PBL Netherlands Environmental Assessment Agency

DECARBONISATION OPTIONS FOR THE DUTCH TYRE INDUSTRY

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Decarbonisation options for the Dutch tyre industry

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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 ECN part of 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: K.M. Schure (PBL), Klara.Schure@pbl.nl, or A.W.N van Dril (TNO), Ton.vanDril@tno.nl

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This report was reviewed by Apollo Vredestein B.V. PBL and ECN part of TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

Contents

FINDINGS

Summary

In the Netherlands, Apollo Vredestein in Enschede is the largest tyre manufacturer. The company mainly produces two categories of tyres: passenger car and agricultural tyres. Its products are sold in the market under two brands, namely, Vredestein and Apollo. In 2015 the production capacity for passenger car tyres was 6.4 million tyres a year (approximately 18,000 tyres/day). The production volume in 2015 is estimated to be 6.2 million tyres.

A tyre is made of several components and raw materials. Most of these components are manufactured in the plant to later be assembled and treated providing the desired final product. The production process is divided in three sections:

- Section 1 includes the mixing units and rubber slabs production. The rubber is softened with mills, and then the chemicals are added and mixed. The resulting mix is transformed in rubber slabs.
- Section 2 includes the production units of the main components of a tyre: the body plies, belts, beads, treads and sidewalls which are produced in extruders and calendars. Subsequently these components are assembled to form a green tyre or uncured tyre.
- Section 3 corresponds with the vulcanisation process. During this process, the green tyre is introduced in a mould to shape the tread, and heated at 190 °C and 14.5 bar for 10 minutes, using steam.

The direct greenhouse gas emissions from the plant are due to natural-gas used in heat and steam production. Electricity consumption causes indirect greenhouse gas emissions. The main decarbonisation options are natural gas substitution by using biomass boilers, electric boilers, hybrid boilers or hydrogen boilers.

Table S1 Energy consumption and emissions, per section, in 2015. Source: (Rudolf M. , 2018).

Section	Electricity consumption (final) (MJ/kg tyre)	Electricity consumption (primary) (MJ/kg tyre)	Natural gas consumption (MJ/kg tyre)	Total electricity consumption (final) (TJ/year)	Total electricity consumption (primary) (TJ/year)	Total natural gas consumption (TJ/year)	Direct* emissions (kt CO_2)	Indirect** emissions (kt CO_2)
Section 1	2.0	5.0	-	112	279	-	-	20.8
Section 2	0.7	1.7	-	39	96	-	-	7.2
Section 3	1.1	2.9	5.2	64	160	287	16.3	12.0
Building	0.1	0.2	0.2	5	12	11	0.6	0.9
Total	3.9	9.8	5.4	219	547	299	16.9	40.8

* The emission factor used for natural gas is 56.6 kg/GJ (Netherlands Enterprise Agency, 2018).

** The emission factor used for electricity consumption is 74.6 kg/GJ_{prim}. The primary energy factor for electricity is 2.5 (Rudolf M. , 2018).

The most energy-intensive phases in the lifecycle of a tyre are the raw materials production and the use phase of a tyre. In the Netherlands approximately 100% of the tyres are

recovered. Recycling of materials, such as rubber, steel, textile and carbon black, can reduce the energy consumption and emissions in the production chain. Reducing the rolling resistance of tyres can reduce the emissions during the use of the tyres.

FULL RESULTS

Introduction

This report describes the current situation for the tyre production 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.

Scope

This report describes the tyre production in the Apollo Vredestein plant which is situated in Enschede. Moreover, the decarbonisation options for this plant are analysed and discussed. The main decarbonisation options are natural gas substitution by using biomass boilers, electric boilers, hybrid boilers or hydrogen boilers.

In the Netherlands, tyre producers include: Apollo Vredestein B.V. (Ir. Schiffstraat 370, 7547 RD, Enschede).
Production processes include tyre manufacturing; products include: passenger car tyres and agricultural tyres.

Reading guide

Section 1 introduces the Dutch tyre industry. Section 2 describes the current situation for tyre production processes in the Netherlands, and Section 3 describes the relevant products of these processes, while options for decarbonisation are systematically quantified and evaluated in Section 4. The feasibility of and requirements for those decarbonisation options are discussed in Section 5.

1 Tyre production in the Netherlands

In this section an overview of the tyre manufacturing industry is presented. First, the European tyre industry is introduced and the trends of vehicle sales are described. Subsequently, an introduction to the history, production and emissions from the Apollo Vredestein plant is provided.

1.1 Tyre industry in Europe

In Europe the tyres production was 4.94 million tonnes in 2016 (ETRMA, 2017). In total approximately 300 million of passenger car tyres and 18 million of truck tyres are produced each year. Currently, the European manufacturers represent 66% of the global market. Apollo Vredestein sells tyres in Europe and approximately 100 countries outside Europe (Apollo Tyres, 2019).

The growth of the automotive industry is important for the sales of the tyre manufacturing industry. Globally, the trend of light vehicle sales is fairly flat except for China and Canada for which sales decreased in 2018 (Automotive, 2018). In Europe sales slightly increased. In particular in Western Europe and in Eastern Europe the sales rose by 0.2% and 1.9%, respectively (total sales were 15 million and 3.8 million vehicles, respectively). Furthermore, the vehicle parc in 2016 in Europe was 328 million units. In the Netherlands there were 8.22 million cars (ETRMA, 2017).

1.2 The Apollo Vredestein plant

In the Netherlands, Apollo Vredestein in Enschede is the largest tyre manufacturer. The Apollo Vredestein plant was founded in 1946 under the name NV Nederlandsch-Amerikaansche Autobanden-fabriek Vredestein by NV Rubberfabriek Vredestein and B.F. Goodrich (20% shares). In 1971, B.F. Goodrich took over the company selling the Vredestein products globally. In 1976 the Dutch state acquired 49% of the Vredestein shares. Later, from 1990, the company was owned by three Dutch investors until 2009 in which the Indian company Apollo Tyres Ltd acquired Vredestein and changed the name to Apollo Vredestein B.V. (Apollo Tyres, 2019).

The company mainly produces two categories of tyres: passenger car and agricultural tyres. Its products are sold in the market under two brands, namely, Vredestein and Apollo. In 2017 the revenues were predominantly from passenger car tyres, 83% of the total revenues, while 14% corresponded to agricultural tyres. In 2018 the total revenues were EUR 471.6 million and the number of employees was 1,719 in total (Grant Thornton, 2018).

The production capacity for passenger car tyres is 6.4 million tyres a year (approximately 18,000 tyres/day). The average weight of tyres produced in the plant is approximately 9 kg considering the total kilos of tyre and the total number of tyres produced in 2011 (Rudolf M., 2018). The capacity is approximately 60,000 tonnes/year. However, part of the production is planned to be transferred to the new plant operating in Hungary. The production capacity in Enschede is planned to be reduced to 16,000 tyres/day, but the production tonnage will remain at current levels (Tyrepress, 2018).

The direct greenhouse gas emissions from the plant are due to natural gas use for heat and steam production. In Figure 1 it can be seen that in the last years emissions have shown a downward trend. The company is currently looking for solutions to reduce its emissions (Grant Thornton, 2018) (Rudolf M. , 2018).

