considered a secondary aggregate, differentiating from aggregates from the sizing. Fillers are generally fine grated materials usually collected in powder form (Speight, 2015). The objective of adding a filler to a bituminous mixture is to extend and enhance the performance of the bitumen. It is common to consider the filler as a bitumen additive rather than as a component of the aggregate.

4.2 Types of asphalt mixes

As mentioned in Chapter 2, there are three types of asphalt mixes: hot asphalt, warm asphalt and cold asphalt, their main properties and applications are further detailed in the next paragraphs.

4.2.1 Hot mix asphalt (HMA)

The hot mix asphalt is normally composed of 95% of aggregates and 5% bitumen. Hot mix asphalt is mostly applied in large-scale paving, such as roads, parking lots, and driveways. In terms of properties, the hot asphalt presents good resistant regarding weather changes, presenting good heat adsorption and allowing faster melting of ice and snow when compared to other mixes. Another benefit of the hot asphalt is the time for settlement, the mix cools down quickly after being poured, which allows less traffic disruptions. The durability of pavements with hot mix asphalt is high and its flexibility to shrink and expand reduces the chances of cracking in roads due to temperature changes. Despite the material properties advantages, hot asphalt is more expensive than other types of mixes and might not be suitable for countries with constant low temperatures because it can only be poured on a road when the ambient temperature is above 4 ^{o}C (Colorado Pavement Solutions, 2021).

4.2.2 Warm mix asphalt (WMA)

The warm asphalt mix should present the same properties as the hot mix asphalt, the difference is in the production process, which uses lower temperatures when compared to the conventional hot mix asphalt production. There are many different technologies that have been developed to produce WMA, some relate to plant modifications and others consist on adding additives to the mix and/or to the asphalt binder (Virginia Asphalt Association, 2020). However, the methodologies to produce WMA are still under development, a few of these techniques are explained in Chapter 3.

4.2.3 Cold asphalt mix

Cold asphalt mixes, as the name suggests, are produced with lower temperatures compared to the hot and warm mixes. The most common application of the cold mix is to repair roads. It can also be utilized as a paving material to pave low-traffic or rural roads, being not very suitable for bearing heavy loads and vehicles, such as large trucks and buses mainly because of its lower durability when compared to HMA and WMA.

Research by Choudhary (Choudhary, 2012) presents the design of cold mixes for use in different courses of pavements, focusing on the use of cold mixes in the construction of rural roads. Conclusions of this research show that the cold mix can be laid on low to medium volume roads. For rural road building, it can be used as a surface course or a bituminous base course. Another result is that with the incorporation of additives in the cold mix, the properties can be comparable to the properties of HMA. Some of these additives are: polymeric fibres, Ordinary Portland Cement (OPC), polyvinyl acetate and limestone waste from the stone crushing industry. Furthermore, cold mix can be used as a paving mix in some locations such as the north east region of India. The research investigated the cure rates and mechanical qualities of the cold asphalt mix and concluded that these rates and qualities can be improved. Lastly, in order to develop a better understanding of the actual performance of such cold mixes, large scale field trials and laboratory experiments should be performed for various traffic, climate and terrain conditions.

4.3 Governance

Since 2008 the European Standards for asphalt were introduced. All 27 EU members should comply with the standards and the individual national regulations should be consistent with them. This regulation was developed aiming to harmonize European countries' specifications and test methods (Bullock, 2008). These standards can be divided in two families: product standards (EN 13108) and testing standards (EN 12697).

The different asphalt mixes present in the product standards (EN 13108) are described as follows by the European Asphalt Pavement Association (EAPA, 2022):

- Asphaltic concrete (AC): the European Asphalt Standards defines AC as the mix in which aggregate particles are continuously graded or gap-graded, forming sort of a mesh structure. It is often used as surface layer.
- Asphalt Concrete for very thin layers (AC-TL): presents thickness of 20-30 mm and a gap-graded disposition of aggregates, resulting in an open surface texture. It is used mainly as surface course.
- Soft asphalt (SA): this is a mix type that contains soft bitumen (low viscosity) and it presents high malleability.
- Hot rolled asphalt (HRA): this is a dense mixture composed by fine aggregates, filler and high viscosity bitumen. It is normally used as a surface layer and presents high durability.
- Stone Mastic Asphalt (SMA): the SMA structure is composed by coarse aggregates and bitumen, bounded by a resin (mastic mortar). It presents high mechanical stability and good noise reduction properties, due to these properties, it is normally applied as surface layer for pavements.
- Mastic Asphalt (MA): this mixture presents no voids in its structure, presenting a high volume of filler and bitumen. This mixture has high durability and it is often used as surface layer.
- Porous Asphalt (PA): the structure of this mixture type is built in such a way that interconnected voids are significantly present to allow passage of water and air. The main characteristics of this type of asphalt is noise reduction and easy water draining.
- Double-Layered Porous Asphalt (2L-PA): the structure of the top layer has thickness of about 25 mm and the second layer is constituted of porous asphalt with course aggregate. The finer top layer results in less vibrations on the road and, therefore, it allows better noise reduction than single layer asphalt.
- Asphalt for Ultra-Thin Layers (AUTL): mixture that present gap-graded aggregate particles, leading to an open surface texture. It has thickness between 10-20 mm and it is normally applied as surface course laid on a connection layer. It is more commonly produced via the hot production method.

