PBL Netherlands Environmental
Assessment Agency

DECARBONISATION OPTIONS FOR THE DUTCH POTATO PROCESSING INDUSTRY

K.J. West, J.J. de Jonge, M. van Hout

15 June 2021

MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation options for the Dutch potato processing industry
© PBL Netherlands Environmental Assessment Agency; © TNO
The Hague, 2021
PBL publication number: 3658
TNO project nr. 060.33956 / Publication number: TNO 2020 P11023

Authors

West, K.J., De Jonge, J.J., van Hout, M.

Acknowledgements

We are grateful for feedback from Hylke Brunt (Vereniging voor de Aardappelverwerkende Industrie), Valeria Lucinschi and Henk van den Bovenkamp (Kuipers), Alain de Puydt, Dimitrie Knopfmacher and Jan van de Wolfshaar (TOMRA), and Bas Janssens (Wageningen Economic Research).

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 (which is named TNO EnergieTransitie after 1-1-2020). 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, K.M. Schure (PBL), Klara.Schure@pbl.nl, or A.W.N. van Dril (TNO), Ton.vanDril@tno.nl.

This publication is a joint publication by PBL and TNO Energy Transition and can be downloaded from: www.pbl.nl/en. Parts of this publication may be reproduced, providing the source is stated, in the form: West, K.J., De Jonge, J.J., van Hout, M. (2021), Decarbonisation options for the Dutch potato products industry. PBL Netherlands Environmental Assessment Agency and TNO EnergieTransitie, The Hague.

Erratum

An earlier version of this report was published in July 2020. Compared to the earlier version, the energy intensity of potato flakes production was updated which led to different values in several of the Tables.

PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning. PBL contributes to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all of PBL's studies. PBL conducts solicited and unsolicited research that is both independent and scientifically sound.

TNO EnergieTransitie has a twofold mission: to accelerate the energy transition and to strengthen the competitive position of the Netherlands. TNO conducts independent and internationally leading research and we stand for an agenda-setting, initiating and supporting role for government, industry and NGOs.

This report was not reviewed by the companies mentioned. PBL and TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

Contents

List of abbreviations

CAPEX	Capital expenditures
CBS	Centraal Bureau voor de Statistiek
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CFC	Chlorofluorocarbon
CHP	Combined heat and power
CO_2	Carbon dioxide
ECT	Evaporative compression technology
EU ETS	European Union Emissions Trading System
FTE	Full time employees
GJ	Gigajoule
H_2	Hydrogen
H_2S	Hydrogen sulfide
HCFC	Hydrochlorofluorocarbon
kt	Kilotonnes
kW	Kilowatt
MHz	Megahertz
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network
MJA3	Meerjarenafspraken energie-efficiënte
NEa	Nederlandse Emissieautoriteit (Dutch Emissions Authority)
NO_x	Nitrogen oxides
OPEX	Operating expenditures
PEF	Pulsed electric field
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
TJ	Terajoule
TRL	Technology readiness level
UASB	Upflow anaerobic sludge blanket
UDG	Ultra-deep geothermal
VAVI	Vereniging voor de Aardappelverwerkende Industrie

FINDINGS

Summary

The Dutch potato processing, one of the largest in the world, produces about 2.5 million tonnes of processed potato products, including a large variety of products such as frozen French fries, chilled potato products, potato flakes, and crisps. Nearly 90% of these products are exported. There are 18 major sites in the Netherlands where potatoes are processed, and 7 large companies active in the sector. The industry emitted about 400 ktCO$_2$ in 2017, of which 267 ktCO$_2$ were covered by the European Union's Emissions Trading Scheme (EU ETS). Processing raw potatoes into consumer products involves large amounts of steam and fuel for heating, and electricity for cooling, freezing, and mechanical work; the overall energy intensity of the sector is estimated at about 3.3 GJ/tonne of product, though the energy requirements for different products can vary significantly.

Table S1: Estimated production, energy consumption and CO$_2$ emissions of the Dutch potato processing sector in 2017

	2017 estimate
Total production [kt processed potato products]	2 541
Natural gas consumption [TJ]	8 243
Biogas consumption [TJ]	381
Electricity consumption [TJ]	996
CO$_2$ emissions [ktCO$_2$]	467

Note: The emissions factor used for natural gas is 56.6 kg/GJ (Rijksdienst voor Ondernemend Nederland, 2018). Methodology for these estimates is discussed in Appendix A.

Key decarbonisation options for the potato processing sector include:

- **Material efficiency**: Reducing product waste in the process, particularly in the peeling, sorting and blanching steps would reduce material needs and therefore energy requirements and CO$_2$ emissions (both onsite and upstream) to meet product demand. Valorization of remaining waste streams via biogas production could also reduce the energy needs and CO$_2$ emissions of the sector.
- **Energy efficiency**: Peeling, blanching and frying are key process steps where new technologies are being developed to reduce energy consumption. Implementation of these, along with good practices, could reduce energy demand.
- **Fuel substitution**: The use of low-carbon or carbon-neutral energy sources in place of natural gas would eliminate the direct CO$_2$ emissions associated with the sector. These can include biogas, green gas, hydrogen, or carbon-free electricity to provide heat and steam to the process.

This report describes the current status of the potato processing sector of the Netherlands at a national level, and gives recommendations on the tools that could be used to decarbonise potato processing by 2050, in order to support the broad goals of decarbonisation of the Dutch industrial sector. The estimates in this report are based on publicly available literature and data to provide insight into the scale of the energy consumption and emissions of the sector at the national level. Individual facilities' and companies' energy intensity levels and CO$_2$ emissions are not discussed (except for reported emissions under EU ETS); these can vary widely based on product- and site-specific technologies, constraints, and practices. Factors beyond the companies' direct control, such as quality of the potato harvest and product demand, may also influence their CO$_2$ emissions and energy consumption in the future.

FULL RESULTS

Introduction

The Climate Agreement set out the ambitions to decrease the total CO_2 emissions in The Netherlands by at least 49% in 2030 compared to 1990 levels (Afspraken van het Klimaatakkoord, 2020). This is in line with the goals set by the Paris agreement: a maximum increase in average global temperature of 2°C, and preferably limiting warming to 1.5°C. The MIDDEN project – the Manufacturing Industry Decarbonisation Data Exchange Network – aims to support industry, policy makers, analysts and the energy sector in their common efforts to achieve deep decarbonisation, by providing data and analysis on the industrial sector of the Netherlands. This report describes the current situation of the Dutch potato processing sector and the options and conditions for its decarbonisation. Mapping decarbonisation options is an ongoing process. The MIDDEN project will update and further elaborate on options in the future.

Scope

Production locations include:

- Agristo (Tilburg)
- Aviko (Cuijk, Lomm, Steenderen, Venray, Warffum)
- Farm Frites (Oudenhoorn)
- LambWeston Meijer (Kruiningen, Bergen op Zoom, Oosterbierum, Broekhuizenvorst)
- McCain Foods (Lelystad, Lewedorp, Wezep)
- PekaKroef (Odiliapeel)
- PepsiCo Nederland (Broek op Langedijk).

Processes include:

- Grading and sorting; washing and cleaning; peeling; cutting/slicing; sorting; blanching; frying; cooling; freezing; drum drying; packaging; water treatment; and energy utilities. Not all processes are applicable to all product types.

Products include:

- Processed potato products, with PRODCOM codes:
  - 10311130 - Frozen potatoes, prepared or preserved (including potatoes cooked or partly cooked in oil and then frozen; excluding by vinegar or acetic acid)
  - 10311460 - Potatoes prepared or preserved, including crisps (excluding frozen, dried, by vinegar or acetic acid, in the form of flour, meal or flakes).

The main decarbonisation options are:

- Material efficiency
- Energy efficiency
- Bio-based fuels
- Hydrogen as fuel
- Ultra-deep geothermal
- Electrification.

Reading guide

Section 1 gives a general introduction to the potato processing industry in the Netherlands. In Section 2 we describe the current situation of the processes in the potato processing sector in the Netherlands and in Section 3 we describe the relevant products of these processes. Options for decarbonisation are systematically quantified and evaluated in Section 4. The feasibility and requirements of those decarbonisation options are discussed in Section 5. Finally, the appendix gives more information about the methodology used in the study.

1 Potato processing industry in the Netherlands

This research will focus on firms that are part of the Dutch potato-processing industry. This sector includes the processing of raw potatoes into final consumer products[1]. The Dutch potato processing sector is among largest in the world. In 2017, the sector produced just over 2 million tonnes of frozen potato products, and about 400 thousand tonnes of other potato products including crisps and chilled potato products, from an input of about 4 million tonnes of potatoes. The sector's 2017 turnover was about €1.6 billion, and it employed approximately 4 000 FTE (Centraal Bureau voor de Statistiek, 2019a). Investments in the Dutch potato-processing sector are approximately 100 million euros annually (Vereniging voor de Aardappelverwerkende Industrie (VAVI), 2019).

The Netherlands is now the world's tenth largest producer of potatoes, and third largest potato processor in the world (FAOSTAT, 2019) (Vereniging voor de Aardappelverwerkende Industrie (VAVI), 2019). About 3.9 million tonnes of potato were processed into about 2.1 million tonnes of product in 2018 (Vereniging voor de Aardappelverwerkende Industrie (VAVI), 2019) (Centraal Bureau voor de Statistiek, 2019b). Almost 85% of the product output volume consists of pre-fried products. These products are either shipped frozen or cooled. More than 85% of the total product volume is produced for export. The sector's primary energy input was 10 296 TJ in 2017 (Rijksdienst voor Ondernemend Nederland, 2019). Approximately 75% of total primary energy use is natural gas, 25% is electricity use, and 4% is other fuels, including biogas. In 2017, energy costs were about 2.6% of the sector's monetary yields, a share that is higher than the foods- and stimulants industry average of 1.2% (Centraal Bureau voor de Statistiek, 2019a).

Six large companies currently active in the Netherlands – Agristo, Aviko, Farm Frites, Lamb Weston/Meijer, McCain, and Peka Kroef – are members of the national potato processing industry association, Vereniging voor de Aardappelverwerkende Industrie (VAVI). These firms operate 17 different industrial sites in the Netherlands, of which 10 are covered by the EU ETS (Nederlandse Emissieautoriteit, 2019). Other firms also produce processed potato products in the Netherlands, but are not part of VAVI or EU ETS. Additionally, although the crisps (potato chips) industry is not covered by VAVI, it is part of the potato processing sector in national statistics. The largest crisps producer in the Netherlands, Pepsico Netherlands, in Broek op Langedijk, the producer of Lays (formerly Smith chips), is covered by EU ETS and will be considered within the scope of this report. The accompanying dataset covers only the sites covered by EU ETS, excluding the 6 others discussed in the report.

---

[1] Potato production in the agricultural sector is outside the scope of this report, as are the upstream emissions related to agriculture. Potato starch is also excluded from this analysis, and is covered in a separate MIDDEN report.

Figure 1.1. Map of 18 major potato processing facilities in the Netherlands

Table 1.1. Profile of major potato processing companies active in the Netherlands

Company name	Global annual turnover 2017	Employees in NL	Potato processing sites in NL	Estimated annual output capacity	Main products
Agristo	€345 million	760 (NL and BE)	1	220 kt (Tilburg)	Frozen French fries and other frozen products
Aviko	€600 million	750	5	120 kt (Lomm) 400 kt (Steenderen) 50 kt (Venray) 30 kt (Warffum) unknown (Cuijk)	Precooked products (frozen/ chilled/fresh); potato flakes
Farm Frites	€350 million*	400	1	260 kt (Oudenhoorn)	Frozen and chilled potato products
LambWeston Meijer	€780 million (EMEA region)	1 400 (Europe)	4	130 kt (Bergen op Zoom) 130 kt (Oosterbierum) 130 kt (Kruiningen) 90 kt (Broekhuizenvorst)	Frozen potato products
McCain Foods	€6.4 billion*	20 000 (global)	3	220 kt (Lelystad) 90 kt (Lewedorp) 50 kt (Wezep)	Frozen French fries and other frozen products
Peka Kroef	€116 million*	325	3	150 kt (Odiliapeel) unknown (Asten) unknown (Venray)	Chilled potato products
PepsiCo Nederland	€56 billion (parent company)	630	1	70 kt (Broek op Langedijk)	Crisps

Notes:
Companies: Only VAVI members and PepsiCo Nederland (which is part of EU ETS) have been included, though there are other firms active in the Dutch potato processing sector.
Turnover: FarmFrites turnover is for 2016. LambWeston/Meijer turnover refers to the EMEA region (Europe, Middle East and Africa) and employees refers to Europe. McCain Foods turnover is CAD 9.5 billion, and number of employees is global. Peka Kroef turnover value is for 2013. Turnover for PepsiCo Nederland refers to the parent company PepsiCo, and is given as USD 63 billion.
Employees: Agristo employees include Belgium.
Capacity: Estimated output capacities are rounded to the nearest 10 kt. Sources include permitting documents and news articles, and estimates are based on hourly output numbers, potato inputs, and overall company capacity values. No information was available for Aviko – Cuijk, Peka Kroef – Asten or Peka Kroef – Venray.