Table 1 Greenhouse gas emissions, per year, from the Apollo Vredestein plant (permit number: NL-200400199). Source: (NEa, 2019)

Year	Emission (tCO eq)
2009	16,592
2010	18,258
2011	17,315
2012	17,245
2013	17,322
2014	17,086
2015	16,889
2016	16,561
2017	16,264
2018	16,242

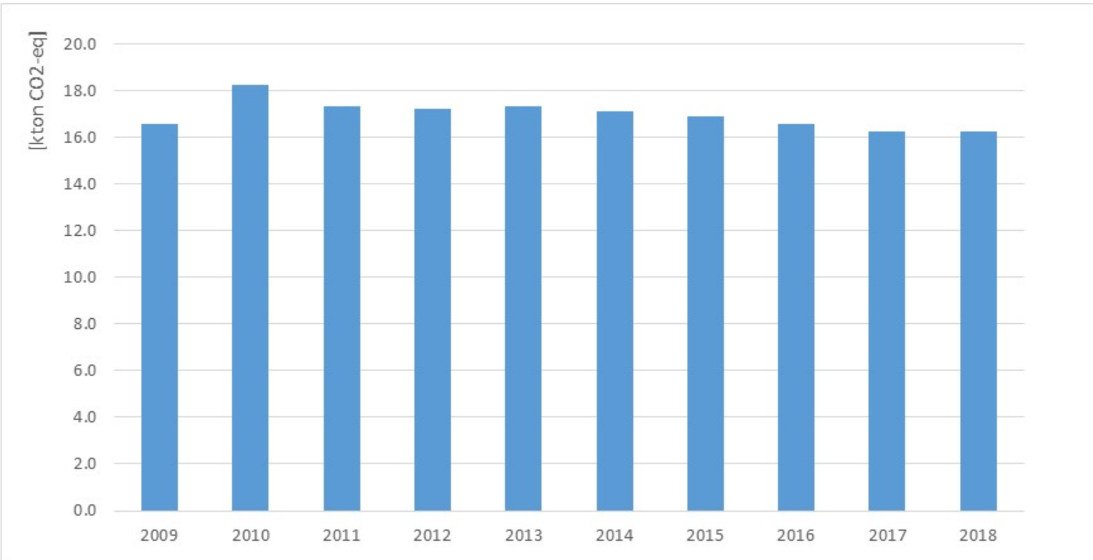

Figure 1 Greenhouse gas emissions, per year, from the Apollo Vredestein plant. Source: (NEa, 2019)

2 Tyre production processes

In this section the production process of tyres is presented. A tyre is made of several components and raw materials. Most of these components are manufactured in the plant to later be assembled and treated providing the desired final product. The production process is divided in three sections:

- Section 1 includes the mixing units and rubber slabs production. The rubber is softened with mills, and then the chemicals are added and mixed. The resulting mix is transformed in rubber slabs.

- Section 2 includes the production units of the main components of a tyre: the body plies, belts, beads, treads and sidewalls which are produced in extruders and calendars. Subsequently these components are assembled to form a green tyre or uncured tyre.

- Section 3 corresponds with the vulcanisation process. During this process the green tyre is introduced in a mould to shape the tread.

These three sections are described in detail in Section 2.1, 2.2 and 2.3, respectively. Finally, a mass balance and energy balance are applied to the Apollo Vredestein plant process in Section 2.4.

2.1 Section 1: Rubber compounds

Section 1 includes the mixing units and rubber slabs production. First a compound is formed using several raw materials to reach the required properties. Among these materials are rubbers (polymers), carbon black (filler), pigments, antioxidants and additives. The materials are mixed in the so-called Banbury machine and the process occurs at high temperature and pressure. Once the conglomerate is homogenised a black material is obtained (Apollo Tyres, 2019). The properties of the compound are controlled with the temperature, mixing power, time of cycle and speed of the rotor (NHTSA, 2006).

Next, these batches are squeezed through rollers to obtain slabs or thin sheets which are stored and sent to the following units for further processing (section 2).

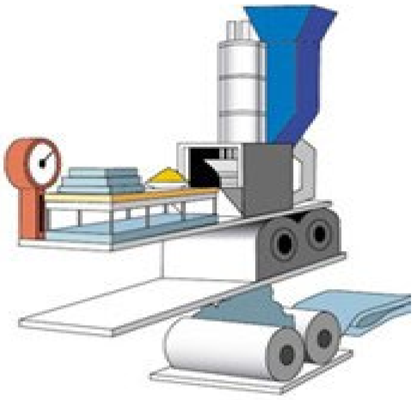

Figure 2 Banbury mixer and rollers to produce compound slabs (MAXXIS, 2018)

2.2 Section 2: Components manufacturing & assembly

Section 2 includes the production units of the main components of a tyre. These components are manufactured through extrusion or calendaring processes. Eventually, all the components are assembled to form a tyre. The components and their manufacturing processes are described below.

Figure 3 A simplified scheme of tyre components (V&F AUTO, 2016)

Body plies
Body plies are made of a reinforcing material and a rubber compound. The body plies provide stability and strength to the tyre. In this manufacturing process first a reinforcement material (rayon, polyester, nylon, aramid) in the form of filaments is twisted and cabled to form cords. Afterwards, these cords are woven to form a fabric. During this process two thin sheets of rubber are pressed and squeezed from both sides of the fabric through calendaring. Finally, the fabric is cut and rotated in order to place the cords oriented across the roll around which the fabric is stored (NHTSA, 2006).

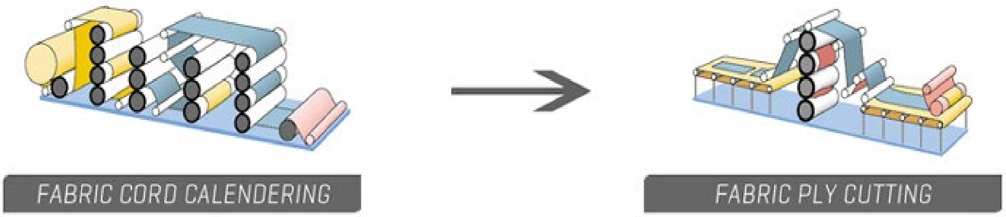

Figure 4 Fabric calendaring and cutting process (MAXXIS, 2018)

Stabiliser ply
The stabiliser ply or belt is made of steel cords that are fed to the process to make a sheet. After, the woven sheet is conducted through a calendar (rolls) where rubber layers are pressed on the sheet and between the cords. The ply is finally cut, rotated and stored as a continuous band. These plies provide impact resistance and stability (NHTSA, 2006).

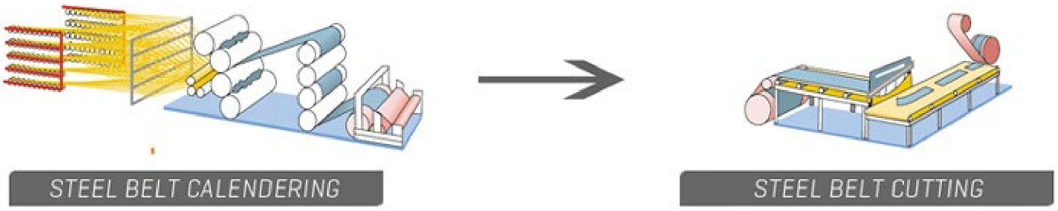

Figure 5 Steel belt calendaring and cutting process (MAXXIS, 2018)

Bead bundle
A bead wire, which is bronze plated, is covered with rubber in an extrusion process. In the extrusion process the rubber is forced through an opening (die) providing the desired shape. The resulting thread is wrapped around a cast that provides the specific shape and diameter. The final product is a bread hoop which is placed in the tyre assembly process (NHTSA, 2006).