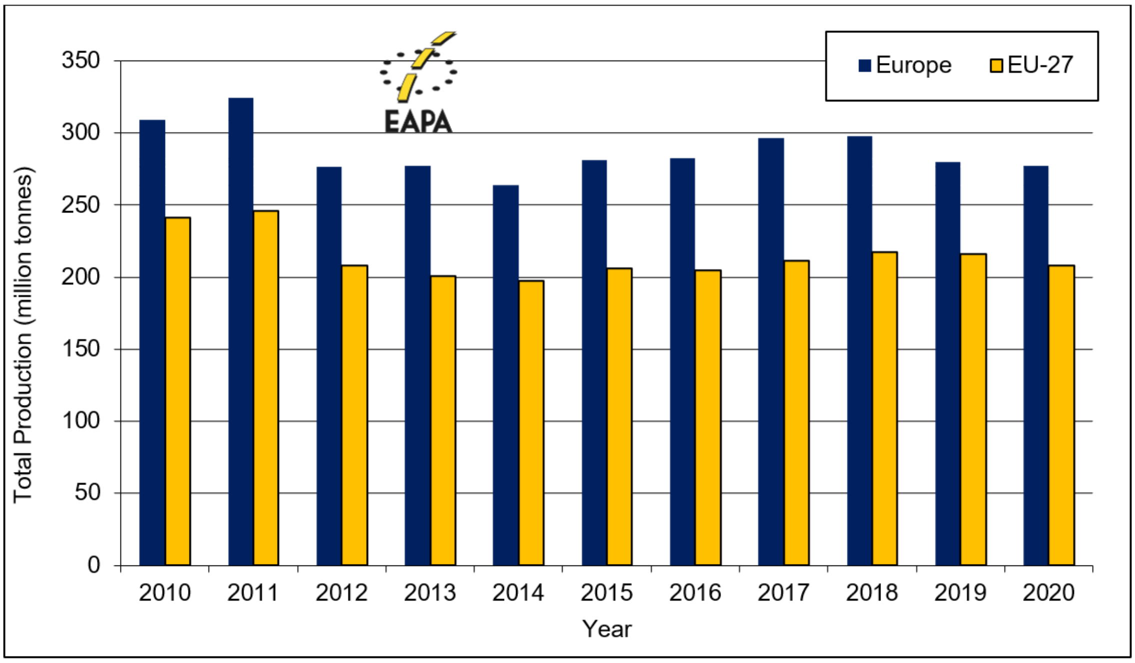
These regulations for asphalt products include specific indication of maximum temperatures for mix production, but no minimum temperatures. The only requirement is that the in-situ density should be satisfactory. Therefore, the minimum temperature should be established by the manufacturer (Rubio et al., 2012). Also, the selection of raw materials, RAP share, and bitumen specifications are up to the contractors to choose. Which places the responsibility of the final product's quality on the contractor to meet the specifications for road construction such as those included in the Type Test EN13108-20 (Mohajeri, 2015).

The ultimate aim is to specify the products in terms of fundamental, performance based properties. The first, or empirical approach, focuses on recipes composition and requirements for constituent materials with additional requirements based on performance related tests. The second, or fundamental approach, specifies the asphalt mix in terms of performance-based requirements linked to limited prescription of composition and constituent materials, offering a greater degree of freedom (CEN, 2006).

4.4 European Market

The total production of HMA and WMA mixes decreased in 2020 by 3.7%, compared to 2019 for EU-27 and by 1% for all European countries (EAPA, 2020). Between 2014-2019, the production grew as can be noticed in Figure 17. In 2020, Germany presented the highest production, among the European countries, with a total production of 38 million tonnes, followed by Turkey (31.7 million tonnes) and Italy (30.1 million tonnes) (EAPA, 2020). The profile of the European asphalt market is strongly related to the road network development in each country. Germany's paved roads are, for instance, around 5 times larger in length when compares to the Dutch network (Autotraveler, 2022).

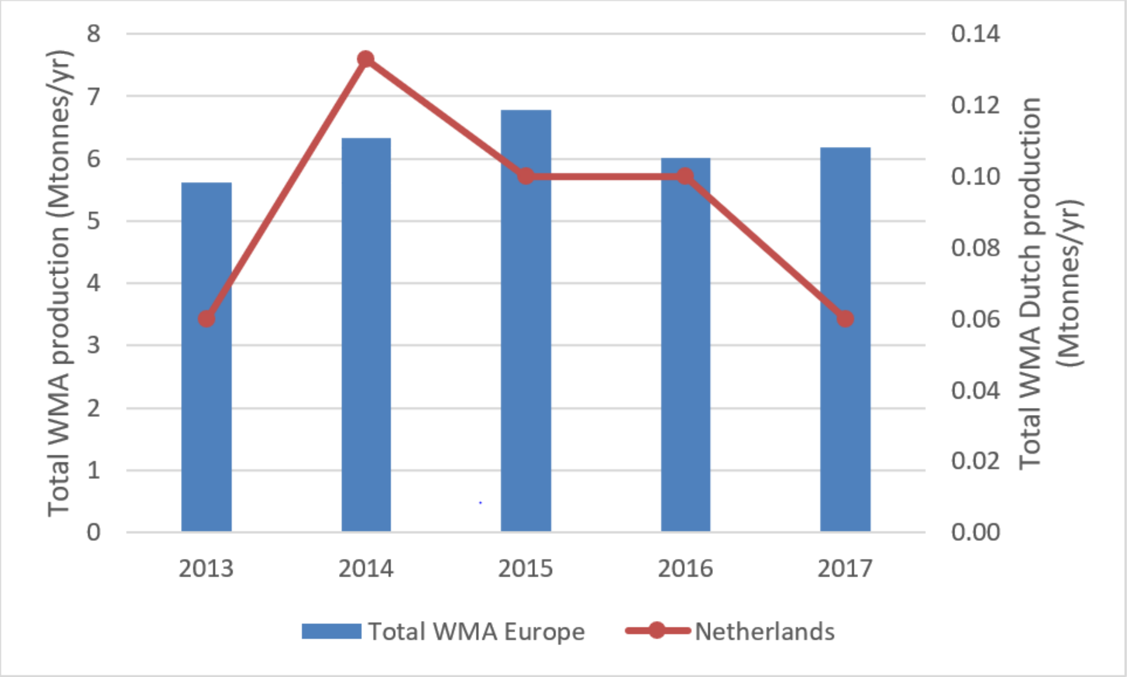
Figure 17
Total production of hot and warm asphalt mixes in EU-27 and EU-28 (including UK) plus Norway, Switzerland and Turkey (extracted from (EAPA, 2020))



On average, 59% of the HMA and WMA mixes were produced for surface courses, 22% for base courses and 19% for binder courses. On average, around 83% of the surface courses were composed by asphalt concrete (AC) in Europe in 2020, followed by stone mastic asphalt (SMA), representing 14% (EAPA, 2020).

The production of WMA remained stable between 2013-2020, representing in average only 2.4% (6.7 Mt) of the total HMA and WMA mixes production in Europe (281 Mt). The European champion in WMA production in 2020 was France, with a production share of 44.1%, followed by Norway (20.1%). No data after 2017 was provided for the Netherlands considering the WMA production, however, the production value in 2017 for this type of asphalt was 0.06 Mt, which is around 1% of the total WMA produced in Europe for the same year (EAPA, 2020). Figure 18 presents the comparison between the total production of WMA in Europe and in the Netherlands between 2013-2017.