Sources: AGF.nl, 2016; Arcadis Nederland BV (2015); Aviko, 2019; Aviko, 2016; capitalmind, 2019; de Gelderlander, 2019; FarmFrites, 2016; LambWeston, 2018; McCain, 2019b; PotatoPro.com, 2018; PotatoPro.com, 2019a; PotatoPro.com 2019b; Procesverbeteren.nl (2015); van der Boom (2019); Vlam.be, 2019; Wallays, 2014; Witteveen+Bos (2015).

Agristo is a Belgian-owned company that operates four production facilities, one in the Netherlands, in Tilburg, which they acquired from LambWeston/Meijer in 2001. The location has 2 production lines, of 60 and 160 thousand tonnes per year capacity, for a total of 220 thousand tonnes of frozen sliced potato products per year. As of 2015, the company produces more than 400 thousand tonnes of processed potato products per year. They produce mainly frozen French fries, though they produce smaller amounts of other specialty frozen products. Retail sales account for more than half of their total production, with most of the remainder being sold to the food service sector. The company sells their used cooking oil to external companies for biodiesel production, and peels from potatoes are turned into livestock feed (Agristo BV, 2019; Agristo BV, 2017; Carmen, 2014).

Aviko is a Dutch company founded in 1962 by potato growers in the Achterhoek, which is now owned by Royal Cosun, which also owns processing companies that deal with other agricultural products, such as sugar beets. Aviko processes about 1.6 million tonnes of potatoes annually, and is the fourth largest producer of potato products in the world (the second in Europe). It has 5 locations in the Netherlands in Oostrum/Venray, Cuijk, Warffum, Lomm, and Steenderen, where it produces potato flakes as well as frozen, chilled, fresh and precooked potato products. Its dried potato product business is held by a subsidiary called Aviko Rixona. Aviko also has production facilities across Europe and around the world. Globally, Aviko processes 1,7 million tonnes of potatoes per year, and supplies about 24% of the European potato product market. Biogas is produced from wastewater treatment in Lomm and Steenderen (operated off-site by another company, and biogas sold back to Aviko) (Aviko Potato, 2019; Boerderij.nl, 2019) (Waterstromen, 2020a; Waterstromen, 2020b).

Farm Frites is a potato processing company with headquarters and a production facility in Oudenhoorn, Zuid Holland. The company was established in 1971 and is family-owned. It has six other production facilities worldwide, with a total processing capacity of 1,3 million tonnes per year, and exports to 80 countries. According to its Sustainability Report, about 5% of FarmFrites energy consumption is from renewable sources, and it aims to install a solar farm nearby to supply solar electricity (FarmFrites, 2018; NRC.nl, 2019).

LambWeston Meijer is the result of a merger between Lamb Weston from the US, and Meijer from the Netherlands, and is a subsidiary of the larger company LambWeston Meijer Holdings. It is the world's second largest producer of frozen potato products, processing 6.3 million tonnes of potatoes annually. Its parent company, Lamb Weston Meijer Holdings has 24 factories worldwide, of which 6 are in Europe. Its factories in Kruiningen (also company headquarters), Bergen op Zoom, Oosterbierum, and Broekhuizenvorst (acquired from Oerlemans Foods in 2017), along with 2 other European factories in Austria and England, have a total capacity of 890 kilotonnes/year, and turnover of €780 million. LambWeston Meijer processes 1.7 million tonnes of potatoes per year, and 300 kiloonnes of potato byproducts are used as animal feed. The company has a target of 30% reduction in energy intensity compared to 2008 by 2020. Of their total energy consumption of about 3.8 PJ in 2018 in primary energy terms, about 3.6% came from renewable fuels. Biogas is produced as a byproduct of the water treatment process on site, which is either used as fuel for boilers or sold to third parties. The Kruiningen plant will begin selling waste heat from the process to a third party in FY2019, where it will be used for a drying process for onions (LambWeston, 2019b; LambWeston, 2019c; LambWeston, 2019d).

McCain Foods, a Canadian company, is the world's largest producer of frozen potato products, and also produces other prepared foods and frozen vegetables. McCain has 55 factories in 12 countries around the world. It processed 6.5 million tonnes of potatoes into end products in 2016. McCain opened its first facility in the Netherlands in 1972, and now has 3, in Lelystad, Lewedorp, and Wezep. The Wezep facility was part of CêlaVita, which McCain took over in 2012. According to the company's sustainability report, more than half of their production lines globally produce biogas from their wastewater via anaerobic digestion. The biogas is then used to generate electricity in a gas engine (McCain, 2019a; McCain, 2019b). The Wezep facility recovers residual heat for use at a local swimming pool (Biind.nl, 2018).

Peka Kroef was founded in the province of North Brabant in 1970 as a family business, and now has factories in Odiliapeel, Venray, and Asten. The company focuses mainly on chilled, parboiled packaged potato products, and has about 325 employees. Peka Kroef purchases steam from a nearby biomass boiler unit owned by Attero, fueled mainly by wood chips. The 10.2 tonnes per hour of steam is used for steam peeling and blanching of potatoes. Biogas is also produced from PekaKroef potato byproducts in the water treatment process, which is then used in auxiliary boilers and burners on site, along with the use of residual process heat to preheat incoming air and boiler feed water (Peka Kroef, 2019a; Peka Kroef, 2019b) (Attero, 2017).

PepsiCo Nederland has 630 employees in the Netherlands, and is a subsidiary of PepsiCo. They have 3 production facilities in the Netherlands, one of which produces potato chips for the brand Lays, in Broek op Langedijk. The others manufacture food products for Quaker (Rotterdam) and Duyvis (Zaandam). PepsiCo, the parent company, owns 22 food and beverage brands worldwide, sold in more than 200 countries, with more than 260 thousand employees globally. PepsiCo processes more than 1 million tonnes of potatoes in Europe (PepsiCo, 2019; PepsiCo, 2017).

The above descriptions are not exhaustive, and are intended only to give a general view of the potato processing sector in the Netherlands. Other companies are also active in the sector that have not been described here. Estimates in this report of energy consumption and CO_2 emissions aim to cover the full scope of the potato processing sector as defined above.

2 Processes for potato processing

Though the potato processing sector produces over 100, diverse products, there are some common steps in the production chain that take place in many of the sector's plants which can be analyzed from the perspective of sector-wide reductions in energy consumption and CO_2 emissions.

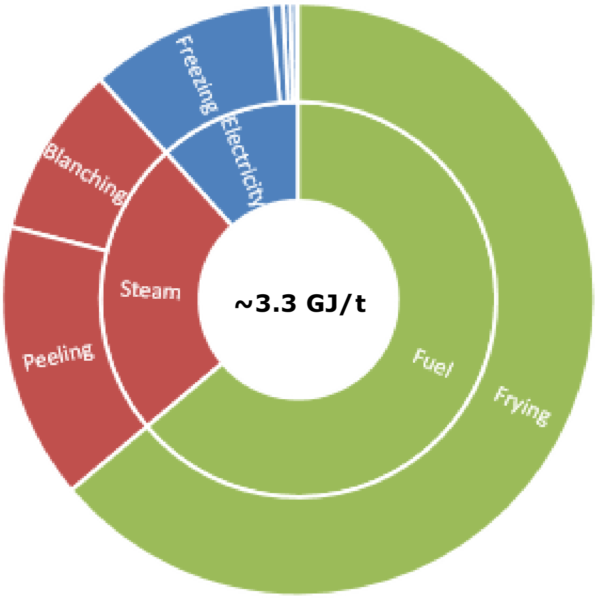
The potato processing sector transforms fresh, raw potatoes into preserved final products. These products can be frozen or unfrozen, cooked or uncooked, and in a variety of forms from French fries and crisps to flour or flakes, for which energy intensity of production varies significantly.[2] Frozen processed potato products (mainly French fries) account for the vast majority of the sector's production; in 2017, these were 84% of the reported production from the sector (CBS 2019).

In a typical potato processing plant producing frozen French fries, the potatoes come in as raw products and are consequently: graded and sorted; washed; peeled; washed; cut; blanched; fried; cooled; frozen; and packaged. The production lines are continuous, though typically the equipment is modular and may in some cases be provided by different suppliers. The freezing, frying, peeling and blanching processes are by far the most energy-intensive steps. The typical energy consumption per unit of frozen French fries is shown below, and fuel directly used in burners at the frying step consume by far more energy than any other process in the production line. Oil turnover, or the rate at which frying oil is replaced with fresh oil, is an important factor in determining how long continuous operation can continue. The total frying oil content is a key determining factor in both the oil turnover rate and the energy consumption (Lucinschi & van den Bovenkamp, 2020).

---

[2] This report defines the potato processing sector as the PRODCOM sector 1031 (NACE Rev 2), "Potatoes; processed and preserved."

Figure 2.1. Typical final energy consumption per tonne of frozen potato product produced in the Netherlands



Source: Adapted from Walker et al., 2018; Masanet et al., 2008; and Rijksdienst voor Ondernemend Nederland, 2016.

Notes: Values from the above sources have been combined to better represent the state of the Dutch potato processing sector in 2017 and the most common processes, and scaled based on primary energy consumption data reported to RVO as part of the Meerjarenafspraken energie-efficiënte (MJA3) programme since 2008. Values in literature for potato processing can vary significantly; for example, Walker et al. (2018) finds a value of about 4.8 GJ/tonne frozen French fries, before scaling to the Dutch primary energy values.

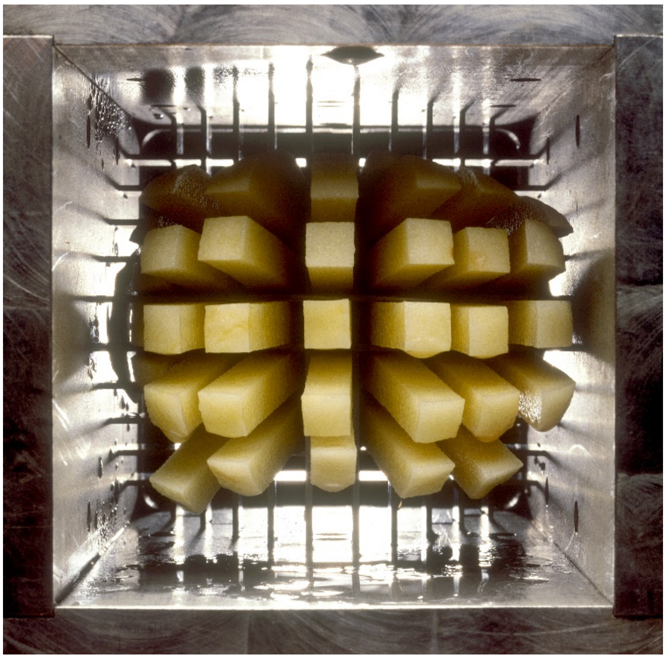
Grading and sorting are the processes by which damaged or unsuitable potatoes are removed from the processing stream, and remaining potatoes are sorted by size, color or other characteristics desired for different products. The larger potatoes are typically used for crisps and French fries, while smaller potatoes can be used for other products such as potato flakes. While in developing countries, this is still typically done manually, in the Netherlands, this is now typically either automated or aided by screen graders, belt sorters, vibrating screens, or optical sorters, or some combination of those. Optical sorting equipment is becoming more prevalent and allowing for increasingly detailed sorting. This process can occur before or after washing. Aviko's Steenderen facility, for example, uses optical sorting integrated at several places in their line (Masanet, et al., 2008) (Walker, et al., 2018) (Orehov, 2019) (TOMRA, 2013).

Washing and cleaning refer to the removal of contaminants from the raw potatoes, such as dirt, stones, insects, leaves, and stems, before further processing. For potatoes, this is typically done in several steps, though the requirements depend on the incoming product. This may also include sanitizing and anti-microbial detergents. This can also be combined with transport to the next step in the process, via water flumes that carry potatoes through channels (Masanet, et al., 2008) (Walker, et al., 2018).