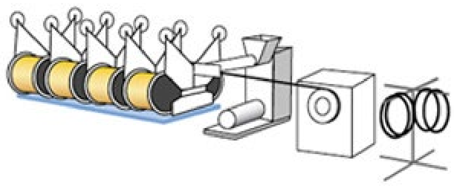

Figure 6 Bead bundle extrusion process (MAXXIS, 2018)

Inner liner, treads and sidewalls
The inner liner is located on the inner surface of a tyre. This thin ply is made of a rubber compound which is passed through a calendering process.

Treads and sidewalls are manufactured with an extruder which shapes the rubber compound by forcing the rubber through a die. After the extrusion the product is cooled and cut to obtain tread rubber (NHTSA, 2006).

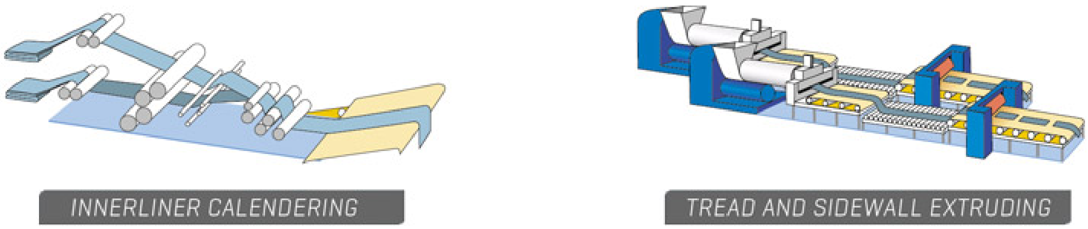

Figure 7 Inner liner, tread and sidewall manufacturing process (MAXXIS, 2018)

Assembly of the components
The tyre is assembled on a rotating drum which is a building machine that shapes radial tyres providing a form similar to the final product. First the inner liner is rolled over the drum. On top of the inner liner two body plies are placed followed by the beads which are situated on both sides of the body ply. Subsequently, the body ply is turned up over the beads (NHTSA, 2006).

Next, the sidewall compound is placed in form of strips over the turned-up ply on each edge. Finally, the steel belts and the tread are positioned in the assembly. The former provides the resistance to punctures while the latter is in contact with the road. This process results in a green tyre or uncured tyre (Apollo Tyres, 2019).

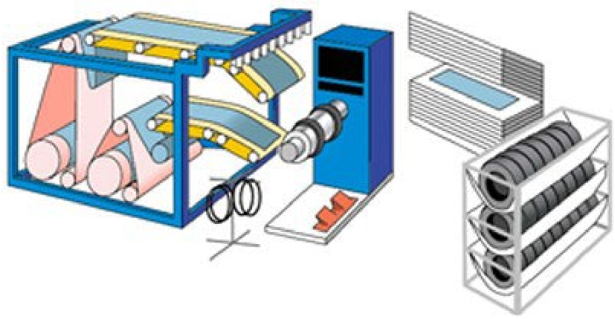

Figure 8 Tyre assembly process (MAXXIS, 2018)

2.3 Section 3: Vulcanisation unit

The result from the assembly process is a green tyre which has to be cured in a mould. This final process provides the tread the pattern designed. Moreover, it vulcanises the tyre. The curing process is performed at 190 °C and 14.5 bar for 10 minutes, using steam (Apollo Tyres, 2019).

Figure 9 shows a diagram of all the units of the production process integrated.

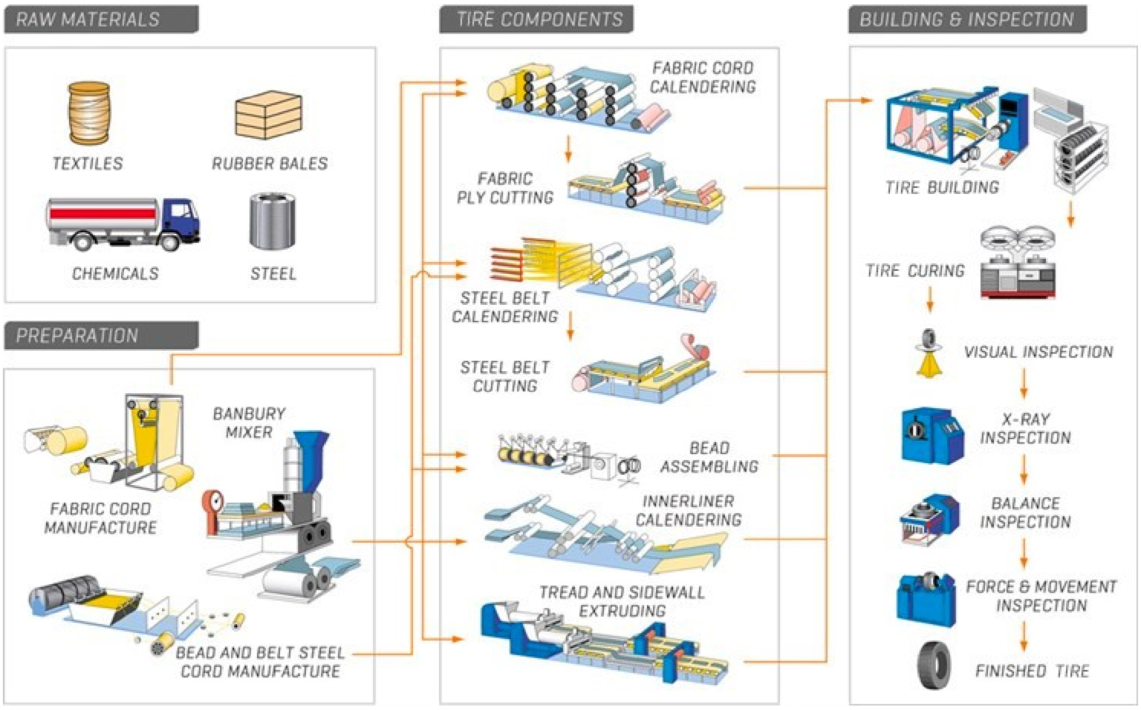

Figure 9 Production units in a tyre manufacturing process (MAXXIS, 2018)

2.4 The Apollo Vredestein process: mass balance and energy balance

The production process described previously is particularised for the Apollo Vredestein plant using information about the tyre composition and the energy consumption provided by the company (Rudolf M. , 2018). For each section, the mass balance, energy balance and emissions are quantified for the production of one tyre.

Mass balance

The raw materials fed into the process to produce one tyre are shown in Table 2. Part of these materials leave the process as scrap and are not contained in the final product. The scrap leaving the process represents 6% of the raw materials used for producing a tyre. In the Apollo Vredestein plant passenger car and agricultural tyres are produced. According with the total kilos of tyre produced in the plant the average weight per tyre is estimated to be 9 kg.

Chemicals, textile and fillers (silica) can be quantified separately based on a general passenger tyre composition. The proportion of fillers, textile and chemicals are estimated according with the composition presented in the literature (U.S. Tire Manufacturers Association, 2019).

Table 2 Raw materials used in Apollo passenger car tyre manufacturing and final product composition (Rudolf M. , 2018).

Apollo Tyre components	Share (%)	Raw materials[1] (kg/tyre)	Section
Synthetic rubber	26	2.5	1
Natural rubber	16	1.5	1
Carbon black	15	1.4	1
Steel	11	1.0	2
Others[2] (Chemicals, textile, fillers)	32	3	
- Chemicals	15	1.4	1
- Fillers (silica)	12	1.1	1
- Textile	5	0.5	2
Total	**100**	**9.5**	

The raw materials are introduced in the corresponding sections of the process according with the production process described.

Energy balance

The tyre manufacturing process uses electricity and natural gas as energy sources. The electricity is mainly consumed to run the machinery of the units while the natural gas is used to produce steam. The energy balance is calculated for each section of the production process.