Figure 18
Total production of hot and warm asphalt mixes in Europe and in the Netherlands between 2013-2017 (based on data from (EAPA, 2020))



Regarding cold asphalt mix, the most recent available data for the Netherlands is from 2017 and the total production value was 23 kt, which represented 0.3% of the total asphalt production in the country for the same year. Therefore, HMA is the main type produced in the Dutch asphalt industry, with a production share of around 89% in 2017.

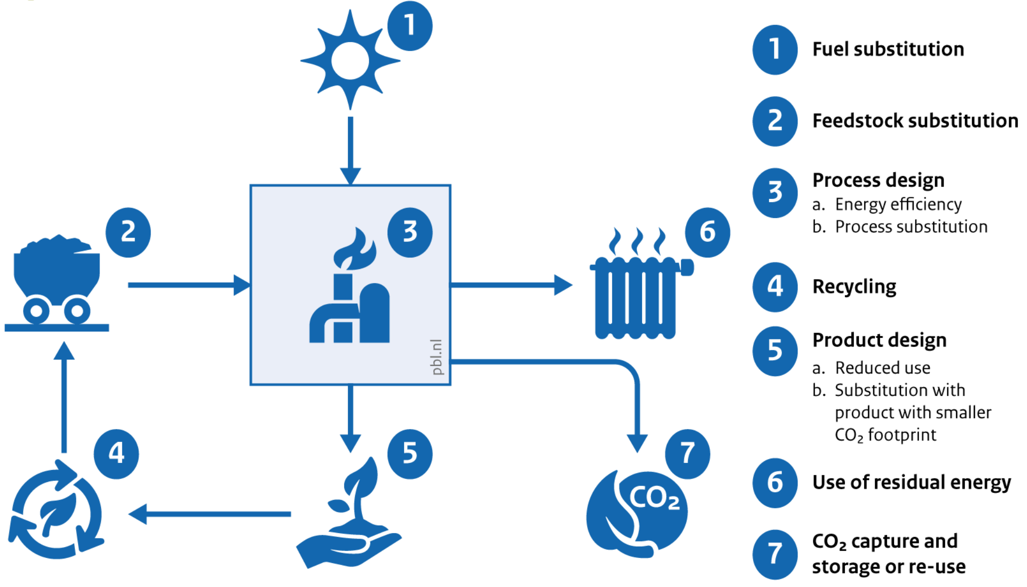
5 Options for decarbonisation

The EAPA has three main goals of the asphalt industry's contributions to climate-neutrality and preservation of Europe's natural environment (EAPA, 2019):

- Decarbonisation of road transport
- Sustainable construction and maintenance
- Research and innovation

This chapter provides examples of decarbonisation options for the asphalt industry itself, derived from literature. This list of options is not exhaustive and provides only a limited view of the total potential of future developments of production processes and technologies in the asphalt industry. In this research, three main options for decarbonisation of the asphalt sector are presented; fuel substitution, feedstock substitution and recycling (1, 2 and 4 in Figure 19). The remaining decarbonisation options are less directly applicable to the asphalt industry or highly site-specific and were therefore not investigated further in this study. Some of them are briefly mentioned in the discussion section.

Figure 19



CO_2 reduction categories

Bron: PBL

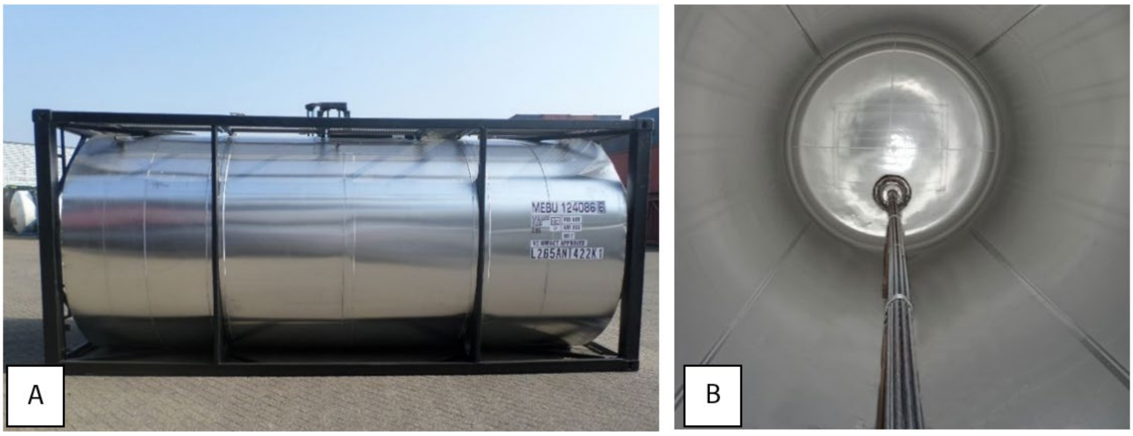
5.1 Fuel substitution

In the asphalt industry, fossil fuels are the most common source of energy that powers the heating systems used at HMA plants. This usage happens in different stages, as shown in Chapter 2, and are related to the heating and drying of feedstock and asphalt mix within the industrial production process. Natural gas is currently the most common fossil fuel used in the Dutch HMA asphalt plants, having with oil, propane, waste oil, and other fuels accounting as alternative options. All are heavy carbon emitters, showing the importance of resourcing decarbonisation options for this process as key to achieve zero emission in the sector. In this section, we will describe some of those alternatives.

5.1.1 Electrification

Some alternatives for electric heating are already present in the market, such as the electric heating bitumen tanks. Those processes are currently considered auxiliary electric heating, with relatively small demand of heat and capacity. This equipment is commonly used and can vary between different technologies, such as special tanks with different heating compartments (Figure 20-A) or normal tanks with an electric immersion heater (Figure 20-B) (Meeberg, 2020). These heaters are used to keep bitumen at discharge temperature (160-200°C). Gradually increasing the use of the equipment while reducing the use of gas or fossil fuel heaters is an improvement that is already supported by the best practices in this industrial sector (Bizarro et al., 2021). Their use can also give valuable insights on how to scale up electrification to support other more energy-intensive processes.

Figure 20
A: Electric bitumen heating tank; B: Immersion electric heater (Meeberg, 2020)



The bigger challenge for asphalt decarbonisation is on the process that consumes larger amounts of heat. Those are related to heating and drying of asphalt mix (or RAP) on the rotary drums with fuel burners, and are an essential step in asphalt production. The necessity of large heating power and the use of natural gas as fuel make them the main source of carbon emissions in the manufacturing process. Table 6 compares the energy demand for heating processes according to the current asphalt industrial production per tonne of asphalt mix, as shown previously in Table 2 and Table 3. It can be seen that the electric heating processes represent a small portion (4.2-6.6%) of the total demand for heat in the asphalt production.