Peeling is the process by which the outer skin of the potato is removed. There are a number of common peeling methods; each aiming to remove the skin without wasting too much of the potato. The most common method, steam peeling, involves exposing potatoes to high pressure steam at about 180°C-200°C, then releasing the pressure causing the peels to detach. Mechanical peeling (knife peeling) involves rotating blades pressed against vegetables (or the inverse). Abrasion peeling, where rotating abrasive rollers rub the skin off of the potatoes, is also sometimes used. (Clark, Jung, & Lamsal, 2014)

Each has advantages and disadvantages based on the characteristics of the raw material and the final product, and can also be used in other food processing sectors. There are tradeoffs between different processes in terms of investment cost, water and energy use, and product quality. For example, wet caustic peeling can reduce water and energy use compared to steam peeling, but the chemicals contaminate waste water and solid waste, creating constraints on their reuse. Steam peeling is the most common and considered to be the state of the art; most major producers of French fries use steam peeling. Steam peeling consumes about 150 to 430 kJ steam per kg of potato input, while mechanical peeling uses about 14 kJ electricity per kg of potato input.[3] The peels, along with other trimmings not used for final products, are typically sold for animal feed. In 2016, an estimated 1.4 million tonnes of potato peel and trimmings were sold for animal feed production. (Somsen, 2004) (Masanet, et al., 2008) (Walker, et al., 2018) (Wageningen University & Research, 2018).

Figure 2.1. French fry slicing at Steenderen



Source: Vereniging voor de Aardappelverwerkende Industrie (VAVI), 2020.

Cutting or slicing reduces the size of the potatoes and gives them the shape of the final product. The process depends on the desired final product shape. For French fries, this is typically done using water knife cutting, where potatoes are pumped at high speed through sharp metal grids that cut the potato, tuned to the particular potato size (shown below in Figure 2.1). Different blades and configurations can produce different shapes, such as very thin slices for crisps, and serrated blades for crisps with ridges. In the production of potato flakes, potatoes are also cut using a water knife prior to cooking, and flakes are formed in the drum dryer (described below) after cooking. More complex shapes sometimes require either multiple knife arrays, or specific mechanical cutting equipment designed for the final product needs. The electricity consumption of the process can range from 0.4 kWh/tonne product to 7.2 kWh/tonne product, depending on product type and requirements (Masanet, et al., 2008) (Orehov, 2019) (Walker, et al., 2018).

---

[3] These values are for the peeling process step only, and do not include overall impact based on differences in material losses.

Sorting to ensure potatoes have the desired size and shape occurs after slicing. Depending on the product, this can be carried out using a number of technologies, for example: optical sorters use cameras, lasers, and other optical technologies to find and remove foreign objects, and potatoes with discoloration and other visual deviations, length sorters (either vibrating or optical) separate French fries by length, potato sorters sort peeled potatoes by diameter using conical rollers, and sliver removers with gaps between rollers allow small pieces to fall through. This is often a mechanical process driven by electric motors (Masanet, et al., 2008) (Walker, et al., 2018).

Blanching is briefly exposing the prepared potatoes to a high temperature, via a bath of hot water, for a short period of time. The purpose is not to cook the potatoes, but rather to reduce enzyme and bacterial activity that might degrade the quality of the product's appearance, flavour or odour. This step can also reduce the volume of the product (depending on the product shape and characteristics) through the release of water and gases inside the potato, which can make the subsequent steps more efficient. Typical blanching temperatures for crisps are between 65°C and 95°C, while for French fries the temperatures are around 60°C to 85°C. (Joint Research Centre, 2018) (Masanet, et al., 2008) (Walker, et al., 2018) (Xiao, Pan, & et al., 2017).

Frying is the main cooking process for processed potato products, where blanched potato products are cooked in oil. First potatoes are dried to remove excess moisture, to preserve the life of the frying oil as well as for the consistency of the product. Pre-drying and frying are typically a continuous process, where products move on a conveyor belt through a bath of vegetable oil at around 200°C, remaining in the bath from around 30 seconds to several minutes. For French fries, frying temperatures range from about 160°C to 175°C, and the frying time depends on the final product (partially or completely fried). For crisps, frying temperatures range from 160°C to 190°C, and cooking times are typically between 1,5 and 3 minutes. Fried products leave the fryer and excess oil is removed and typically reused in the fryer. The fried products are then salted or seasoned as they move over a belt. (Joint Research Centre, 2018). The frying oil can be heated using electricity, steam, or direct fuel combustion; energy consumption is around 0.8 to 2.8 MJ per kilogram fried potato product, depending on the product characteristics (Masanet, et al., 2008) (Walker, et al., 2018). This can account for up to 80% of total energy consumption for potato chips.

Heat recovery from the fryer is possible and already implemented in many production lines. This process entails separating water vapor from evaporated oil, and using the latent heat of that water for preheating in other process steps (of water for blanching or of drying air, for example). This can reduce thermal energy consumption by 23% (van Loon, 2005).
Cooling refers to the cooling of products after cooking, for chilled final products, as well as the cold storage of chilled and frozen products prior to shipping. Energy consumption for cooling depends on a variety of factors, including ambient temperature, product temperature, size of cooling equipment, product size, and length of cooling. However, this is typically not a very energy-intensive step of the process, using on average just 3% of the total electricity consumption of the process for processed potato products (Masanet, et al., 2008) (Walker, et al., 2018).

Freezing, which preserves pre-cooked products, requires cooling the product to a low temperature, anywhere from -15°C to -40°C. Freezing must take place quickly to avoid product damage. The Aviko facility in Lomm, for example, can freeze up to 20 tonnes of French fries per hour in two freezing lines (Engie, 2016). This requires a significant amount of electricity, estimated at around 80 to 280 kWh per tonne of frozen product (Joint Research Centre, 2018). This is typically done using mechanical freezing, where products are exposed to a blast of low-temperature air as they move on a conveyer belt. This is commonly carried out in a freezing tunnel, with zones that pre-cool, refrigerate and freeze the product as it moves through the tunnel. This allows the product to be frozen quickly, avoiding damage and agglomeration. While other vegetables and fruits may be frozen before or after packaging, pre-cooked potato products are typically frozen before packaging. This step applies to only the frozen processed potato products, which made up about 84% of the Dutch production in 2017, up from 61% in 2008 (Centraal Bureau voor de Statistiek, 2019b) (Masanet, et al., 2008) (Walker, et al., 2018) (van Loon, 2005).

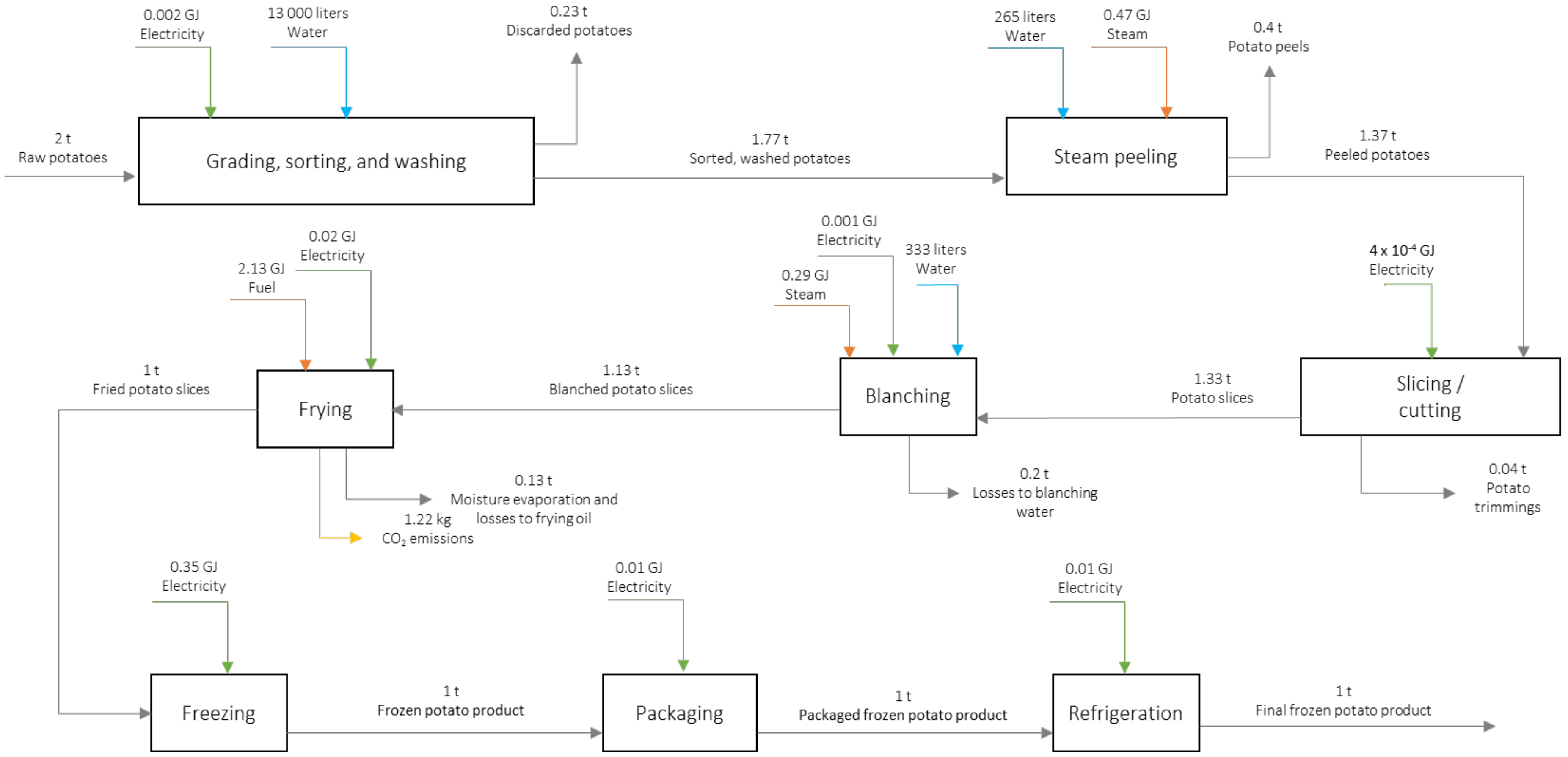
Drum drying is the process by which cooked potatoes are transformed into flakes. The cooked potatoes are heated with steam in a drum, and the potatoes dry while a rotating screw conveyer forms the flakes. Unwanted materials, such as potato peel or potato that is too hard, collects at the bottom of the drum to be removed (Kiremko Food Processing Equipment, 2019). This process uses a significant amount of thermal energy, about 1.7 to 3.0 GJ/tonne potato input. Because of the evaporation of most of the moisture content of the potatoes, the yields for this step are quite low, around 20% on a mass basis. (Walker et al 2018)

Packaging also requires just a small share of the total electricity consumption per tonne of product, also around 3%. These processes, which are typically automated, can use a variety of equipment to package potato products in bags or boxes, pack shipping boxes, and create pallets for bulk shipping. This equipment can include electric motors and compressed air actuators, among others (Masanet, et al., 2008).

Water treatment is an important part of the process, as waste from the potatoes enters the used water from washing and peeling. In some facilities, during water treatment, biogas is produced via anaerobic digestion from the organic waste in the untreated water.

Electricity and steam can be supplied via the electricity grid and heat networks or from on-site energy **utilities**, such as natural gas boilers, biogas boilers or a CHP unit in the case of larger producers.