Section 1 includes the mixing units (6 mixers) and rubber slabs production. In this section electrical energy is consumed, mainly due to the Banbury machine.

Section 2 includes the manufacturing units of the main components of a tyre and the assembly units. In this section electricity is consumed. In this section heat is produced, mainly due to the friction between the compound and the mills.

Finally, section 3 corresponds with the vulcanisation process. This is the most energy-intensive unit. Steam is produced in natural-gas-fired boilers. The steam provides the heat for the tyre vulcanisation. Furthermore, electricity consumption occurs in the water pumps, the vulcanisation machine (pressure to produce the final shape) and air compression.

The percentage of energy consumed in each section was provided by the company based on 2013 data. It is stated that energy consumption per tyre has not changed since 2013 (Rudolf M. , 2018).

1 The raw materials include the 6% of scrap added to 9 kg/tyre.
2 This section includes chemicals, textile and fillers. These components are separately estimated based on other sources and presented below.

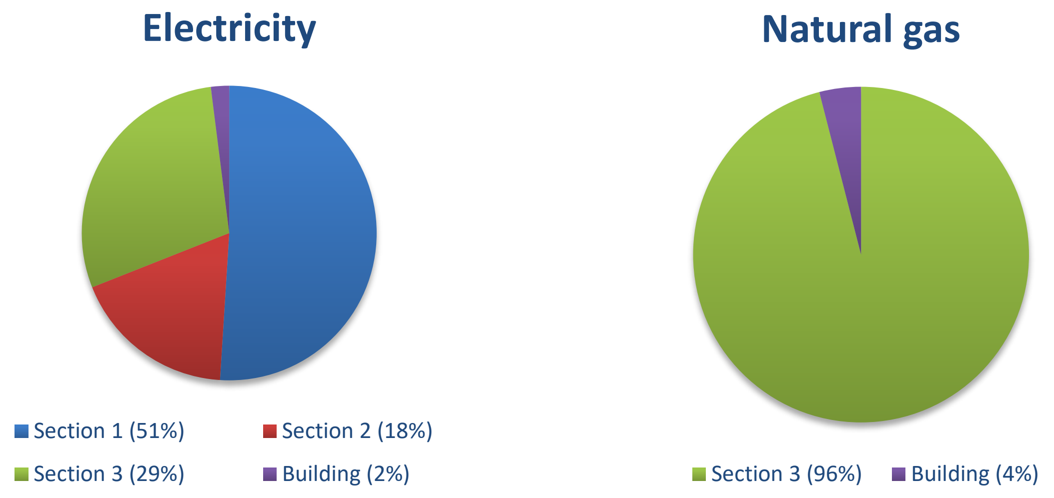

Figure 10 Distribution of electricity and natural gas consumption in the production process for 2013

The company provided information about the total electricity and natural gas consumed in 2015. These values are divided over the sections based on the energy distribution in 2013.

Table 3 Energy consumption and emissions, per section, in 2015 (Rudolf M. , 2018)

Section	Electricity consumption (final) (MJ/kg tyre)	Electricity consumption (primary) (MJ/kg tyre)	Natural gas consumption (MJ/kg tyre)	Total electricity consumption (final) (TJ/year)	Total electricity consumption (primary) (TJ/year)	Total natural gas consumption (TJ/year)	Direct* emissions (kt CO_2)	Indirect** emissions (kt CO_2)
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Section 3	1.1	2.9	5.2	64	160	287	16.3	12.0
Building	0.1	0.2	0.2	5	12	11	0.6	0.9
Total	**3.9**	**9.8**	**5.4**	**219**	**547**	**299**	**16.9**	**40.8**

* The emission factor used for natural gas is 56.6 kg/GJ (Netherlands Enterprise Agency, 2018).

** The emission factor used for electricity consumption is 74.6 kg/GJ_{prim}. The primary energy factor for electricity is 2.5 (Rudolf M. , 2018).

The production volume for 2015 was estimated to be 6.2 million tyres considering a production with an average weight of 9 kg/tyre (Rudolf M. , 2018). Furthermore, the direct and indirect emission intensities are 0.3 kg CO_2/kg tyre and 0.7 kg CO_2/kg tyre, respectively.

Finally, the load factor is estimated considering a production capacity of 6.4 million tyres a year and a production volume of 6.2 million tyres. Accordingly, the load factor is 97%.

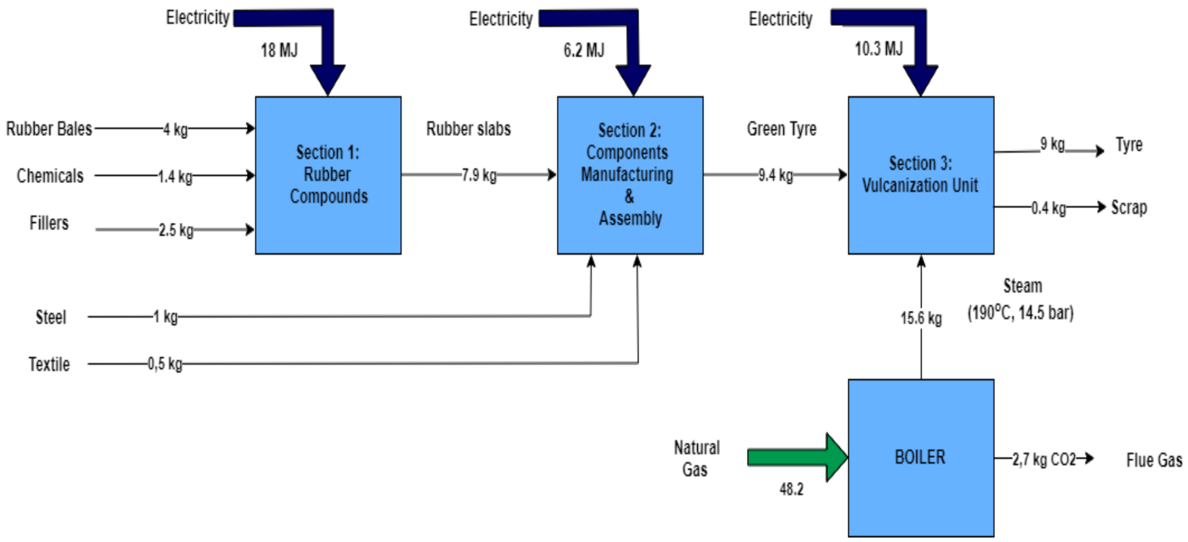

Figure 11 Diagram of mass balance and energy balance for a production process with an average weight per tyre of 9 kg

3 Tyre products and application

This section is intended to identify the environmental impact of every step in the life cycle of tyres, including the raw materials production, transport, manufacturing and use. Moreover, the end-of-life management of a tyre can provide insight into the possible options to reduce the environmental impact (in particular the materials recycling). During this entire life, from the production to the recycling processes, it is important to understand how a tyre manufacturer can improve sustainability.

First, the product (tyre) and its applications are described in Section 3.1. Afterwards, in Section 3.2 an overview of the energy intensity and emission intensity in the tyre life cycle is analysed identifying possible decarbonisation solutions and the role of the tyre manufacturers in this process. In Section 3.3, the end-of-life management of tyres in Europe and the Netherlands is explained. Finally, the materials recovered from the recycling processes and their applications are presented in Section 3.4.

3.1 Tyre application

In the Apollo Vredestein plant the main products are passenger and agricultural tyres. These tyres need to provide a balance between safety, handling and fuel consumption. There are different categories of tyres manufactured as well as different sizes per category. The products of Apollo Vredestein are divided by type of vehicle and seasons. There are tyres manufactured to perform in all seasons and tyres for winter or summer (Vredestein, 2019).