Table 6
Energy source and demand for heating process in the Dutch asphalt sector per tonne of asphalt mix (based on TNO and Ecochain, 2020)

HEATING PROCESS STEP	Natural Gas Demand[1] (MJ/t)	Electricity (MJ/t)
Rotary drum heating and drying	211.7 - 270.9	-
Bitumen heating - electricity	-	1.38 - 5.13
Heated asphalt mix storage	-	10.51 - 11.27
TOTAL	211.7 - 270.9	11.9 - 16.4
TOTAL (%)	93 - 96%	4.2 - 6.6%

1) *Natural gas: 31.65 MJ/m³(RVO, 2021);*

One option for reducing those carbon emissions is to increase the electrification of heating processes, expanding it also to the drum heaters by using electric resistances to produce heat. The electric heating system for asphalt is very comparable to a direct flame heating system, the process and equipment would be also very similar, but with electric heating coil and rotatory drum replacing the original equipment with burner and fire tube components (Heatec, 1999). Even though it is similar, a full decarbonisation using 100% electric heating drums requires adaptations in the production process and new equipment investments. Table 7 estimates the use of electric heating in three scenarios, two as a complementary source of heat for natural gas and the last one with 100% electrification. Alternative 1 is equivalent to introducing another bitumen heating tank; Alternative 2 consists in introducing auxiliar electric heating for the larger heating processes and Alternative 3 refers to full electrification. Table 7 also shows the amount of CO_2 emitted and the electric power required by each option per tonne of asphalt produced for asphalt plants with RAP and Figure 8 presents the same figures for asphalt plants without RAP.

Table 7
Dutch asphalt industrial electrification demand - use case for Dutch asphalt plant (with RAP)

Scenario	Unit	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	%	100	90	70	0
Electricity	%	0	10	30	100
Demand of natural gas 1)	(m³/tonne)	9.29	8.36	6.50	0
Demand of natural gas 2)	(MJ/tonne)	294	265	206	0
Demand of electricity 3)	(MJ/tonne)	0	118	222	327
Direct CO_2 emissions 4)	(kg/tonne)	16.6	15.0	11.7	0
Electric power 5	(W/tonne)	0	1.12	2.12	11.24

1) *Based on TNO and Ecochain, (2020);*

2) *Natural gas: 31.65 MJ/m³(RVO, 2021);*

3) *The conversion from electricity to heat was considered to have an efficiency of 90%;*

4) *CO_2 emissions per MJ of fuel based on RVO (RVO, 2021);*

5) *Electric power based on 8500 load hours per year and 90% conversion of electricity to heat.*

Table 8
Dutch asphalt industrial electrification demand - use case for Dutch asphalt plant (without RAP)

Scenario	Unit	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	%	100	90	70	0
Electricity	%	0	10	30	100
Demand of natural gas 1)	(m³/tonne)	8.12	7.31	5.68	0
Demand of natural gas 2)	(MJ/tonne)	257	231	180	0
Demand of electricity 3)	(MJ/tonne)	0	7.93	23.8	79.3
Direct CO_2 emissions 4)	(kg/tonne)	14.6	13.1	10.2	0
Electric power 5)	(W/tonne)	0	0.98	2.95	9.82

1) Based on TNO and Ecochain, (2020);

2) Natural gas: 31.65 MJ/m^3(RVO, 2021);

3) The conversion from electricity to heat was considered to have an efficiency of 90%;

4) CO_2 emissions per MJ of fuel based on RVO (RVO, 2021);

5) Electric power based on 8500 load hours per year and 90% conversion of electricity to heat.

Switching from natural gas to electricity would require replacing the conventional equipment with new ones. Electric drum heaters/dryers are still a technology under development with no specific market cost available. The CAPEX estimation considers the costs for drum heaters to be equivalent to another breakthrough heat electrification technology, such as electric furnaces. DNV GL (2018) presents cost estimations for 10 MW_{input} electric furnaces, considering different components and structural changes (transformers, cables and network connection). The estimation of investment needed for deploying a similar capacity drum mixer for asphalt plants is based on the estimated value of around 4.5 million euros per MW of electric power consumed. The OPEX costs are estimated to be 3% of the investment cost for O&M (DNV GL, 2018). The cost estimations for this decarbonisation option for each alternative presented are shown in Table 9 per ton of asphalt produced for asphalt plants with RAP and Table 10 show the figures for asphalt plants without RAP.

Table 9
OPEX and CAPEX for electrification of asphalt industrial plants – use case for Dutch asphalt plants (with RAP)

Scenario	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	100%	90%	70%	0
Electricity	0	10%	30%	100%
Electric Power (W/tonne/yr)	0	1.1	2.1	11.2
CAPEX (€/tonne/yr) – cost spread over 1 year production1)	n/a	€ 5.06	€ 9.56	€ 50.58
CAPEX (€/tonne/yr) – cost spread over equipment lifetime (25 years)2)	n/a	€ 0.20	€ 0.38	€ 2.02
OPEX (€/tonne/yr)3)	n/a	€ 0.15	€ 0.29	€ 1.52

1) Assuming the investment costs for new equipment – electric drum heater and dryer – are comparable to an electric furnace with same capacity, around 4.5 MEUR per MW of power. Cost spread throughout a 1 year production (DNV GL, 2018)

2) Considering just the initial investment divided by the lifetime of 25 years – not considering discount rates or currency corrections.

3) Considering O&M costs of 3% of the CAPEX (DNV GL, 2018).

Table 10
OPEX and CAPEX for electrification of asphalt industrial plants – use case for Dutch asphalt plants (without RAP)

Scenario	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	100%	90%	70%	0
Electricity	0	10%	30%	100%
Electric Power (W/tonne/yr)	0	0.98	2.95	9.82

Scenario	Current situation	Alternative 1	Alternative 2	Alternative 3
CAPEX (€/tonne/yr) – cost spread over 1 year production[1)]	n/a	€ 4.42	€ 13.26	€ 44.19
CAPEX (€/tonne/yr) – cost spread over equipment lifetime (25 years)[2)]	n/a	€ 0.18	€ 0.53	€ 1.77
OPEX (€/tonne/yr)[3)]	n/a	€ 0.13	€ 0.40	€ 1.33

[1)] *Assuming the investment costs for new equipment – electric drum heater and dryer –are comparable to an electric furnace with same capacity, around 4.5 MEUR per MW of power. Cost spread throughout a 1 year production (DNV GL, 2018)*

[2)] *Considering just the initial investment divided by the lifetime of 25 years – not considering discount rates or currency corrections.*

[3)] *Considering O&M costs of 3% of the CAPEX (DNV GL, 2018).*

5.1.2 Hydrogen

There are many types of hydrogen that differentiate from each other according to their production process. The main categories are grey hydrogen, blue hydrogen, green hydrogen, and hydrogen as a by-product of other production processes. Grey hydrogen is by far the largest volume of hydrogen presently available, but it is produced via steam methane reforming (SMR) using natural gas and generating CO_2 emissions, so it is not the preferable option looking in the perspective of reducing the emissions for the whole value chain. The embedded emissions of hydrogen as by product depend much on the production process, therefore it is harder to access to what extent it can be considered a viable sustainable option. The other two options, blue hydrogen produced by SMR with carbon capture and storage and green hydrogen produced via electrolysis using renewable energy, are the main options with lower carbon footprint that can be considered (Marchant, 2021).