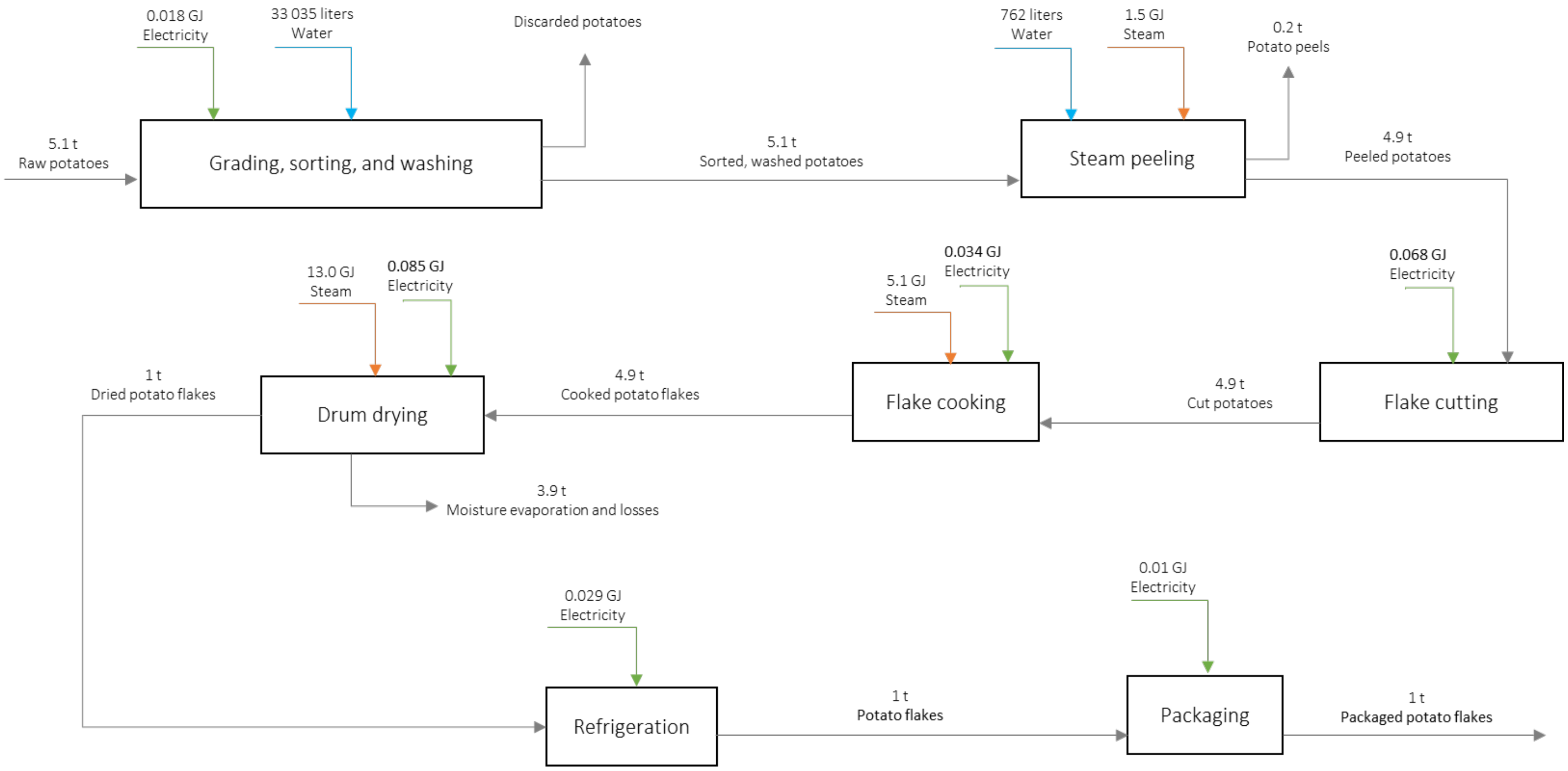
Figure 2.2. Process flow diagram for 1 tonne frozen potato product



Notes: Mass of potato products excludes packaging. It is assumed that chilled potato products processing consumes the same amount of energy, minus the freezing energy use, and that crisps production excludes both freezing and refrigeration. For the purposes of the estimates made in the report, steam is assumed to be provided by a gas boiler with 90% efficiency, and the sector is assumed to use 4% biogas in their fuel needs, based on the most recent reporting to RVO.

Sources: Adapted from Walker, et al. 2018, Masanet, et al. 2008, and Rijksdienst voor Ondernemend Nederland, 2016.

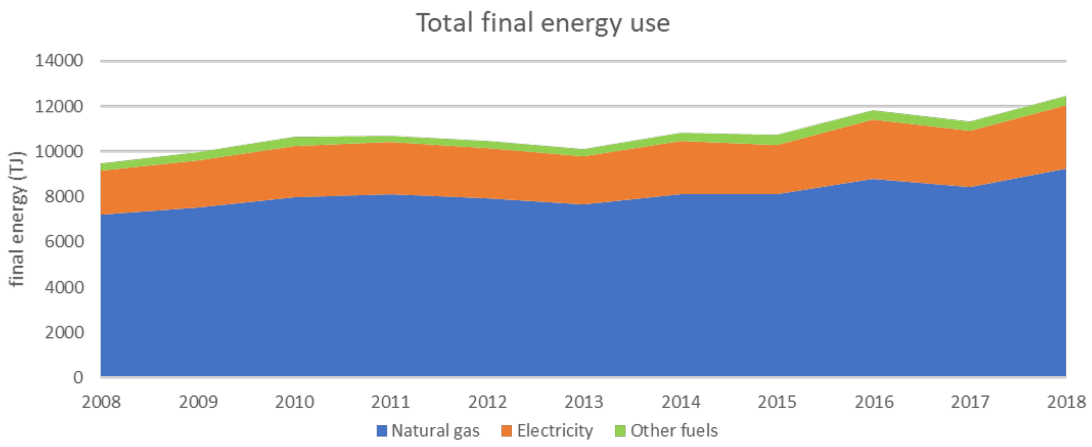
Figure 2.3. Process flow diagram for 1 tonne potato flakes



Notes: Mass of potato products excludes packaging. Here steam peeling is shown, but mechanical peeling is also sometimes used in Dutch potato processing facilities, and energy intensities of those facilities has been adjusted in the overall calculations. For the purposes of the estimates made in the report, steam is assumed to be provided by a gas boiler with 90% efficiency. No estimates were available of discarded potato mass, but some losses can occur at the grading and sorting steps.
Sources: Adapted from Walker, et al. 2018, Masanet, et al. 2008, and Rijksdienst voor Ondernemend Nederland, 2016.

Total final energy consumption and related CO_2 emissions for the potato processing sector have been estimated based on a 2018 life cycle assessment for several food processing sectors (Walker, et al., 2018) and a 2008 study of the United States' fruit and vegetable processing industry (Masanet, et al., 2008), normalized to account for energy efficiency reporting to the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO) as part of the Meerjarenafspraken energie-efficiënte (MJA3) programme since 2008, in combination with production statistics from the Centraal Bureau voor de Statistiek (CBS), the potato processing sector association (Vereniging voor de Aardappelverwerkende Industrie, VAVI), and reported emissions under the EU ETS.

Figure 2.3. Final energy consumption in the Dutch potato processing sector



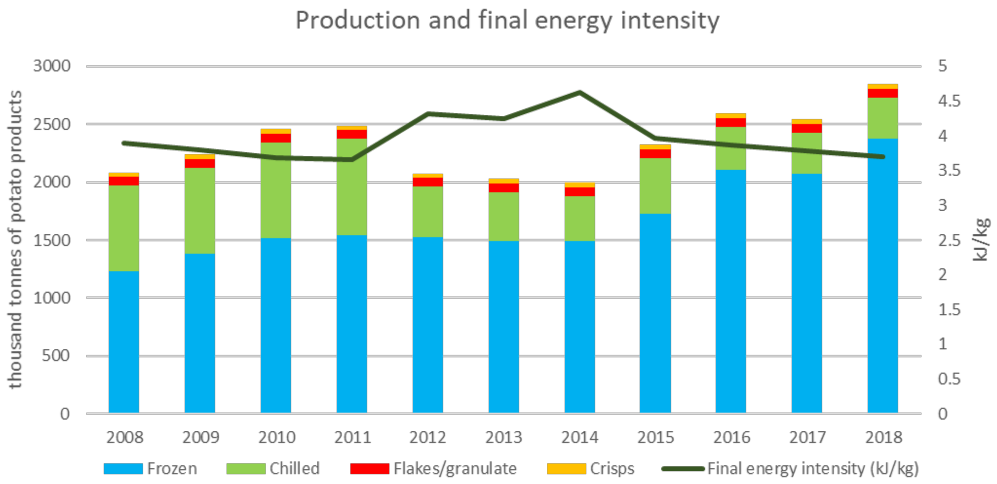
Source: Calculations based on Walker et al., 2018, Masanet et al., 2008, Rijksdienst voor Ondernemend Nederland, 2016, and Centraal Bureau voor de Statistiek, 2019b.

Despite significant electricity use in the sector, particularly for freezing, more than 80% of the energy used for a typical frozen processed potato product comes from natural gas (slightly lower in primary energy terms). According to the 2015 MJA sector report for the potato processing industry, the total input in 2015 in primary energy terms of renewable energy was 377 TJ, or about 4% of the total primary energy supplied to the sector. The major renewable energy measures that have been taken in the sector are use of biogas, purchasing steam from a biomass plant, and producing biomass from waste products of the sector (Rijksdienst voor Ondernemend Nederland, 2016).

In the years since the earliest available production statistics in 2008, production has fluctuated between about 2 million tonnes and 2.75 million tonnes of process potato products. The sector has become significantly more energy efficient over time, as reported in the voluntary agreements programme, having improved its efficiency more than 25% since 2005 in primary energy terms, through a combination of process efficiency, chain efficiency, and generation of sustainable energy sources (Rijksdienst voor Ondernemend Nederland, 2019a). The final energy intensity per tonne of processed potato product trended downward from 2008 to 2011 and 2015 to 2018, as did CO_2 intensity per tonne of product. From 2011 to 2015, however, the efficiency of the sector decreased partly due to the poor quality of the domestic potato harvests, leading to lower yields as more potatoes were required to be processed per tonne of pre-baked potato product (PotatoPro.com, 2011). Comparing total processed potatoes and national production of processed potato products, the ratio of tonnes of potatoes input to the sector to final potato products dropped dramatically from 2011 to 2012, from 0.72 to 0.58, and has gradually recovered to near 2010 levels by 2018 (0.71) (Vereniging voor de Aardappelverwerkende Industrie (VAVI), 2019b) (Nederlandse Aardappel Organisatie, 2019) (Centraal Bureau voor de Statistiek, 2019b). In dry years, such as 2018, the potato harvest can produce smaller potatoes than usual, which can be problematic and decrease efficiency for potato processors in the following year (FreshPlaza.com, 2018).

In the past five years, production increased steadily, and over the past decade the share of frozen potato products, which require additional energy use compared to other preserved potato products (such as crisps or chilled processed potatoes), climbed consistently. Despite these trends, final energy intensity and CO_2 intensity per kilogram of processed potato output declined.

Figure 2.4. Production of processed potato products and overall final energy intensity



Source: Author estimates based on Walker et al., 2018, Masanet et al., 2008, Rijksdienst voor Ondernemend Nederland, 2016 and Centraal Bureau voor de Statistiek, 2019b.

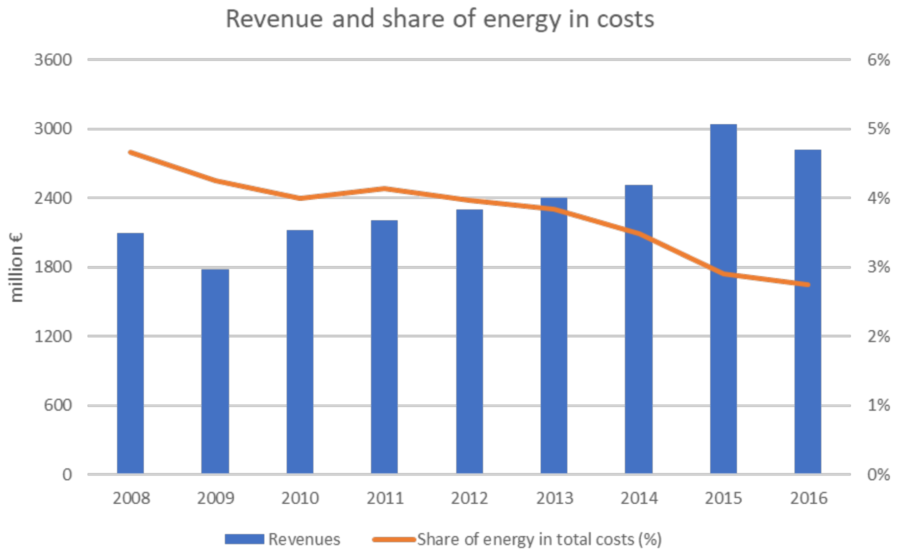
Under the Meerjarenafspraken energie-efficiënte (MJA) programme, the participating companies across various industrial sectors have set a target to collectively reach energy savings of 30% by 2020 in primary energy terms compared to 2005 (Rijksdienst voor Ondernemend Nederland, 2019a)[4]. The fifteen participating companies from the potato processing sector use about 4% of the total primary energy of all MJA3 participants, and have improved their energy efficiency by about 27% since 2005.

As process efficiency has improved over time, the share of energy costs in the sector's total costs has steadily decreased, while the sector's revenue has been on a steady growth trend since 2008. While price fluctuations in potatoes, energy, and other inputs play a role in these trends, making it difficult to draw conclusions from these figures, it is clear that energy costs play an important role in the sector's total costs.

---

[4] Energy savings are calculated based on decomposition analysis, excluding volume effects.