The transport sector represents one third of the energy consumption in Europe and in 2015 it accounted for 22% of the total greenhouse gas emissions. These emissions are derived from the use of fuels and between 5% and 10% of the consumption is related to the rolling resistance of tyres. The regulation in Europe is directed to increase safety, economic efficiency and environmental efficiency improving the fuel efficiency as well as reducing noise levels. These parameters are reflected in the tyre labels which aim to the costumer decision and therefore are important for the tyre manufacturers (European Commission, 2018).

3.2 Tyre life cycle environmental impact

In this section the environmental impact of each stage in the life cycle of a tyre is analysed to identify the main sources of emissions and consequently determine relevant solutions and pathways for decarbonisation. Moreover, the role of the tyre manufacturers in the decarbonisation of the life cycle is discussed.

The life cycle of a tyre starts from the raw materials manufacturing and finishes at the use of the tyre. Each of these steps contributes to the total environmental impact. The Gross Energy Requirement values of the main components are shown in Table 4.

Table 4 Gross Energy Requirement of tyre main components

Material	Gross Energy Requirement* (MJ_{prim}/kg material)
Natural rubber	8
Synthetic rubber	110
Carbon black	125
Steel	36

* *The Gross Energy Requirement values of the main components were provided by Apollo Vredestein* (Rudolf M., 2018)*.*

From the above presented data, it can be concluded that carbon black, synthetic rubber and steel production have a significant impact in the production chain. Moreover, these three components represent approximately 42% of the tyre composition. Therefore, recycling these materials is important to reduce the energy consumption and the emissions.

In Table 5 the energy consumed from the production until the use phase of a passenger car tyre is presented (Rudolf M., 2018). The most energy-intensive phases are the raw materials production and the use phase of a tyre.

Table 5 Energy consumption per passenger tyre in the production and use of a tyre

Phase	Gross Energy Requirement* (MJ_{prim}/tyre)
Raw materials production	723
Tyre manufacturing	122
Transport	42
Use	1,766

**The energy consumed in the life cycle of a tyre was provided by Apollo Vredestein.*

The tyre manufacturers can influence the tyre life cycle using recycled materials from more environmentally friendly processes. To this purpose tyre manufacturers can work together with suppliers in order to achieve the quality required for recycled materials. This action is also prompted by the costumers which are concerned about the environmental impact of the tyres (Rudolf M., 2018). Also, reduction in the scrap produced during the tyre manufacturing would decrease the amount of raw materials used, saving energy and emissions during the production of these materials.

In addition, the tyre manufacturers are working to reduce the rolling resistance of the tyres which would reduce the emissions during the use of the tyres. Apollo Vredestein has expressed its ambition to reduce the rolling resistance from 6.5 kg/kg to 4.5–5 kg/kg (Rudolf M., 2018). In Europe the improvement of rolling resistance can result in a reduction of 1.5 Mt to 4 Mt CO_2 per year in 2020 (ETRMA, Annual Report 2017, 2017).

The CO_2 emission reduction also depends on the policy implemented. A European Commission report (European Commission, 2018) analyses four options and estimates the emission reductions for 2030, for these policy options. The emission reduction varies between 1.1 Mt/year and 9.5 Mt/year. The policy with the higher impact (option 4 in the EU document) in terms of energy saving and emission reductions by 2030 represents 0.8% and 1% of the respective EU targets (30% energy efficiency and 40% greenhouse gas emission reduction).

The efforts made in the European tyre industry to reduce emissions were first mainly directed to energy efficiency, resulting in an efficiency improvement of 20% since 2004 (ETRMA, Annual Report 2017, 2017).

3.3 End-of-life management

The management of tyres is a relevant issue and different systems have been implemented in the EU countries. In particular, in the Netherlands responsibility for the end-of-life tyres (ELTs) is assigned to the producers from 2003 (extended producer responsibility). RecyBEM is in charge of the collecting system of all the tyres (ETRMA, End-of-life Tyre, 2015).

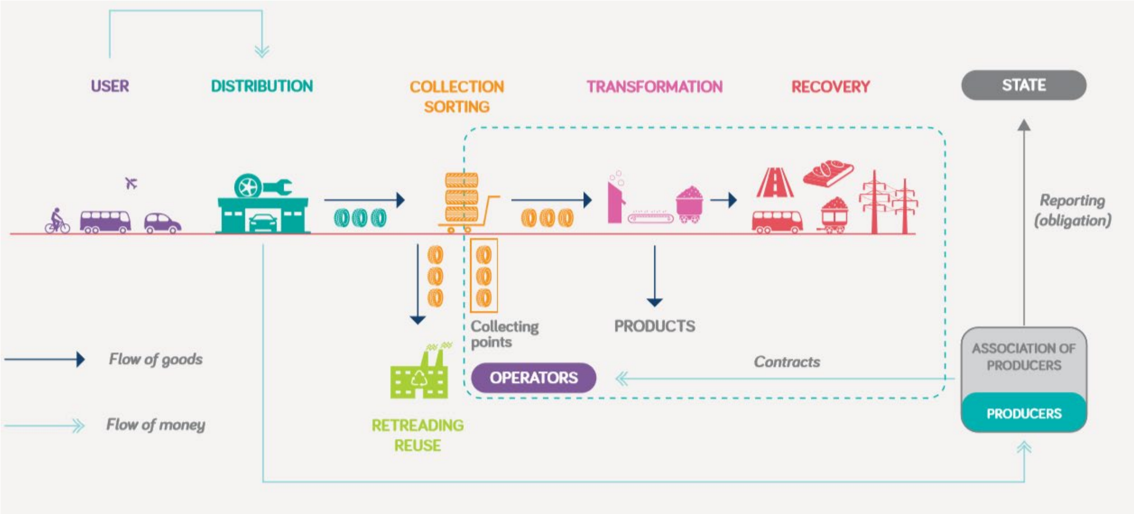

Figure 12 Diagram of the tyres management in an extended producer responsibility system (ETRMA, End-of-life Tyre, 2015)

This system is largely implemented in the EU. In 21 countries the responsibility is assigned to the producers. The ELT management organisations collect the tyres and organise the subsequent treatment. Furthermore, the number of tyres collected has to be equivalent to the number of tyres sold during that year or the previous year. In this system the manufacturers and importers pay a fee to the ELT company. In addition, the latter has the obligation to report to the national authorities (ETRMA, End-of-life Tyre, 2015).

The tonnes of ELTs recovered and recycled in 2015 corresponded with a recovery rate of 92% in Europe. The evolution of the ELTs use is presented in Figure 13. Circular economy is important in the life cycle of a tyre. In Europe 28% of the tyres collected went to energy recovery and 46% to material recycling in 2015 (ETRMA, Annual Report 2017, 2017).