Hydrogen can also be used as a fuel replacement, directly substituting the natural gas in a gas-firing process: hydrogen is burned and the heat produced is loaded to the drum mixer. The new process would still require adaptations and changes to the equipment, replacing the burners and the operating parameters (temperatures, pressure and volume of gas increases). Also, higher temperatures could lead to an increase in NO_x emissions (Lewis, 2021).

Using a natural gas/hydrogen blend mixture as fuel can be a good transition approach for industrial heat treatment furnaces to reduce carbon emissions in a shorter term with mild to no impact on the operational and investment costs (Mayrhofer, Koller, Seemann, Prieler, & Hochenauer, 2021). Mayrhofer et al. (2021) studied the technical and economic impact of replacing fossil fuel with a blend mixture (from 20-100% hydrogen) considering different types of burners. The results of this study show that converting natural gas to blends in an old plant can impact directly the thermal output because in general the larger the hydrogen concentration the lower the LHV (MJ/m^3) and the higher the adiabatic flame temperature. This is due to the increased fuel gas volume-flow rate, resulting in higher pressure loss, which can bring challenges to a conventional systems.

Also, a lower Wobbe index (a measure on how interchangeable different fuels are) was calculated for higher concentrations of hydrogen (60-80%), suggesting that structural adaptations on the burner might be necessary when increasing the hydrogen concentrations – see Appendix A. The Wobbe index indicates that it is necessary to adapt the industrial installations to support the use of

Hydrogen as an alternative fuel for concentrations higher than 30%vol. hydrogen. Table 11 shows the amount of hydrogen needed to decarbonise facilities with RAP per ton of asphalt produced for asphalt plants with RAP and Table 12 presents the numbers for asphalt plants without RAP. These calculations use the conventional system as basis, as described in Chapter 2. The thermal efficiency for burning hydrogen was considered to be the same as burning natural gas.

Table 11
Hydrogen demand for decarbonizing asphalt industrial plants – Use case for Dutch asphalt plant (AC with RAP)

Scenario	Unit	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	%en	100	90	60	0
Hydrogen	%en	0	10	40	100
Demand of natural gas	(m^3/tonne)	9.39	8.36	5.57	0
Demand of natural gas	(MJ/tonne)	294	265	176	0
Demand of hydrogen	(m^3/tonne)	0	2.72	10.9	27.2
Demand of hydrogen	(MJ/tonne)	0	29.4	118	294
Direct CO_2 emissions [1]	($kgCO_2$/tonne)	16.6	15.0	9.99	0
Direct NO_x emissions [2]	(gNO_x/tonne)	1.40	1.72	2.73	5.07

[1] *CO_2 emissions per MJ of fuel based on RVO (RVO, 2021);*

[2] *100% hydrogen scenario is an extrapolation based on the other scenarios. Retrieved from (Mayrhofer, Koller, Seemann, Prieler, & Hochenauer, 2021).*

Table 12
Hydrogen demand for decarbonizing asphalt industrial plants – Use case for Dutch asphalt plant (without RAP)

Scenario	Unit	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	%en	100	90	60	0
Hydrogen	%en	0	10	40	100
Demand of natural gas	(m^3/tonne)	8.12	7.31	4.87	0
Demand of natural gas	(MJ/tonne)	257	231	154	0
Demand of hydrogen	(m^3/tonne)	0	2.38	9.52	23.8
Demand of hydrogen	(MJ/tonne)	0	25.7	103	257
Direct CO_2 emissions [1]	($kgCO_2$/tonne)	14.6	13.1	8.73	0
Direct NO_x emissions [2]	(gNO_x/tonne)	1.23	1.50	2.39	4.43

[1] *CO_2 emissions per MJ of fuel based on RVO (RVO, 2021);*

[2] *100% hydrogen scenario is an extrapolation based on the other scenarios. Retrieved from (Mayrhofer, Koller, Seemann, Prieler, & Hochenauer, 2021).*

The CAPEX investment, in a best-case scenario, is related to adapting an existing drum mixing plant to support higher volumes of fuel. Depending on the facility, the original control systems and burners can be used, which drops the investment costs. Table 13 and Table 14 present the expected costs for such an adaptation based on benchmark values for heating systems adaptation to hydrogen, according to Hy4Heat (2019). The investment cost of such adaptation depends heavily on the asphalt production configuration and equipment, which can be seen in Table 13 for asphalt plants with RAP and Table 14 for asphalt plants without RAP.

Table 13
CAPEX and OPEX of using hydrogen for decarbonizing asphalt industrial plants – Use case for Dutch asphalt plant (AC with RAP)

Scenario	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	100%	90%	60%	0%
Hydrogen	0%	10%	40%	100%
CAPEX (€/tonne)[1]	n/a	€ 0.24	€ 0.47	€ 1.18
OPEX without energy costs (€/tonne)[2]	n/a	€ 0.04	€ 0.07	€ 0.18

[1] *Assuming the investment costs for adapting a heating system based on natural gas to hydrogen and 1 year LCO – represents a best case scenario adaptation from the benchmarks retrieved from similar heating installations with the average Dutch industrial site capacity – EURO 2020 (Hy4Heat, 2019);*

[2] *Considering O&M 15% of the increased CAPEX (Hy4Heat, 2019)*

Table 14
CAPEX and OPEX of using hydrogen for decarbonizing asphalt industrial plants – Use case for Dutch asphalt plant (without RAP)