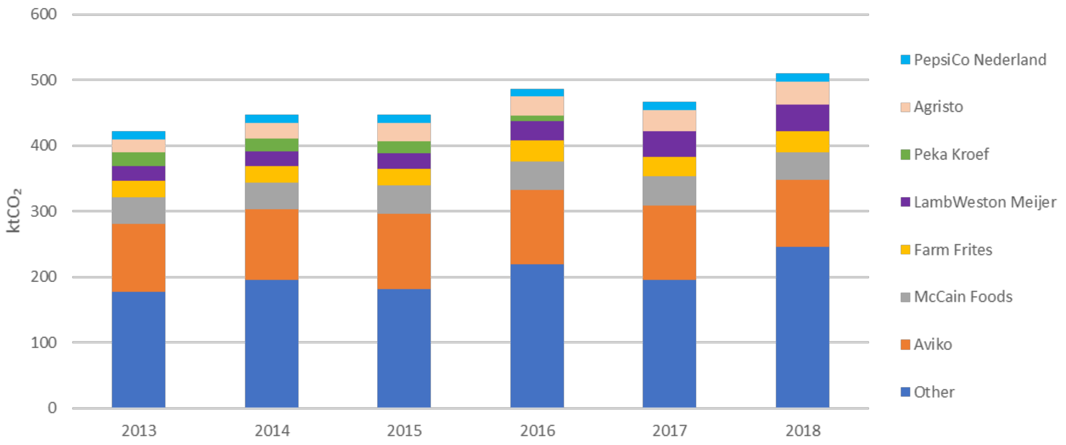
Figure 2.5. Revenue of potato processing sector in the Netherlands, and share of energy costs in total costs



Source: Calculations based on Walker et al., 2018, Masanet et al., 2008, Rijksdienst voor Ondernemend Nederland, 2016 and Centraal Bureau voor de Statistiek, 2019b.

The Dutch potato processing industry reached an estimated 418 $ktCO_2$ in 2017, of which 271 $ktCO_2$ were reported by the companies shown below under the EU ETS. Reported CO_2 emissions under the EU ETS have remained nearly flat since 2015. It is difficult to assess the sector's progress toward decarbonization based on reported emissions alone, as facilities may become subject to EU ETS or exempt from it in any of the given years; for example, Agristo B.V. is included from 2013 onward but had not participated in EU ETS before 2013, and Lamb Weston Meijer Oosterbierum continues to operate but is no longer reporting emissions under the trading scheme since 2010. For some companies, not all of their facilities are included in EU ETS, so this may not show the complete picture of their CO_2 emissions. The estimated total for the non-ETS companies is based on reported national production levels and estimated specific energy consumption based on life cycle assessment literature. For 2018, about 460 $ktCO_2$ is estimated.

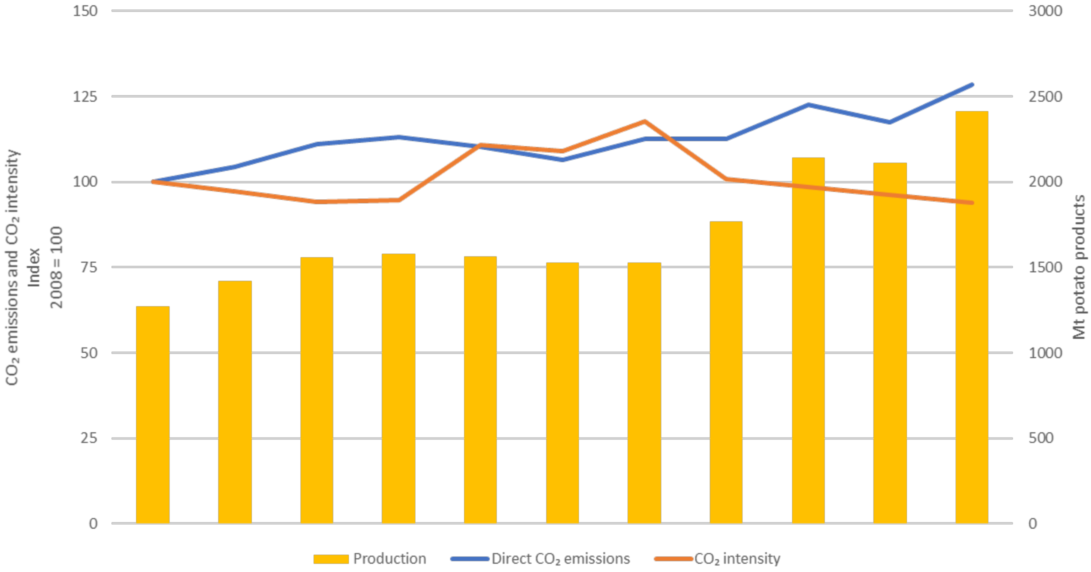
Figure 2.6. CO_2 emissions in the potato processing sector, by company and year



Source: Specific company emissions as reported under EU ETS for 2008 to 2017, and estimation for remainder based on Walker et al., 2018, Masanet et al., 2008, RVO, 2016 and CBS, 2019, and NEa, 2019. Peka Kroef did not report any CO_2 emissions under the EU ETS in 2017, despite continuing operations; this is due to their purchasing of steam from a nearby biomass boiler utility that began operating in 2015, and installing biogas auxiliary boilers in 2016.

The temporary increase in energy intensity from 2011 to 2015 resulted in a similar increase in CO_2 intensity during those years. Though CO_2 intensity is slightly lower per tonne of potato product as it was in 2008, total emissions of CO_2 from the sector, however, continue to grow, as production levels rise. In 2017, the sector is estimated to have emitted about 470 ktCO_2, of which about 60% is covered by the EU ETS. The carbon dioxide emissions from this sector are equivalent to about 1% of the total CO_2 emissions from the Dutch industrial sector in 2017.

Figure 2.7. Production and indexed total direct CO_2 emissions and CO_2 emissions intensity



Source: Calculations based on Walker et al., 2018, Masanet et al., 2008, Rijksdienst voor Ondernemend Nederland, 2016 and Centraal Bureau voor de Statistiek, 2019b.

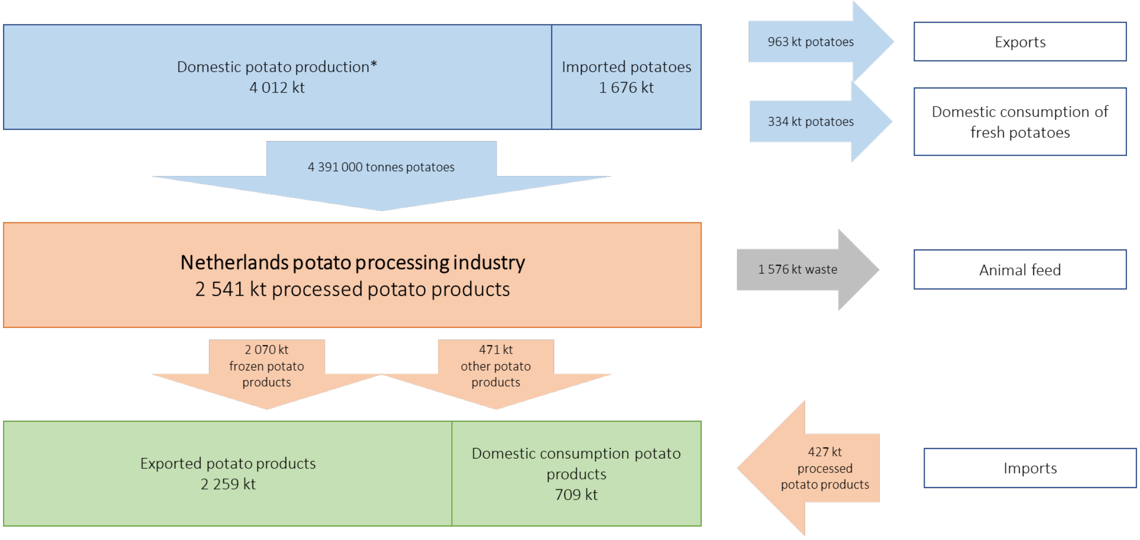
3 Potato use and final products

In 2017, the Dutch potato processing sector processed more than 4.3 million tonnes of potatoes into about 2.5 million tonnes of product. These products included frozen potato products (such as frozen French fries), chilled potato products (such as peeled and precooked whole potatoes), potato flakes (used primarily for further processing, but also into consumer goods such as mashed potato mix), and crisps (also called potato chips; produced in a variety of shapes and flavours). Frozen products are the dominant product, with about 80% of total production in 2017 (see Figure 2.4). These products are produced with both domestically grown potatoes and with imported potatoes. The final products are also traded internationally, in addition to the more than 700 thousand tonnes consumed in the Netherlands.

Global demand for processed potato products, in particular for French fries, is growing at about 3 to 4% per year. The Chinese and Russian markets for potato products has seen strong growth in recent years, with several European companies, including Farm Frites and Lamb Weston Meijer, setting up operations there to meet the demand. Dutch potato processors have steadily increased their capacity both in the Netherlands and abroad, but have had to look increasingly to imported potatoes to feed their processes, as the cultivation of potatoes in the Netherlands is not growing at the same rate. Meanwhile, they also look to material efficiency to reduce the input of potatoes needed. Typically, a factory can cost-effectively purchase potatoes from within about a 150 kilometer radius, though imports from further can occur if necessary to obtain the quality of quantity of potatoes needed to meet demand (Boerderij.nl, 2018).

In 2017, the Netherlands also exported about 963 thousand tonnes of fresh potatoes for consumption (excluding seed and starch potatoes). The majority of these fresh potatoes exported by Dutch producers are traded within the EU; 71% were exported within the EU in 2018 (FAOSTAT, 2019). A large share of the processed potato products produced in the Netherlands are also destined for export: in 2017, more than 2.2 million tonnes were sent abroad (Eurostat, sd). Of those, about 45% remain in the EU, with the most common destination in the EU being the United Kingdom, with more than 400 thousand tonnes, followed by Germany. Exports of frozen potato products to Germany between 2010 and 2017 more than doubled in value terms (Dolman et al, 2019).

Figure 3.1. Production and consumption of processed potato products in the Netherlands



Sources: Baltussen, et al., 2016; Centraal Bureau voor de Statistiek, 2019b; Eurostat, 2019; Nederlandse Aardappel Organisatie, 2019; PotatoPro.com, 2017; Rabobank Group, 2019; Wageningen University & Research, 2018.

Note: Some values are based on reported data, and others are estimated. Seed potatoes and starch potatoes have been excluded from the figure above.

The byproducts of the sector are also used: potato peel waste makes up the largest share of all byproducts from the potato processing sector, and today is typically used as animal feed, though use as fertilizer and for waste incineration can also occur. In 2016, 1.4 million tonnes of potato peel waste were sold for cattle and pig feed (Wageningen University & Research, 2018). Other options for potato peel waste include biogas production based on an anaerobic digestion process (Achinas, Li, Achinas, & Euverink, 2019).

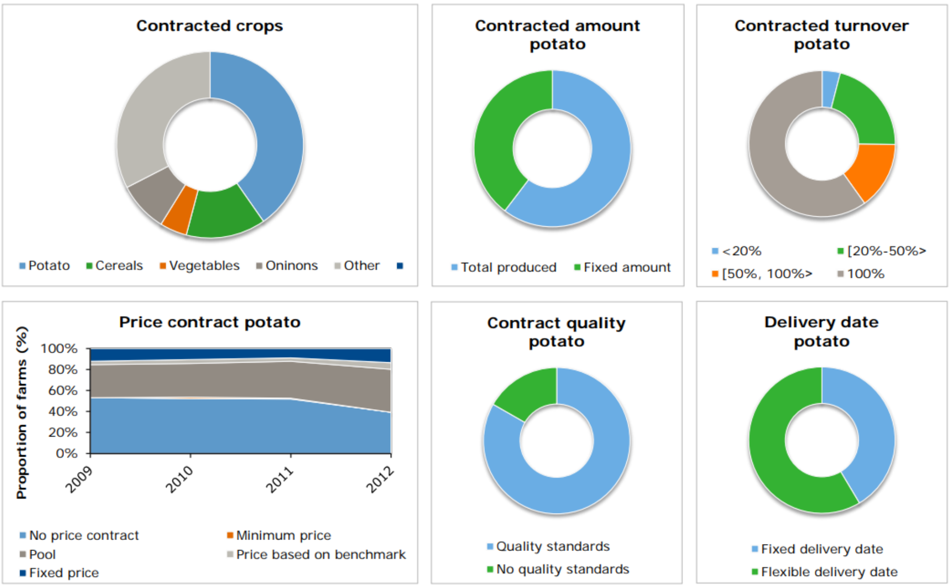
Though the average size of holdings in the Netherlands has been increasing, there are still many potato growers selling to the potato processing sector, and the yields per hectare in the Netherlands are high compared to many other countries, reaching about 44 tonnes per hectare (the global average is about 20 tonnes per hectare) (ABN AMRO, 2008) (RaboBank Group, 2019). In the Netherlands in 2018, nearly 165 thousand hectares were cultivated for potato crops, of which about 76 thousand hectares were for ware potatoes, 44 thousand for seed potatoes, and 45 thousand for starch potatoes (Centraal Bureau voor de Statistiek, 2020b). In total about 16% of the total arable land area of the country is used for potato cultivation, higher than any other EU country. Including seed and starch potatoes, the Netherlands produced more than 6 million tonnes of potatoes in 2018, or almost 12% of the total EU harvest (Eurostat, 2019). Of those, about 3.1 million tonnes were consumption potatoes, 1.3 million were seed potatoes, and 1.5 million were starch potatoes (Centraal Bureau voor de Statistiek, 2020a).