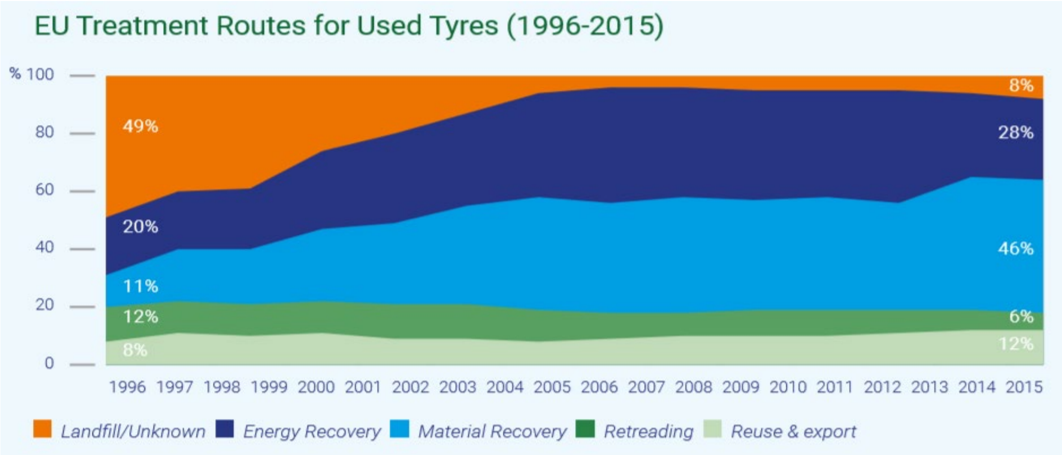

Figure 13 Evolution of percentage of ELTs from 1996 to 2015 (ETRMA, Annual Report 2017, 2017)

In the Netherlands approximately 100% of the tyres are recovered. In 2017 approximately 8.9 million tyres were collected, corresponding with 103 percent of the tyres brought into the Dutch market. In the Netherlands for every tyre brought into the market one used tyre is collected and directed to different application as is shown in Figure 14. The information about tyres recycling in the Netherlands was retrieved from the annual report of the RecyBEM association. The costs of this service are public and corresponded with 1.30 euros per tyre in 2017 (RecyBEM, 2018).

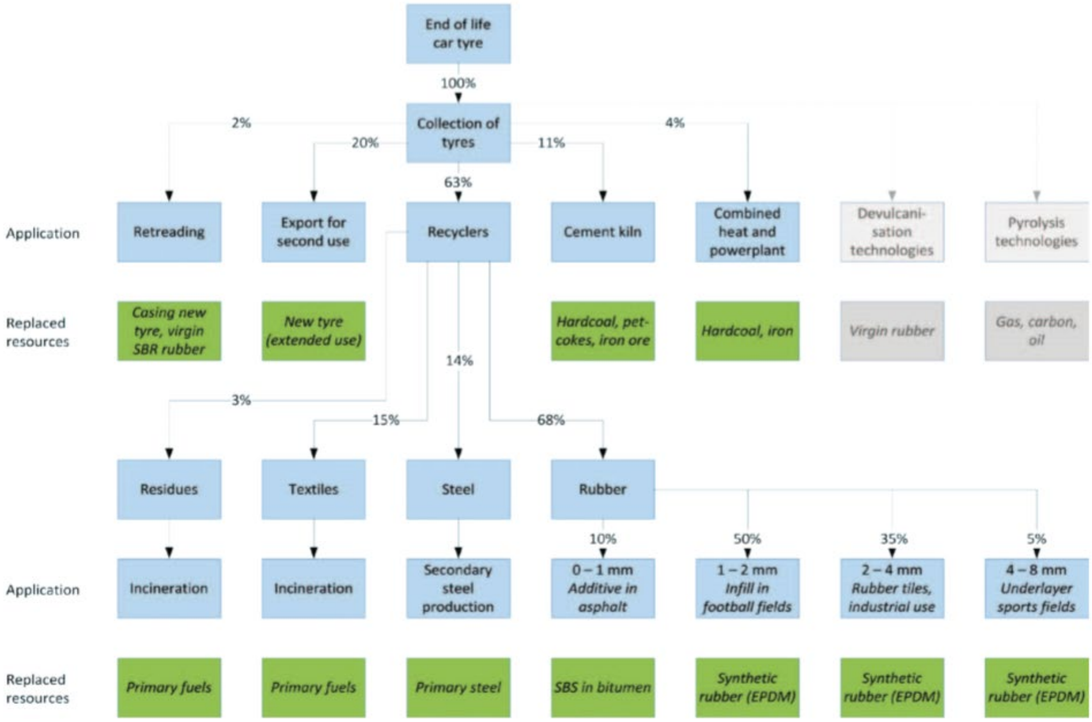

Figure 14 ELTs in the Netherlands (RecyBEM, 2011)

In 2017 the tyres collected were distributed in the system as it is shown in Table 6. Most of the tyres were recycled or directly reused as an occasion tyre extending their lifetime.

Table 6 Tyre end of life in the Netherlands in 2017 (RecyBEM, 2018)

ETLs destination	Share (%)
Material reuse	61
Occasion tyre (reuse)	32
Tread renewal (reuse)	1
Alternative reuse	0.4
Fuel (energy recovery)	5

RecyBEM which is in charge of collection of tyres and ARN which is responsible for recycling end-of-life tyres collaborate with Ecotest (which provides an instrument to do the Life Cycle Assessment according to the ISO standards) to analyse the impact in terms of CO_2 footprint, recycling and costs of processing 1 tonne of passenger car tyre via RecyBEM/ARN system.

According to Ecotest, in 2017 as a result of tyre recycling more than 24 million kilos of rubber were recovered in addition to nearly 6 million kilos of steel. Consequently 65 million kilos of CO_2 were avoided as well as 14 million kWh of electricity were saved (RecyBEM, 2018).

In Figure 15 it can be seen that 1 tonne of passenger car tyre collected can save 969 kg of CO_2. These total emissions result from the different end-of-life management options, the most relevant decarbonisation options for the tyre end-of-life management are recycling and retreading. Within the recycling options rubber granulate avoids the largest amount of emissions (RecyBEM, 2011).

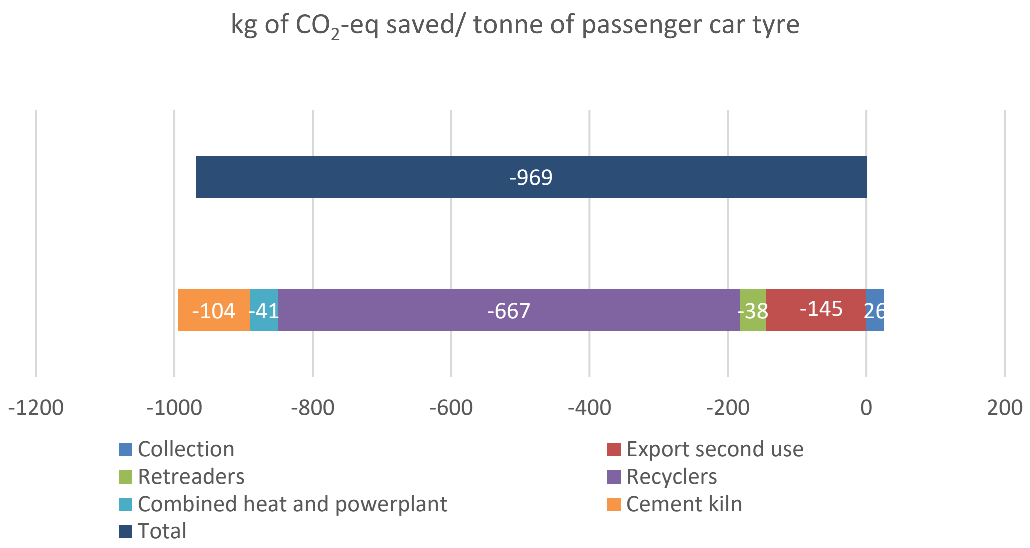

Figure 15 CO_2 footprint of 1 tonne of passenger car tyre collected by RecyBEM (RecyBEM, 2011)

Materials recycling is particularly important as it can provide large savings in CO_2 emissions. Therefore, RecyBEM is focusing on the circular economy within the tyre chain, for instance RecyBEM supports the development of the devulcanisation of rubber. Research into devulcanisation was done by the University of Twente in collaboration with the University of Groningen (RecyBEM, 2019) (Saiwari, 2013).