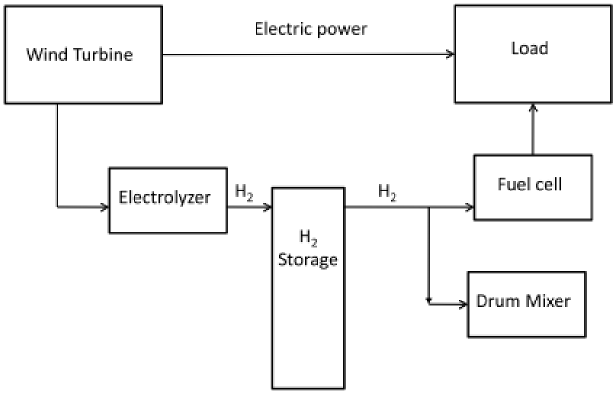
Scenario	Current situation	Alternative 1	Alternative 2	Alternative 3
Natural gas	100%	90%	60%	0%
Hydrogen	0%	10%	40%	100%
CAPEX (€/tonne)[1]	n/a	€ 0.21	€ 0.41	€ 1.03
OPEX without energy costs (€/tonne)[2]	n/a	€ 0.03	€ 0.06	€ 0.15

[1] *Assuming the investment costs for adapting a heating system based on natural gas to hydrogen and 1 year LCO – represents a best case scenario adaptation from the benchmarks retrieved from similar heating installations with the average Dutch industrial site capacity – EURO 2020 (Hy4Heat, 2019);*

[2] *Considering O&M 15% of the increased CAPEX (Hy4Heat, 2019).*

Other technologies coupling on site green hydrogen production could be explored. For example, the viability of employing a hybrid wind energy system as a clean source of energy to power a complete HMA and WMA production facility is investigated by Gopalakrishnan et al. (2012). The hydrogen storage tanks can be housed in a wind energy plant based on hydrogen storage that will be built on site. Figure 21 shows a scheme on how this arrangement could work in favour of a HMA and WMA plant.

Figure 21
Overall schematic of a Hot Mix Asphalt plant powered by hydrogen storage based wind energy (figure from Gopalakrishnan et al. (2012).



5.2 Feedstock substitution

Bitumen is one of the main feedstocks of asphalt production, as shown in Chapter 3. As a non-renewable resource directly produced from oil exploration, bitumen supply can be strongly impacted in a fossil-free future and looking for alternatives is necessary from both an environmental and strategic perspective.

5.2.1 Lignin and other biobased binders

Bitumen is a by-product of oil production and is used to bind the surfaces of paved roads. Some researchers, concerned about its environmental impacts and future supply with a foreseen petroleum refining decrease have started to explore viable alternatives. One promising alternative is the use of bio-bitumen, created with lignin as natural binder.

Lignin is a natural polymer that can be found in all terrestrial plants. Its molecules are made from phenylpropanoid building units and contain most of the wood methoxy content (Fachuang Lu, 2010). Lignin can be used for multiple purposes, from biobased energy generation to higher value applications such as bio-asphalt. Its complex polymer structure gives the component binder-like properties similar to bitumen, being able to replace it as shown in many experiments (Avantium, 2021).

Figure 22
Powdered lignin (Mitchell, 2014)

Lignin directly reduces CO_2 emissions on asphalt production because it can be processed in lower temperatures (140°C instead of 170°C of bitumen), reducing the amount of fuel needed (Kennedy, 2021). Besides, it is a bio-based feedstock with lower value chain emissions, depending on which layers of asphalt are replaced, the type of lignin used, and the calculation method chosen. For instance, based on a Dutch annual production capacity of 8 million tonnes of asphalt, an LCA analysis shows that using 50% lignin could represent a reduction of approximately 200,000 tonnes of CO_2 (Kennedy, 2021).

To guarantee that the biobased product is a sustainable alternative, it is important to be certain that it performs better from both sustainability as well as technical perspectives when compared to the current fossil practice. If it performs better, then it can be a sustainable business case. If either the environmental footprint is higher, or the technical performance/durability is lower, then lignin does not have the potential to significantly reduce CO_2 emissions. Therefore, research shows it is important to evaluate the two parameters that determine the sustainability score: the resource origin and the production process (Lieten, 2018). In the case of lignin, this relates much to the form of which the product was extracted and its environmental impacts. Besides, many independent environmental research organizations (such as the Intergovernmental Panel on Climate Change - IPCC and the National Council for Air and Stream Improvement - NCASI), distinguish biogenic carbon from fossil carbon (NCASI, 2021) (IPCC, 2001). The essential difference between fossil carbon and biomass carbon is that the first one releases carbon that has been sealed in the ground for millions of years, while the latter emits carbon that is already part of the biogenic carbon cycle. In that way, in the asphalt sector, the use of bitumen increases the total amount of carbon in the biosphere-atmosphere system while lignin operates within this system (NCASI, 2021).

In collaboration with the province of Groningen, there are now test bio-based roads and cycling lanes in the Netherlands, which are paved with a bitumen-like product created from the natural binder lignin. The 250-metre-long lignin-based road section can be found in the north of the Netherlands and is used daily by automobiles and large vehicles (Avantium, 2021). There are also some other experimental roads and a bike path at Wageningen University & Research, testing the same lignin-based asphalt. According to the project specialists from Wageningen Food & Biobased Research, there are already eight demonstration roads built in the Netherlands with this type of new binder, with 50% lignin and 50% bitumen and 4 years of promising built-in experience (Gosselink, 2020).

Table 15 show the demand for feedstock for different ratios of bitumen and lignin and their respective costs and carbon reductions (scope 3) per ton of asphalt produced. The numbers of demand are based on the average consumption of bitumen in the Dutch asphalt industry in an exchange ratio of 1:1 bitumen/lignin (Gosselink, 2020). The indirect emission reduction (scope 3) is estimated according to the LCA study mentioned in (Kennedy, 2021) for bio-based asphalt. Estimating those emission is a complicated process, highly dependent on the system boundaries and assumptions applied to the LCA study, therefore those number should be used with caution. There is no concrete reference on the industrial adaptation needed for the production of biobased asphalt, but some investments are expected considering the difference between bitumen (a high viscosity liquid) and lignin high-grade (a solid powder material).