The flows and yields shown above, however, can be quite variable from year to year, based on the quality and price of raw materials. Potato harvests in recent years have been increasingly variable, leading to volatility in availability, prices, and quality of potato harvests.

Several options are available to potato farmers to sell their crops: they can sell these potatoes in direct contracts with purchasers, on the basis of prices and volumes either fully or partially fixed in advance of the harvest; they can sell them directly on the open market in an exchange; or they can sell them into a pool through which a group of growers receive the same average price over the growing season. Futures and options for potatoes are also traded on some commodity markets, including in Amsterdam and Hannover (Boerderij.nl, 2018). The exact ratio between potatoes traded freely on the spot market and those sold via contract is not known, but most potatoes in the Netherlands are sold under contract arrangements. Fixed price contracts have been gaining importance in recent years (Janssens et al., 2011).

Price contracts are common for potato farms, within varying structures, potentially including quality standards, fixed or flexible delivery dates, and fully fixed or benchmark-based pricing. As shown in Figure 3.2, about 50% of farms in the arable farming sector (which includes all crops cultivated on plowed land) have some form of price contract arrangement, higher than in most other agricultural sectors. While data is limited, researchers have found that price contracts limited the volatility of potato prices received by farmers (van Asseldonk and van der Meer, 2016).

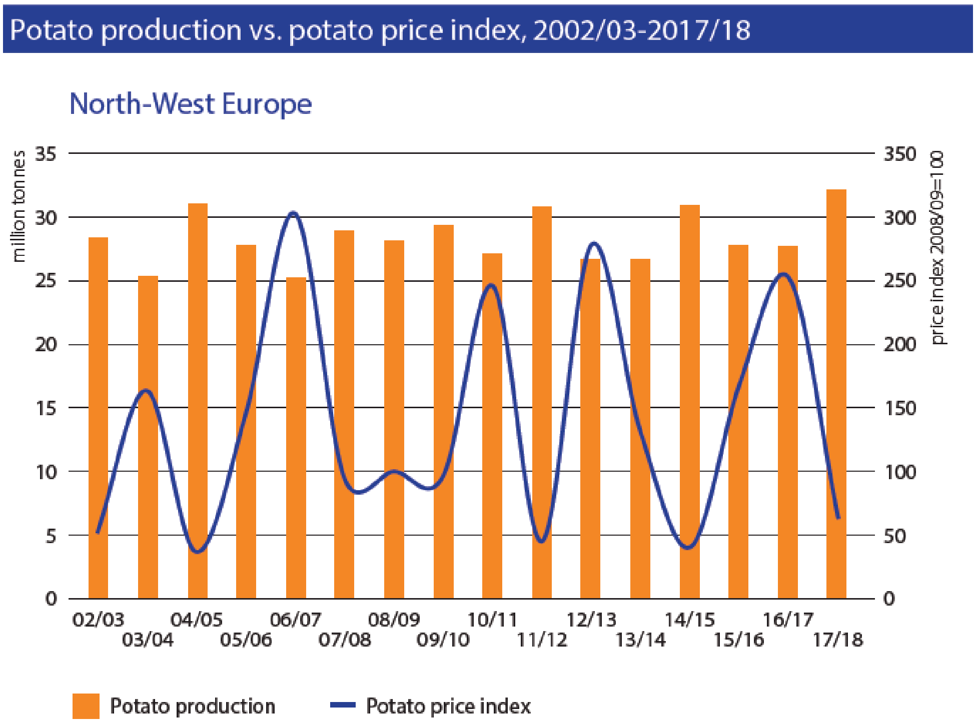
Figure 3.2. Price contracts in arable crop farming in the Netherlands



Source: van Asseldonk and van der Meer, 2016.

Spot price information is made publicly available twice per week via the PotatoNL website, allowing all growers to access price information about transactions made on the stock exchange of 10 product categories of Dutch potatoes (Wageningen University & Research, 2018). Spot prices reached their highest point since 2010 in June 2013, at €34.90 per 100 kg, and their lowest point in September 2014, at €3.00 per 100 kg. Prices are seasonal, generally peaking in the summer months, but can still vary significantly from year to year, and are sensitive to shifts in supply and demand.

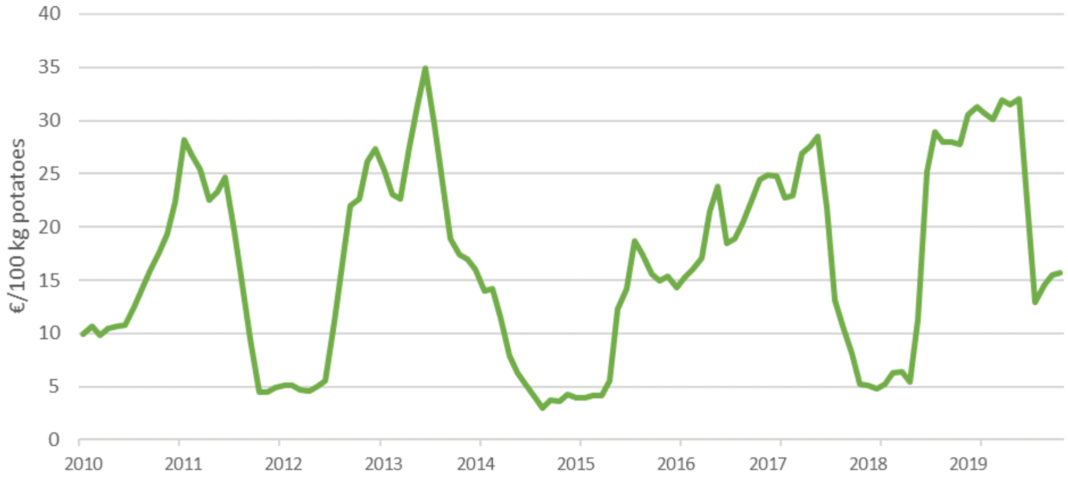
Figure 3.3. Potato production vs. spot price index, North-West Europe



Source: Rabobank Group, 2019.

The volatility of spot prices presents a significant challenge to potato growers and to the entire potato processing supply chain, especially in an economic downturn or supply shock, when either supply or demand differs from expectations. Uncertainty about the cost of the main raw material in this industry would be a barrier to long-term investment. Some potato processors try to mitigate the risk by positioning themselves to be able to import potatoes from other markets; however, potatoes are not typically shipped over long distances due to the risk of spoilage. Many potato processing companies purchase about 70% of their potato needs via fixed-price contracts, about 20% under volume contracts, and the remaining 10% on the spot market, in order to minimize their exposure to price risks. Contracts with growers are typically fixed one year to a year and a half before processing, in order to ensure steady operation of production lines (Janssens et al., 2011). Dutch potato processing companies are also now increasingly opening processing facilities overseas, where they can access local potato supplies and produce final products near where they will be consumed.

Figure 3.4. Potato spot prices in the Netherlands, 1 January 2010 to 1 December 2019



Source: Wageningen University & Research, 2019.

4 Options for decarbonisation

In the potato processing sector, the focus with regards to decarbonization is on resource efficiency, fuel substitution, and CO_2 emissions reduction options. The industry typically looks at sustainability for the complete chain from farmer to consumer, though this report will primarily address options for the potato processing segment; agriculture, transport, and other upstream and downstream emissions are beyond the scope of this report.

Energy efficiency

Peeling

In addition to their reductions in material losses, efficient peelers can also have benefits in terms of energy efficiency. A case study of an efficient steam peeler installed by TOMRA at a potato processing facility in Switzerland claimed the design could reduce energy consumption by up to 25%, while also reducing peel loss, water usage, and maintenance costs (TOMRA, 2014). Efficient steam peelers are the recommended standard in the MJA3 Maatregellijst of energy efficiency options (Rijksdienst voor Ondernemend Nederland, 2019b).

Additionally, steam peelers can also incorporate heat recovery technology, to recover and utilize excess heat leaving the peeler. A brochure from Andritz Gouda claims its “E-condenser” can recover up to 65% of the thermal input to a steam peeler. This refers to a capacity of 35 tonnes of potatoes per hour and results in a payback period between 1 and 3 years (Andritz Gouda, 2019).

Preheating with Pulsed Electric Field technology

Pulsed Electric Field (PEF) technology can replace traditional steam preheating of potatoes, reducing water usage compared to steam preheating by 90%, improving characteristics of potatoes (for example, creating a smoother cutting surface), and reducing energy consumption for preheating by up to 85% (Fauster, et al., 2018) (PotatoPro.com, 2018). Lamb Weston Meijer installed PEF technology to replace its conventional preheating process at one of the lines at its facility in Kruiningen, mainly to reduce water usage (LambWeston, 2019a). It succeeded in reducing fresh water use by 8% and energy use by 5% (PotatoPro.com, 2017).

Blanching

Hot water blanching is the typical, conventional process for reducing enzymatic activity in potatoes. It consumes significant energy and water, and the blanched potatoes must be dried (either with air or with water) afterwards. The waste water from this process also requires significant treatment afterwards to remove nutrients leached from the potatoes as well as any additives (often used to preserve colour and deactivate enzymes). The process can be operated either continuously on a moving belt or in batches, typically in a drum blancher. Currently, most producers do not recover this waste water nor the heat it contains. Its benefits include simplicity and low capital investments. Blanching is used in a variety of fruit and vegetable processing industries, beyond only French fries and crisps, and new technologies are being developed that can deliver similar products more efficiently. Some alternative processes that could reduce energy consumption or CO_2 emissions in this section are discussed below.

Radio frequency or microwave blanching, operating by reversing an electromagnetic field around the material at 1 to 300 MHz or 300 to 3000 MHz respectively, would eliminate the need for hot water, allowing the blanching process to be electrified. Furthermore, microwave heating is rapid, uses less energy than hot water blanching, and reduces processing times. However, its drawbacks include water loss to evaporation, limited penetration depth, non-uniform heating and lack of precise temperature control. Radio frequency heating for drying potato products is already commercialized (Pereira & Vicente, 2010).

Electrical resistance heating (also called ohmic heating or Joule heating) for the blanching step depends on induced electrical currents within the food material to create heat, and would also allow complete electrification of the blanching process. It would require shorting heating times and improve product quality by reducing leaching. This type of blanching could handle large volumes. Like microwave blanching, it can create difficulties in controlling the temperature of the product. Additionally, low frequency electrical resistance heating, which would be most efficient in terms of heat generation, could lead to electrolysis of water creating oxygen and hydrogen, which might lead to unwanted discoloration and emissions. Electrodes corrode when immersed in water, and thus might need to be regularly replaced.

Infrared blanching, operating in the frequency between visible light and microwaves, could have a better energy efficiency, shorter processing time, and larger heat transfer coefficient than conventional blanching. However, its heat penetration into thick substances (such as potato slices) is limited, and thus would need to be used in combination with other heating technologies. Surface discoloration may also be a problem. Infrared blanching could be combined with the use of hot air to mitigate some of these problems.

With funding from the European Union, Aviko has been developing a closed loop blanching process with water and energy benefits. The process would allow the same water to be reused, despite leaching of some potato solids into the water, reducing both water and energy consumption. The process involves converting sugars in the water back into the other organic compounds, so that the water becomes saturated with those compounds and no further potato solids leach out. The company claims this process saves about 94 MJ per tonne of potatoes, through reduced natural gas use to heat water, about a 20 to 25% reduction in primary energy consumption for blanching compared to values in the literature (Walker, Beretta, Sanjuán, & Hellweg, 2018) (Masanet, et al., 2008). The process was first demonstrated in the Aviko plant in Steenderen, and has since been implemented at other Aviko facilities (European Commission, s.d.) (Royal Cosun, s.d.).

The chosen blanching technology will depend on the characteristics of the particular potato, as well as the final product's dimensions and desired characteristics. Hybrid technologies are also being researched to try to find more optimal, resource efficient blanching options (Xiao, Pan, & et al., 2017).

Multi-flow injection in frying section

Multi-flow injection – injecting hot frying oil into the fryer at varying points through the section – can improve reduce energy consumption for frying by reducing temperature fluctuations in the oil and improving heat transfer efficiency. The multiple injection points begin at the inlet of the fryer and are spaced throughout the length of the fryer depending on the temperature profile requirements for the final product, allowing more precise temperature control for a uniform temperature, which optimizes energy use and ensures standard product quality (Lucinschi & van den Bovenkamp, 2020).