3.4 Applications of recycled materials

In this section the materials recovered from the recycling processes and their applications are presented. The materials are rubber, steel, textile and carbon black.

The composition of the rubber recovered from tyres varies with each type of tyre and brand. Therefore, recycling rubber into virgin rubber with the desired mechanical properties to produce a new tyre is difficult. The rubber is mostly recycled as shred, granulate, powder and crumb. The granulate and powder are produced in ambient or cryogenic size reduction (ETRMA, End-of-life Tyre, 2015). Moreover, the passenger car tyres have restrictive specifications which require the use of pure raw materials such as natural rubber and resin. Therefore, the rubber recovered from the devulcanisation process has limited applications for passenger car tyres (Rudolf M., 2018).

The steel recovered from tyres is highly demanded as a feedstock for steel manufacturers, because of its high quality. Moreover, steel wire from tyres is also demanded in the concrete industry as a reinforcement material (ETRMA, 2015).

The textile is more difficult to recover because it is usually contaminated with rubber. This material can be used as an insulation material (according with the building standards) as well as a source of energy (ETRMA, 2015). In addition, it can be pyrolysed for material recovery.

Carbon black is recycled through a carbonisation process (pyrolysis). The carbon black recovered has to reach the required specifications of the tyre production process. According to Apollo Vredestein (Rudolf M., 2018) these specifications are being addressed in collaboration with recyclers. Potential suppliers have to comply with the specifications for the two grades of carbon black that are largely consumed in the plant. In addition, another disadvantage is that the current recycled carbon black is more expensive than the virgin material (Rudolf M. , 2019).

The European Innovation Partnership on Raw Materials has launched an initiative in 2016 to develop a strategy to increase the use of tyre recycled materials in the European market. The demand for these materials in Europe is low and a high portion is exported. The objective of the RUBBERTOMARKET is to develop a market for tyre recycling sector which is integrated in the European circular economy strategy. Therefore, development of technology, quality standards and best practices are promoted to produce recycled raw materials for high added value European industry. This initiative will last until 2020 and some activities are improving the quality of the recycled materials to meet the specifications of the market (standards), develop patents, promote R&D projects, show the market the advantages of recycled materials use (European Commission, 2016).

4 Options for decarbonisation

This section evaluates decarbonisation options for the tyre industry. The decarbonisation options are divided into different categories.

Decarbonisation categories that can be relevant are:

- Fuel substitution: natural gas used for steam generation in natural-gas-fired boilers can be substituted by green gas. Alternatively, biomass boilers, biogas boilers, electric boilers, hybrid boilers or hydrogen boilers can be used.
- Heat distribution: supply of steam from the Twence company.
- On-site renewable electricity generation: solar PV.

4.1 Biomass boiler

Combustion boilers are suitable for steam generation in industry. Different fuels can be used. If green gas is used, no modifications are needed to the natural gas boiler. Greenhouse gas emission reduction can also be achieved by using biogas or biomass instead of natural gas.

Apollo Vredestein is currently studying the option to reduce their emissions by using a biomass boiler (Rudolf M. , 2018). The biomass boiler is a combustion boiler and it is formed by a biomass burner and a heat-transfer system which generate steam (IEA, 2010). There are two main types of biomass boilers: fire-tube boilers and water-tube boilers. The former is generally used for capacities up to 30 bar and the latter for higher pressure requirements (Donovan, Tottenham, Bruton, & Luker, 2011).

Biomass boilers are a suitable technology to replace gas boilers. Modern boilers can reach approximately 90% of efficiency. This technology uses pellets or shreds. The feasibility depends on the availability and price of biomass in the future. Biomass boilers are a technology already applicable and easy to include in the processes (Stork, de Beer, Lintmeijer, & den Ouden, 2018). The technical lifetime of industrial boilers can vary between 25 and 40 years (IEA, 2010). A technical lifetime of 30 years is assumed.

In order to estimate costs for the different options the total capacity of gas-fired boilers in the plant is calculated. In this calculation the following assumptions are made:

- The plant has a total capacity of 6.4 million tyres/year.
- The natural gas used per tyre is 48 MJ/tyre (see Section 2.4).
- The efficiency of the gas-fired boilers is 90%.

Taking into account these assumptions the total thermal output capacity needed is 9 MW_{th}.

Table 7 shows the specification of a steam boiler that can provide 30 bar. The costs of using a biomass boiler in the Apollo Vredestein plant can be estimated based on these techno-economic parameters. For a biomass boiler with a thermal output of 9 MW, the investment is approximately EUR 5.3 million and the fixed O&M costs are EUR 0.41 million per year.

Table 7 Techno-economic parameters for an industrial steam boiler fuelled with wood pellets ≥5 MWth (Lensink S. , 2018)

Wood pellet boiler > 5 MW_{th}	Value	Units
Thermal output	20	MW_{th}
Full load hours heat output	8,500	hr/yr
Investment	590	$EUR_{2019}/kW_{th\_output}$
Fixed O&M	45	$EUR_{2019}/kW_{th\_output}/yr$
Efficiency	90	%

4.2 Heat supply: Twence

Twence is a company located in Enschede which converts waste into raw materials and energy. Twence operates a biomass plant that provides electricity, heat and steam from waste wood and non-renewable organic waste. The steam generated is suitable for industrial applications and used in neighbouring industries (Twence, 2018). Twence supplies steam to AkzoNobel since 2011 through a 2.2 km pipeline (AkzoNobel, 2019).

In 2017, a feasibility study was announced into a steam network that would connect Twence with Apollo Vredestein and Grolsch. Supply of steam to the vulcanisation process at the Apollo Vredestein plant would reduce the consumption of natural gas and, therefore, also the emissions (Twence, 2017). In case Twence will provide the steam required by Apollo Vredestein, a pipeline between the plants has to be built. The pipeline required would be about 6 km long.

4.3 Electric boilers

Electric boilers use electrical current through electrodes to heat the water in the boiler (Cleaver Brooks, 2013). Electrode boilers which can produce saturated steam at 350 ºC are commercially available and have an efficiency of up to 99.9%. Moreover, electrification of utilities has a lower impact than a primary process electrification which requires more redesign and implies more sensitivity to modifications (den Ouden, et al., 2017).

In Table 8 the investments for a 20 MW high voltage electrode boiler for industrial use are presented. The investment costs include installation and grid connection costs (Hers, Afman, Cherif, & Rooijers, 2015). In the case of Apollo Vredestein, no excess grid capacity is available. Therefore, the increase in demand would imply a new grid connection (Rudolf M. , 2019).

Table 8 Techno-economic parameters for an electrode boiler (Hers, Afman, Cherif, & Rooijers, 2015)

20 MW_{th} Electric boiler	Value	Unit
Efficiency	99	%
Technical lifetime	20	years
Investment[3]	60	EUR_{2015}/kW
Fixed O&M	1.1	$EUR_{2015}/kW/yr$
Variable O&M	0.5	EUR_{2015}/MWh
Grid connection	130	EUR_{2015}/kW

[3] Investment cost for the electric boiler including cables and installation

The total capacity needed in the Apollo Vredestein plant is approximately 9 MW thermal output. The investment costs for the Apollo Vredestein plant are estimated in Table 9. It is important to mention that there are additional costs related to the transmission tariffs. Electric boilers have higher efficiencies than gas-fired and biomass boilers and therefore the energy consumption is lower.