Table 15
Demands and carbon reduction of using lignin as a bitumen substitute – Use case for Dutch asphalt plant (with RAP)

	Current situation	Alternative 1	Alternative 2 [1)]	Alternative 3
Percentage bitumen	100%	70%	50%	30%
Percentage lignin	0%	30%	50%	70%
Demand of bitumen (kg/tonne asphalt)	40	28	20	12
Demand of lignin (kg/tonne asphalt)	0	12	20	28
Scope 3 CO_2 reduction (kg/tonne asphalt) [2)]	0	-15	-25	-35
CAPEX (€/tonne) [3)]	N/A	N/A	N/A	N/A

[1)] *50% bitumen and 50% lignin was the recipe used by Gosselink (2020) and that is now being tested. For that reason, this will be the scenario considered as decarbonization pathway on the MIDDEN database.*

[2)] *Indirect emission reduction on Scope 3 compared to base scenario with 100% bitumen production - considering the results of the LCA study on lignin based asphalt production retrieved from (Kennedy, 2021) – estimation very dependent on the system boundaries and LCA study, this is just an indication to be analysed with caution.*

[3)] *No CAPEX data was found on literature. Some level of equipment adaptation is expected, but no specific data on the replacement of bitumen for lignin was found.*

Table 16
Demands and carbon reduction of using lignin as a bitumen substitute – Use case for Dutch asphalt plant (without RAP)

	Current situation	Alternative 1	Alternative 2 [1)]	Alternative 3
Percentage bitumen	100%	70%	50%	30%
Percentage lignin		30%	50%	70%
Demand of bitumen (kg/tonne asphalt)	30.5	21.4	15.3	9.2
Demand of lignin (kg/tonne asphalt)	0	9.2	15.3	21.4
Scope 3 CO_2 reduction (kg/tonne asphalt) [2)]	0	-11.4	-19.1	-27.7
CAPEX (€/tonne) [3)]	N/A	N/A	N/A	N/A

[1)] *50% Bitumen and 50% Lignin was the recipe used by Gosselink (2020) and that is now being tested. For that reason, this will be the scenario considered as decarbonization pathway on the MIDDEN database.*

[2)] *Indirect emission reduction on Scope 3 compared to base scenario with 100% bitumen production - considering the results of the LCA study on lignin based asphalt production retrieved from (Kennedy, 2021) – estimation very dependent on the system boundaries and LCA study, this is just an indication to be analysed with caution.*

3) *No CAPEX data was found on literature. Some level of equipment adaptation is expected, but no specific data on the replacement of bitumen for lignin was found.*

Other bio-based solutions are also on the horizon. Aston University in Birmingham, UK, discovered a procedure last year to break down slurry - the organic element of household garbage, food waste, plastic, paper, and textiles – into a black liquid that resembles bitumen's properties (Yang & Bridgwater, 2018). The bio-bitumen was created by heating the waste to roughly 500 degrees Celsius in the absence of oxygen, in a type of pyrolysis set-up. Pyrolysis is the same process that is used to manufacture charcoal and biochar, and it is frequently utilized to make biofuels. The team was able to alter the characteristics and quantities of the final bitumen-like substance by changing processing parameters such as temperature, processing time, and product collection strategy.

5.3 Recycling and Repurposing

Recycling and re-use of asphalt has been used in the sector since 1915 (Kandhal & Mallick, 1997). This study distinguishes the recycling of asphalt as the re-processing of RAP in the industrial production of asphalt and repurposing as its use to other road layers or civil engineering applications. The EAPA annual publication "Asphalt in Figures" presents new perspectives on the use of RAP. The most recent report shows that, in Europe, the total amount of reclaimed asphalt available for the industry in 2020 was 46 Mt (16.6% of the total asphalt production of the same year). From this number, 64% was re-used on asphalt production sites and 33% was used in recycling unbound road layers and other applications (EAPA, 2020). Those figures show that there is still room to increase the share of RAP asphalt in Europe, and that, in a positive note, most of the RAP extracted is already used for recycling or other form of re-use.

The emissions impact of increasing RAP content on asphalt production depends a lot on the industrial process, the condition of the RAP, and the asphalt recipe. Studies show that increasing the amount of RAP can have a strong potential on decreasing the carbon emissions of asphalt production (Bizarro et al., 2021; Tutu & Tuffour, 2016), as shown in Table 17, retrieved from Bizarro et al. (2021).

Table 17
Energy consumption of the production of one tonne of asphalt for different shares of RAP content (Bizarro et. al., 2021)

Raw material1)	PA	PA	PA	PA	SMA	SMA	SMA	SMA	AC Bin/ Base	AC Bin/ Base	AC Bin/ Base	AC Bin/ Base
% RAP	0%	58%	71%	93%	0%	58%	71%	93%	0%	58%	71%	93%
Final temperature (°C)	175	135	105	105	175	135	105	105	175	135	105	105
Diesel (MJ)	15.81	15.81	15.81	15.81	15.81	15.81	15.81	15.81	7.39	7.39	7.39	7.39
Electricity2) (kWh)	7.99	3.89	15.58	17.58	6.29	2.42	11.91	11.75	15.13	4.67	10.72	10.72
Natural gas (MJ)	240.5	202.7	165.5	160.5	240.3	203.1	170.5	171	251.7	209.1	174.7	174.7

1) *PA = porous asphalt, SMA = stone mastic asphalt, AC = asphalt concrete.*

2) *The electricity consumption is given by the amount needed to heat up bitumen up to the temperature specified for the asphalt mix plus a constant amount corresponding to general asphalt plant operation, which is not dependent on asphalt type. The constant value mentioned in (Bizarro et al., 2021) is 10.23 kWh.*

According to Bizarro et. al. (2021), combining RAP recycling and reducing production temperatures using additives are the combination to achieve the largest reductions in carbon footprints. For HMA, the largest reductions are the production cases with RAP contents above 71%. Three asphalt mixtures, namely porous asphalt (PA), stone mastic asphalt (SMA), and asphalt concrete (AC) were included, each one with different applications and technical requirements. Different models were created to simulate the technological leaps required to achieve asphalt mixtures containing up to 93% RAP. HMA with up to 57% RAP was created at 175°C, while combinations with higher RAP were formed at 135°C and 105°C (Bizarro et. al., 2021).

On the other hand, this could depend a lot on the industrial facilities. The Ecochain study "LCA achtergrondrapport voor Nederlandse branchereferentiemengsels" analyses multiple Dutch production facilities and discuss that increasing the use of RAP could end up increasing the demand for heat for some cases (Ecochain, 2022). The preparation of the material for pre-mixture with the other components can require new heating process that can increase heating parameters. The conclusion that can be retrieved from this analysis is that the extent of the scope 1 emission reduction that can be achieved by increasing recycling depends heavily on the type of process and pre-process utilized.