Heat recovery from fryer

After the frying section, waste heat and frying oil vapours can be recovered for preheating potatoes before drying and blanching. Heat recovery from the water evaporated from the fryer as well as the frying oil vapours is already common practice in the sector, and can reduce thermal energy use by 23% compared to processing without this heat recovery equipment (van Loon, 2005). A detailed study modelling energy flows in the frying section of a typical crisps processing line found an overall efficiency of 70%, and indicated further improvements in heat recovery and process efficiency were possible (Wu, Jouhara, Tassou, & Karayiannis, 2010).

Efficient chillers and freezers
Energy efficient refrigeration and freezing in the production process for frozen French fries and other frozen potato products can be a source of significant electricity savings. While electricity consumption for cooling does not necessarily lead to direct, on-site CO_2 emissions, efficient use of electricity can enable decarbonization of the energy system as a whole. Typically, potato processing requires air blast freezing (also known as mechanical freezing), rather than cryogenic freezing, because of the characteristics of the products. However, within this category, a range of technology options are available; choice of compressors, condensers, and defrost equipment can have considerable effects on efficiency.

New refrigerants, including ammonia, have also been implemented in recent years, after the Montreal Protocol and EU legislation aimed at phasing out ozone-depleting substances such as CFCs and HCFCs as refrigerants. Their substitutes include HFCs, which were added to the list of refrigerants to phase out under the Kigali Amendment to the Montreal Protocol in 2019, in order to contribute to the avoidance of emissions of these fluorinated gases (also called F-gases, a category of potent greenhouse gases).

In addition to selecting the most energy efficient equipment, optimizing operating parameters of these systems is an important element of energy efficiency. For example, freezing time decreases as air speed in the freezer increases, but additional power is required to drive the fans, and those fans generate residual heat. Finding the optimal air speed and freezing time in terms of energy consumption can have significant energy efficiency benefits, and is highly dependent on site-specific constraints (such as floor space) and product characteristics (such as shape and size). (New food magazine, 2014)

One company, GEA Group, claims to be able to reduce energy requirements significantly (up to 30%) by optimizing the air temperature control system and refrigerant circulation, and using ammonia as a refrigerant. GEA also proposes integrated heat pumps that can recirculate excess heat removed from the freezer to other steps in the process, leading to reduced steam and natural gas consumption. (GEA Engineering, 2017)

It is difficult to assess the current level of efficiency of freezers in the Dutch potato processing sector, given the diversity of products and lack of site-specific data, but efficient cooling and freezing technology and good operating and maintenance practices can reduce the overall energy intensity of the process. Switching to refrigerants with low or no global warming potential, such as ammonia, would also reduce the climate impact of the sector.

Material efficiency
Material efficiency and upgrading the large residual flows from potato processing has been a key area of action for the Dutch potato processing sector. To date those efforts have focused primarily on reducing losses in the process and upgrading the waste for productive uses, such as energy or animal feed. Some key factors that influence yield of final products in this sector include quality of raw potatoes, contamination by foreign substances such as dirt, wood or foliage, and stones in the raw potato feed, unwanted losses in the sorting process, unwanted mass loss in the peeling process, unwanted mass loss during cutting and slicing, spillage or breakage during transport in the process, moisture and diffusion losses, losses

during production disturbances such as maintenance (scheduled or unscheduled) (Somsen, 2004). Some options to reduce unwanted material loss are described below, as well as options to valorize material waste for productive purposes.

Peeling

Peeling typically results in the largest share of unwanted mass losses in the production processes of potato products such as French fries. Some of this has to do with the quality of potatoes; those with smoother skin will result in lower peeling losses, while rougher potatoes lose more mass in the peeling process. Steam peeling, the most common peeling process, has higher unwanted yield losses than other types of peeling, but is commonly used because of its low capital investment needs and maintenance requirements. According to a 2004 study, the steam peeling process removes about six times the thickness of the potato skin (Somsen, 2004). Depending on the final product specifications, quality of raw materials, and optimization of processes, abrasion peeling using rotating equipment with abrasive surfaces to rub off the skin of the potatoes, and caustic peeling in a caustic chemical bath, can also be material efficient options. However, there are tradeoffs to consider. Water use, water treatment needs, energy consumption, ability to use solid waste for other purposes, and investment cost are also factors in the choice of peeling technology.

Steam peeling is the standard in today’s potato processing sector. While it is difficult to quantify the benefits of material efficiency without site-level analysis, as the yields of potato processing are highly dependent on final product characteristics and raw potato quality and size, there is some room for efficiency improvement on average, either through optimization or process substitution. Somsen et al. (2004) found that in factory conditions, steam peeling results in about 8% unwanted material losses on a mass basis.

Sorting

Efficient sorting prior to peeling can reduce material losses as well, both to avoid losses of usable raw material and to avoid energy use for processing of defective products. Some optical sorting equipment can collect information that allows facilities to more accurately assess the necessary peeling time, reducing losses from “overpeeling.” Based on feedback from these intelligent optical sorters, steam consumption can be optimized, resulting in more efficient use of both material and energy. The earlier in the process rejected potatoes are removed, the less energy will be used processing them.

Blanching

Steam blanching, as opposed to traditional hot water blanching (discussed in more detail above) can improve product quality and yield for potatoes, by preventing water absorption by the potatoes as well as leaching of nutrients from potatoes into the hot water bath. This process is considered to be relatively inexpensive. However, it can require additional blanching time, and energy requirements for steam are higher than for hot water.

Biogas production

Biogas can be produced from potato waste produced in the process, via simple and commercially available technology. This is already taking place in some facilities in the Netherlands and around the world. Wastewater from the Peka Kroef facility in Odiliapeel is used to produce 2 million cubic metres of biogas annually via a UASB (upflow anaerobic sludge blanket) anaerobic digestion process (Colsen, sd). This could be implemented in any potato processing plant using the wastewater flows from the process which contain leached potato solids. Additionally, solid potato waste, such as potato peels, could also be used to produce biofuels. This has been successfully implemented in the potato processing sector at a plant in Canada (PotatoPro.com, 2018) (Achinas, Li, Achinas, & Euverink, 2019). The characteristics of a UASB digester with CHP are given in Table 4.1.

Table 4.1. Biogas production with UASB digestion and integrated CHP

Technology characteristics	
CAPEX (€/kWe)	3000-7000
Fixed OPEX (€/kWe/year)	16-70
Technical lifetime (years)	20
Typical reactor tank volume (m^3)	636
Typical reactor tank capacity (kW)	380
TRL	9

Note: UASB digester reactor tanks can be combined in a modular way to create a larger unit. Nursanto 2017 refers to a unit located in Norway with 4 reactor tanks, for a total capacity of about 1500 kW.

Sources: Carlini, et al., 2017; Nursanto, 2017.

Biogas produced from excess potato waste (not used for animal feed) can be used directly, with designated equipment that can handle higher levels of impurities and higher CO_2 content. It can also be upgraded to biomethane (by removing H_2S and CO_2) to allow it to be used in place of natural gas without retrofits to burners and other equipment, and without efficiency losses or corrosion problems. Typical characteristics of water scrubbing for biogas upgrading are given in Table 4.2, below.

Table 4.2. Biogas upgrading with water scrubbing technology

Technology characteristics	
CAPEX (€/MW biomethane capacity)	302
Fixed OPEX (€/MW/year)	11
Technical lifetime (years)	15
Efficiency (% biomethane output to biogas input)	99
Electricity consumption (MJ electricity/MJ biomethane output)	0.05-0.06
Typical size (MW)	6
TRL	9

Source: Danish Energy Agency (Energistyrelsen), 2017.

Utilization of waste streams

Potato peel waste and starch have potential uses as alternative material input or feedstock in other sectors such as medicine/pharmaceuticals, paper and glue, and plastics. Specific applications and costs will depend on nearby potential consumers and their process and material needs. Many of the peels and trimmings from potato processors are currently used as animal feed in the agricultural sector; alternative uses for these products would need to be considered from a systems perspective to ensure optimal use of limited resources.

Fuel substitution

Biogas and green gas

Natural gas provides about 85% of the final energy consumption in the potato processing sector today, and is directly used for burners in the frying section of processing lines. Utilities, either onsite or centralized, which generate electricity and steam for use in the sector, also largely use natural gas. This gas can be replaced with renewable sources leading to reductions in both direct and indirect CO_2 emissions. Biogas, a methane-rich gas from biogenic sources, is the most promising option, as it can be directly substituted for natural gas in these processes. Upgraded biogas with the same characteristics as methane (CH_4), often called green gas, may be used directly without major retrofits to equipment, while biogas with higher CO_2 contents and impurities will require more treatment or retrofits, as some elements present in biogas can cause clogs in boilers and chimneys, or corrosion of equipment.

The most common biogas production routes are via anaerobic digestion of bio-feedstocks, or gasification of woody biomass. Depending on the level of purity, biogas is then either used directly as a fuel, or desulphurised before combustion. Biogas can also be upgraded (becoming green gas) to remove CO_2 and other impurities. Anaerobic digestion is particularly relevant to the potato processing sector because of the availability of bio-based byproducts. A biogas boiler, to replace the conventional natural gas boiler, is described in Table 4.3. Biogas could also be used in burners for the frying section of potato processing plants, but because of the site-specific nature of this equipment, insufficient cost data is available publicly to present in this report.

Table 4.3. Condensing biogas steam boiler

Technology characteristics	
CAPEX (€/kW$_{th}$)	60
Fixed OPEX (€/kW$_{th}$/year)	2
Technical lifetime (years)	25
Efficiency (%)	94% (LHV)
Typical size (MW$_{th}$)	20 (0.5-50)
TRL	9

Note: It is assumed that biogas from anaerobic digestion will have an H_2S content of <500 ppm, within the tolerance of a typical boiler of <1000 ppm. Depending on the characteristics of the biogas, further desulphurisation methods can be applied, either on-site or by an external biogas producer. Costs for desulphurisation range from about €0.11 to €0.21 per Nm^3 biogas treated (assuming H_2S levels of 600 ppm).

Sources: Danish Energy Agency (Energistyrelsen), 2020; Swedish Gas Technology Centre Ltd (SGC), 2012; Danish Technological Institute, 2014.

Solid biomass could also potentially provide the needed fuel for steam generation, though it would be more difficult to apply a solid fuel for direct fuel use in burners. Depending on availability, sustainability, and price, the potato processing companies could install biomass pellet boilers to meet their steam needs, as described in Table 4.4.

Table 4.4. Solid biomass steam boiler

Technology characteristics	
CAPEX (€/kW$_{th}$ output)	518
Fixed OPEX (€/kW$_{th}$/year)	40
Technical lifetime (years)	15
Efficiency (%)	90
Typical size (MW$_{th}$)	5-25
TRL	9

Source: Uslu, 2018.

Electrification

Electrifying heat demand could provide large direct CO_2 emissions savings in the potato processing sector. The sector's indirect (Scope 2) CO_2 emissions would depend on the fuel sources used to produce electricity for the grid (or in dedicated off-site utilities). A transition to low-carbon and renewable energy sources in the power sector would allow the potato processing sector to phase out Scope 2 emissions as well as direct CO_2 emissions.

One of the key electrification options is to use heat pumps, which transfer heat from a lower temperature source to higher temperature sink. As part of the Horizon2020 project "Hot chips", Tocircle Power Systems is testing the integration of evaporative compression technology (ECT) which utilizes waste heat from the fryer, with a 1.5 MW high temperature heat pump, together producing steam at 180°C with a COP of 4. The scaled up 5 MW version will be tested in the frying section of an Aviko French fry production line in Belgium in 2020, aiming to bring the technology from its current TRL level of 6 to TRL 9. This technology could also have applications for potato chips and other frying processes in the food manufacturing sector, as well as other industrial processes operating at temperatures above 100°C (European Commission, 2019) (The Explorer).

Mechanical vapour recompression (described in Table 4.5) could allow potato processing facilities to generate high pressure steam to substitute for traditional natural gas boilers or natural gas CHP, particularly for process steps at temperatures below 100°C, such as preheating and blanching, by utilizing low-pressure steam exhaust from industrial processes to be recompressed into a higher pressure and higher temperature for process use. This would compete with other options for excess heat utilization, such as heat recovery from frying oil vapours via combustion (see above). Steam recompression is commercially available, and can typically be economically applied on sites with a minimum capacity of about one tonne of steam per hour.