Table 9 Estimate of costs of an electrode boiler (based on a thermal output capacity of 9 MW)

9 MW_{th} Electric boiler	Value	Unit
Investment electric boiler & installation	0.54	mln EUR_{2015}
Investment grid connection	1.2	mln EUR_{2015}
Fixed O&M	10	$kEUR_{2015}$/yr
Variable O&M	0.5	EUR_{2015}/MWh

4.4 Hybrid boilers

Hybrid boilers are suitable for replacing gas-fired boilers. This technology switches from electricity to gas and vice versa to generate steam. Hybrid boilers can take advantage of decreases in the electricity price in the short term and can become economically feasible with higher volatility in electricity prices due to its operational flexibility (den Ouden, et al., 2017).

Investment costs for a hybrid boiler are presented in Table 10. The current electricity prices and natural gas prices are not suitable for power-to-heat technology. However, the increasing renewable generation could be positive for the business case of a hybrid boiler (de Wolff, de Ronde, & Boots, 2018).

The costs estimated for the Apollo Vredestein plant (9 MW thermal output) are based in the costs presented in Table 10. The total investment costs are approximately EUR 2.7 million. In addition, the fixed O&M costs are approximately EUR 31,000.

Table 10 Techno-economic parameters for a hybrid boiler

9 MW_{th} hybrid boiler	Value	Unit	Source
Efficiency	99	%	(de Wolff, de Ronde, & Boots, 2018)
Lifetime	20 (12–30)	years	(de Wolff, de Ronde, & Boots, 2018) (VEMW, 2017)
Equipment costs*	173	$kEUR_{2018}/MW_{output}$	(de Wolff, de Ronde, & Boots, 2018)
Grid connection costs**	130	$kEUR_{2015}/MW_{output}$	(Hers, Afman, Cherif, & Rooijers, 2015).
Fixed O&M	3.5	$kEUR_{2018}/MW_{output}$/yr	(de Wolff, de Ronde, & Boots, 2018)
Variable O&M	0.3	EUR_{2018}/MWh_{output}	(de Wolff, de Ronde, & Boots, 2018)

* The equipment costs exclude the engineering, procurement and construction costs of the heat supply because it is assumed there is an existing gas boiler system.

** Grid connection costs depends on the distance to the closest transformer and the required connection.

4.5 Hydrogen boiler

Hydrogen has diverse applications. It can be used as a fuel for transportation and electricity production. In addition, it is an important feedstock for industry to produce chemical products (ammonia, methanol). In the industry, hydrogen can be used to produce high temperature steam (Northern Netherlands Innovation Board, 2017). Currently hydrogen is mainly used in the chemical and petrochemical industry. However, in the future hydrogen use as a fuel can become more common. In the case of the Apollo Vredestein plant hydrogen would be a fuel to generate steam. The hydrogen can be supplied through pipelines, trucks and ships. Pipelines can transport large amounts of hydrogen over long distances.

In the case of the Apollo Vredestein plant the natural gas burners would have to be substituted by hydrogen burners. The hydrogen burners are commercially available (Hart, Howes, & Lehner, 2015). An estimation of hydrogen boiler costs is presented in Table 11. In the Apollo Vredestein plant, the total investment costs for a hydrogen boiler of 9 MW_{th} are EUR 1.3 million and the O&M costs are EUR 0.16 million. The hydrogen could be supplied by trucks in the absence of pipeline infrastructure.

Table 11 Techno-economic parameters for a hydrogen boiler

9 MW_{th} hydrogen boiler	Value	Unit	Source
Efficiency	90	%	(Hart, Howes, & Lehner, 2015)
Lifetime	25	years	(Hart, Howes, & Lehner, 2015)
Investment	140 (120–160)	EUR_{2019}/kW_{th}	(Noothout, de Beer, Quant, & Blok, 2019)
Fixed O&M	17.5 (15–20)	$EUR_{2019}/kW_{th}/a$	(Noothout, de Beer, Quant, & Blok, 2019)

4.6 Solar PV

Apollo Vredestein is studying the possibility of covering the large roof of the plant with bifacial solar panels to provide approximately 11% of their electricity demand. However, the structure of the roof is old and it has to be reinforced.

An overview of costs for solar photovoltaic installations can be seen in Table 12. In addition to the costs presented it is important to mention that the inverters need to be replaced every 12 years. In 2018, the electricity demand was 60.8 GWh. To supply 11% of the electricity demand, a solar-PV system with a capacity of 7.0 MWp is needed. The investment costs can be estimated as EUR 5.1 million and the fixed O&M costs as EUR 91,000. There will be additional costs for reinforcements of the roof.

Table 12 Techno-economic parameters for a roof-mounted PV system (Lensink S. , 2018)

Roof-mounted solar PV	Value	Unit
Installation size	2.5	MWp
Full load hours	950	MWh/MWp/a
Investment	730	EUR_{2019}/kWp
Fixed O&M	12,97	$EUR_{2019}/kWp/a$

5 Discussion

In this section the different decarbonisation options and their feasibility are discussed. Moreover, the preferences in the Apollo Vredestein plant for decarbonisation and important requirements are described.

The tyre manufacturing industry is concerned about the reduction in energy costs, in particular the costs due to the EU Emission Trading System. Moreover, providing an environmentally friendly product is important. Therefore, a reduction in the plant's emissions and the use of materials manufactured in sustainable processes are key for the industry.

A decarbonisation option for the Apollo Vredestein plant in the short term is the use of biomass to provide heat. The feasibility depends on the availability and price of biomass in the future. Biomass boilers are a technology already applicable and easy to include in the processes (Stork, de Beer, Lintmeijer, & den Ouden, 2018). This option is considered by Apollo Vredestein (Rudolf M. , 2018). Natural gas can also be substituted by green gas or biogas.

Currently, electrification of the industry is technically applicable. However, the economic feasibility of this technology in the Netherlands is limited due to costs of the grid connection, power prices and capacity tariffs (den Ouden, et al., 2017). In the case of Apollo Vredestein, the grid connection is an important barrier as important investments are required to modify the electricity infrastructure of the plant. A first step to electrification could be a hybrid boiler in which a gas-fired boiler and an electric boiler alternate depending on energy prices. Hybrid boilers could be an alternative business case to electric boilers which could reduce emissions and provide flexibility services to the grid (Hers, Afman, Cherif, & Rooijers, 2015).

Hydrogen is a potential alternative fuel that could be used in the Apollo Vredestein plant. The feasibility of this solution depends on the availability of a hydrogen supply network (pipelines, trucks) and the price of the fuel. The use of hydrogen as a fuel in industry could become more important in the future. The costs can be reduced if the current natural gas pipelines would be adapted for hydrogen transport.

For Apollo Vredestein providing a more environmentally friendly product is important. For instance, Apollo Vredestein is considering to consume recycled materials. To decide on the introduction of recycled materials, Apollo Vredestein considers the processes in which these materials are retrieved and their impact on the environment in terms of emissions and water use. The requirements of Apollo Vredestein can encourage the use of products from environmentally friendly processes.

Additionally, Apollo Vredestein can reduce the emission during the use phase of the tyres by reducing the rolling resistance. This is a global target already set in the industry. It is important to mention that the tyre specification requirements (e.g. safety, rolling resistance) have to be met. Therefore, there can be limits to the use of recycled materials, and collaboration between the parties is needed.

Apollo Vredestein is also considering to produce electricity from renewable energy sources, in particular installing PV technology on the plant roof. However, the roof is old and cannot support the PV panels. Currently, this project is still being considered.

Carbon capture and storage (CCS) has not been examined in this report. The infrastructure to store the CO_2 is not available at the moment and there are no projects expected in the area.

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