On the same note, the TNO and Ecochain (2017) life cycle assessment study focuses on the use of RAP, from extraction to waste disposal and gives insights on the possible impacts on emissions for the whole value chain. The research shows that the largest part of the environmental footprint lies in the primary production in the plant, accounting for an estimated 80% of the footprint (40% of it by materials and feedstock, 20% transport and 20% by using in the plant itself). The remaining 20% of emissions take place in the construction of equipment (TNO & Ecochain, 2017). Making sure those steps are verified and done responsibly is key for increasing the benefits of the use of reclaimed asphalt in the production process.

6 Discussion

The Dutch asphalt sector is very dependent on developments regarding road construction in the country. The production process does not differ significantly among the asphalt facilities. However, there are several possibilities for product recipes that require different operational conditions. The temperature in which the process is held is the main parameter that can vary for each asphalt mix recipe. In the Netherlands, the majority of the recipes are related to hot or warm mix asphalt, mainly due to the quality requirements and regulations for road construction. Cold mix asphalt has very limited production in the country (0.3% of the total) and it is mostly used for fixing existing roads. The Dutch asphalt production represented around 3% of the total asphalt produced in Europe in 2027. Regarding CO_2 emissions, the emissions for the sector in the country were 99 kt in 2020, which represented less than 0.1% of the total emissions in the Netherlands for the same year.

The decarbonisation options explored in this report for the Dutch asphalt sector include the following categories: hydrogen fuel substitution, heating system electrification, alternative feedstock and recycling. The feasibility of these options is heavily dependent on the development of existing and new technologies and other factors highlighted in Chapter 5 and in the following paragraphs.

The most carbon-intensive processes of the asphalt industry are related to heating and drying steps, which are usually powered by fossil fuels. Thus, fuel substitution is one of the main focus of Chapter 5. One of the fuel substitution options explored is the electrification of the heating systems. As mentioned in Chapter 5, auxiliary electric heating is already a common practice in the sector. For some heating processes, such as bitumen heating, full electric heated tanks are already available and used in the market. The challenge arises in the heating processes that demand higher heating power, such as drum heating RAP and asphalt mixture. In the current market, there are not many full electric alternatives for the fossil fuel-based heating drums with a high power demand. Electrification in this large scale production is still perceived solely as an auxiliary heating process. In Chapter 5, three different emission reduction alternatives are explored: two having electrification as an auxiliary process (10 and 30% of the heat demand) and the other as a full electrification alternative (100% of the heating demand). Given the system boundaries, it is possible to see that the emission reductions are much more significant with full electrification, and so is the investment cost for replacing the equipment and powering the operations. The CAPEX figures were based on general industrial heating systems electrification, which indicates that efforts are necessary not only to decrease the overall investment cost for those technologies but also to analyse more in-depth the costs of more specific heating technologies, such as electric drum heating.

Another fuel substitution alternative examined was using green hydrogen instead of natural gas in the burners. The advantage of using this alternative is that hydrogen could be gradually introduced into the fuel mix without changing the standard equipment configuration (up to 30%vol. of hydrogen in the blend). However, equipment adaptations would be necessary for higher concentrations of hydrogen or full substitution. The introduction of hydrogen as fuel impacts the heating system due to its lower heating value and higher adiabatic flame temperature. Those aspects lead to an increased volume flow rate, higher NO_X emissions and higher pressure loss when considering higher concentrations of hydrogen in the mix. New control systems and burners would be needed for adapting the asphalt heating drums, which impacts directly the CAPEX of this alternative. However, considering the boundaries evaluated in the alternatives explored in this study, the financial impact of variable OPEX could be more relevant than the CAPEX required for necessary adaptations, depending on the market price of hydrogen. Green hydrogen is still an expensive commodity, with limited availability and this would directly affect the operational costs of asphalt production.

Another topic explored in this report was feedstock substitution, focusing on finding alternatives for the fossil bitumen commonly used as feedstock in asphalt production sector. Recent research and demonstrations present a blend of lignin and bitumen as a successful alternative to decrease the dependency on fossil feedstock. Some road demonstrations are already running in The Netherlands using asphalt produced with a 50% blend of lignin and bitumen, already showing positive results. Even though this alternative would not directly reduce scope 1 emissions of the asphalt production process, LCA studies show that it could be a valuable option to reduce the indirect emissions of the sector, depending on the extraction process of the lignin. There are no CAPEX costs available in the literature for this alternative, which shows the necessity of further studying the adaptations required for introducing such a blend on an industrial scale. Variable OPEX costs are highly dependent on the price difference between lignin and bitumen. Other bio-based solutions could also play a role in replacing bitumen in the future, such as refining slurry through pyrolysis and producing a bitumen-like substance, this option is being currently developed by researchers.

Recycling and repurposing is already a common practice well introduced in the asphalt sector. The characteristics of this product allow to reclaim and reprocess it for road layers or other civil engineering applications. The change that could still be promoted in the current process for this option would be increasing the amount of RAP in the asphalt mix since studies show that this could reach levels of up to 71% in some use cases. The emissions impact of using recycled asphalt depends heavily on the extraction process, the reclaimed asphalt (RAP) treatment and the asphalt mix produced. Some studies show that using RAP has the potential to decrease the heat demand from the asphalt production process, which would directly decrease direct emissions. Other studies, however, consider that the RAP needs a pre-heating step that would lead to an increased heating demand in the whole production chain. Regardless, the indirect emissions reduction from this alternative is highly supported by different LCA studies, which confirm it as a good sustainable alternative, with even more potential when combined with renewable fuel options.

Besides those alternatives, improving energy efficiency and optimizing the industrial process can result in a positive impact on the sector's emissions. Energy efficiency improvements are largely stimulated by the best practices literature of the asphalt sector and can reduce energy waste and increase process efficiency. Some of those alternatives are improving the fuel combustion process in the heating drums and changing the mix compositions to reduce the reaction temperature. Other alternative processes routes could also be explored, such as increasing low-temperature asphalt production, reducing carbon-intensive additives and increasing the asphalt's technical performance.

Finally, the Dutch asphalt sector is complex with different production processes and a large number of production sites. Several aspects should be taken into consideration in discussing the decarbonisation alternatives of this sector, such as the specific industrial process and asphalt recipes. Ideally, an alternative should be applied which considers the specific aspects of each production site. Also, external factors such as green electricity, green hydrogen and biomass supply may play a relevant role in the transition of the asphalt sector to a low-emissions future.

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Appendix A

Figure 23

Adiabatic flame temperature, lower heating value and Wobbe index of blends natural gas and hydrogen (Mayrhofer, Koller, Seemann, Prieler, & Hochenauer, 2021)