Table 4.5. Mechanical vapour recompression

Technology characteristics	
CAPEX (€/kW$_{th}$)	260-600
Fixed OPEX (€/kW$_{th}$/year)	3-24
Technical lifetime (years)	10
Coefficient of performance (COP)	3.5-10
Typical size (MW$_{th}$)	8-20
TRL	9

Source: Marsidi, 2018a.

Heat pumps using the reverse Rankine cycle to produce heat up to 90°C are commercially available, and can be adapted to higher temperatures up to 120°C-140°C. However, higher temperature heat pumps (Table 4.6) are at a low level of technology development today, but continuing research and development could reduce the cost and performance of the equipment by 2050. A pilot-scale high temperature heat pump has been installed in the Netherlands at a paper mill, and could be applicable in a number of other industries using steam below 200°C. Heat needs for potato processing up to 140°C – potentially pre-heating of materials and blanching – could be met with high-temperature heat pumps.

Table 4.6. Industrial high-temperature heat pumps

Technology characteristics	
CAPEX (€/kW$_{th}$)	400-5000
Fixed OPEX (€/kW$_{th}$/year)	60
Technical lifetime (years)	15
Coefficient of performance (COP)	4
Typical size (MW$_{th}$)	<20
TRL	5

Source: Marsidi, 2018b.

Currently, steam boilers using natural gas as a fuel are typically used to supply steam for the potato processing sector. Electric boilers (Table 4.7) could meet the steam needs of the potato processing industry while reducing natural gas consumption and therefore direct CO_2 emissions. Electric boilers would be able to provide the high temperature high pressure steam at the same quality as a conventional gas boiler, and are commercially available today.

Table 4.7. Industrial electric boiler

Technology characteristics	
CAPEX (€/kW_{th})	150-190[5]
Fixed OPEX (€/kW_{th}/year)	1.1
Technical lifetime (years)	15
Efficiency (%)	95-99.9%
Typical size (MW_{th})	0.6-70
TRL	9

Source: Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017; Marsidi, 2019.

Geothermal

Steam at the temperatures required by the potato processing sector can also be produced via Ultra Deep Geothermal (UDG) energy projects. This involves drilling wells of at least 4000 m depth, to extract hot water at temperatures around 120-140°C. A typical project consists of two wells drilled into limestone. Cool water is injected through one well, where it is heated by geothermal energy at the bottom of the well. The heated water is pumped out under pressure through the second well, and its heat transferred via a heat exchanger before reinjection. Degassing is also needed to remove natural gas and oil that comes out of the well along with the water.

Several companies in other sectors of Dutch industry, including dairy and paper, are investigating potential UDG applications, but there are currently no UDG facilities in operation in the Netherlands. Researchers have estimated that geothermal could feasibly provide about 50 percent of the process energy requirements for a frozen French fry production line (fryers and freezers would likely require an additional energy source) (Dickson and Fanelli, 2013).

Table 4.8 Ultradeep geothermal energy station

Technology characteristics	
Capacity (MW_{th})	17
Load hours (h/yr)	7000
Electricity use (TJ/yr)	21.8
CAPEX (k€/kW_{th})	2.5[6]
Fixed O&M (EUR/kW_{th}/yr)	107

Source: in 't Groen, de Vries, Mijnlieff and Smekens, 2019.

Hydrogen

Another option for decarbonizing the steam and fuel needs of the potato processing industry could be to use hydrogen boilers. Hydrogen production would need to be decarbonized – produced via electrolysis of water with carbon-free renewable electricity, rather than via steam methane reforming as it is today, or with the addition of carbon capture and storage technology - for this to be considered a sustainable option. Hydrogen can also be produced via biomass gasification, but this process is less efficient, and given the potential future competition for sustainable biomass resources, is a less likely option than the others. The availability of affordable hydrogen from low-carbon sources is a constraint today, but potential cost decreases in electrolyzers and advances in development of hydrogen technology and infrastructure could make this solution more feasible in the future.

---

[5] Typical cost of an electric boiler is EUR 60/KWe, and the rest of the investment costs stem from the grid connection. These costs are highly site-specific. (Berenschot, CE Delft, ISPT, 2015).

[6] Does not include costs of geological research and permits. Costs of a heat distribution network of a length of 0.5 km included.

A 100% hydrogen fuel can be used to replace natural gas, in conjunction with dedicated hydrogen boilers (Table 4.8), or retrofits to burners to account for differences in combustion, particularly flame speed. Increased NO_x emissions with the combustion of pure hydrogen, however, might require oxyfuel combustion (combustion using pure oxygen rather than air), increasing operating costs for purchased hydrogen or energy consumption for air separation units. Alternatively, hydrogen could be used in existing industrial natural gas boilers can be blended with natural gas, within the prescribed limits of existing equipment; this depends on site-specific constraints and operation practices.

Table 4.9 Hydrogen boilers

Technology characteristics	
CAPEX (€/kWth)	120-160
Fixed OPEX (€/kW/year)	15-20
Technical lifetime (years)	20
Efficiency (%)	90%
Typical size (MWth)	20
TRL	9

Sources: Gigler & Weeda, 2019; Noothout, de Beer, Quant & Blok, 2019; van Berkel & Hernandez, 2018.

CCS/CCU

Carbon capture, utilization and storage (CCUS) cannot be economically applied to the direct CO_2 emissions from the potato processing sector, as the direct combustion of natural gas in the processes creates emissions streams that are too diffuse and small-scale. Low concentrations of CO_2 in flue gases from burners means that additional equipment for separation would be needed; and the fact that each individual source of CO_2 emissions is quite small makes those investments quite high relative to their benefit. There may also be space and logistical constraints related to the specific applications of natural gas burners in the frying step of the potato processing line. For utilities, post-combustion CO_2 capture could potentially be applied, and potentially combined with streams from smaller point sources at the facility (depending on physical constraints of the site) from direct fuel combustion in the process.

Captured CO_2 would then need to be transported either by pipeline or by truck, to a storage site, most likely offshore in the North Sea. This would be least costly for sites located near the coast, and especially those located near a port where other carbon capture and storage projects may be implemented. As potato processing facilities are often located near sources of potatoes (see map in Chapter 1), rather than in industrial clusters, the possibilities for a joint project are also quite limited. The largest potato processing facilities in the Netherlands have a capacity of about 400 kt potato products per year, equivalent to roughly 65 ktCO_2 per year, which makes it unlikely to find an economical carbon capture project unless they are located next to an open-access CO_2 pipeline project or are part of an industrial cluster consortium building CO_2 infrastructure.

5 Discussion

In the short term, the potato processing sector can reduce emissions by becoming more efficient with material and energy, and by utilizing existing waste streams for energy purposes. These options do not require major changes to the product or major retrofits to existing process equipment; these can be implemented via improved practices, minor retrofits, or add-on equipment. The main options to be reduce emissions in the short term are efficient boilers for steam supply, efficient peelers to reduce losses and steam consumption, and heat recovery from fryers, where not already implemented. These options do not have any major technological barriers, as the technologies are mature, and can often be retrofitted to existing production lines without replacement of other equipment. The expansion of the SDE subsidy scheme to include more CO_2 emissions reductions options could also improve the business case for these options, particularly for waste heat recovery and heat pumps.

In the longer term, in order to fully decarbonize, the potato processing sector will need to eliminate the use of natural gas, its main source of CO_2 emissions. Because carbon capture and storage is unlikely to play a role in the potato processing sector, this could be done via electrification or substitution with biofuels or hydrogen. Biofuels would require the least extensive process changes, and technology options that are more mature and economical today. However, given the need for decarbonization across the industrial sector as well as the rest of the economy, the competition for sustainable biomass resources could lead to shortage and high prices in the future. The potato processing sector, as it uses mainly low- to medium-temperature heat, may choose to implement other decarbonization options, unlike industrial sectors which have more limited options due to the need for high-temperature heat or feedstock.

From a technical perspective, the use of hydrogen to generate steam and to heat frying oil would not be very difficult, requiring retrofits to equipment and storage facilities; the main challenge facing hydrogen as a decarbonization option in the potato processing sector is cost. The future supply of low-cost green hydrogen is uncertain, and from a societal perspective, it may be used for higher value applications than for low- to medium-temperature process heat, such as for difficult to decarbonize transport fuels or as feedstock. With a sufficiently low-cost supply of hydrogen from renewable sources or from natural gas with CCS, and sufficient infrastructure development, hydrogen use as fuel in the Dutch potato processing sector could be possible.

The electrification of the potato processing sector, particularly the electrification of process heat, today seems to be a more expensive option, but future developments in electricity generation technologies and electricity markets, both in the Netherlands and in Europe, will determine future costs for electricity. A broader reliance on electricity in industry would require more sophisticated regulatory tools and technical capacity in order to manage a larger and potentially more integrated and complex grid. Nonetheless, falling costs for renewable power generation technologies, as well as electrified end-use technologies, such as heat pumps, can quickly change the picture and improve the prospects for electrification of industry.

Dutch infrastructure planning will play an important role in facilitating industrial decarbonization, and the effects on sectors like potato processing should be considered in developing such plans. The potato processing sector can also take a proactive role in decarbonizing, and communicating its preferred options to policymakers.

Furthermore, factors outside the energy system could also impact this sector. For example, societal eating habits are not static – they are culturally specific and continuously evolve over time. As society adapts to climate change, this could have a significant impact on the foods that Dutch consumers eat and the supply chains through which they reach those consumers, as well as consumers in the rest of the world who purchase imported potato products. Eating more locally produced fresh foods could have a potentially large impact on this sector, as many frozen processed potato products are exported globally from the Netherlands. Decreased demand for fried products, and a shift toward raw, boiled or baked potatoes would significantly reduce the energy use of the sector. Similarly, a shift away from frozen food toward fresh foods would also likely reduce energy consumption. However, today processed potato consumption, particularly French fry consumption, is on the rise globally without signs of slowing. A shift away from meat consumption to vegetarian and vegan foods may also lead to increasing potato demand. Global trade in food products is also generally on an upward trajectory, though it is affected by broad economic trends, exchange rates, and shifting trade policies and agreements.

Weather patterns that make northern Europe suitable for growing potatoes may change over time as well. As the global climate warms, more extreme temperature fluctuations, particularly temperatures above 30°C becoming more common in European summer, will have a negative effect on potato crops, as well as changing patterns of rainfall. Adaptation to these changes may include new varieties of potatoes, shifting growing seasons, and shifting areas of cultivation. It is difficult to say how the Dutch potato processing sector in particular will be affected, but the long term outlook for this sector will surely be affected by climate change and the degree to which we succeed in mitigating its effects.

The full decarbonization of the Dutch potato processing sector, based on the assessed technology options, would therefore require significant investments in new and upgraded technology. As with other industrial sectors, creating incentives in the short term to invest in long-term solutions would be beneficial not only in order to accelerate mitigation action but also in order to avoid lock-in effects. Industrial equipment typically has a long lifetime; a typical potato production line has about a 20 year lifetime. Decarbonization efforts will be most cost-effective if they align with investment cycles, to take advantage of windows of opportunity before 2050.

References

ABN AMRO. (2008). Aardappelsector: Toonaangevend door kwaliteit. Retrieved from https://www.abnamro.nl/nl/images/Generiek/PDFs/020_Zakelijk/02_Sectoren/Agrarisch/Aardappelsector_-_Toonaangevend_door_kwaliteit_versie_2.pdf

Achinas, S., Li, Y., Achinas, V., & Euverink, G. J. (2019). Biogas Potential from the Anaerobic Digestion of Potato Peels: Process Performance and Kinetics Evaluation. Energies.

AGF.nl. (2016, January 28). Omzet Farm Frites stabiel in 2014. Retrieved from https://www.agf.nl/article/136240/omzet-farm-frites-stabiel-in-2014/

Agristo BV. (2017). Sustainability Report 2017. Retrieved from https://drive.google.com/file/d/1BybU5uTmTMUq7yYzOAD078XAS0lhtQvJ/view

Agristo BV. (2019). Over Agristo. Retrieved from https://www.agristo.com/en/corporate-over-agristo

Andritz Gouda. (2019). Steam Peeler E-Condenser. Retrieved from http://www.andritzgouda.com/uploads/docs/GMF_leaflet_Steam_Peeler_E_Condenser_blauw_ENGindd.pdf

Arcadis Nederland BV. (2015). "Memo: Vormvrije m.e.r.-beoordeling Aviko te Steenderen." Retrieved from https://repository.officiele-overheidspublicaties.nl/externebijlagen/exb-2015-22676/1/Bijlage/exb-2015-22676.pdf.

Attero. (2017, September 12). Netwerkbijeenkomst over groene STOOM voor industrie: Biomassa energiecentrale Odiliapeel. Retrieved from www.biowkk.eu: http://www.biowkk.eu/wp-content/uploads/2017/05/Attero-Biomassa-energiecentrale-Odiliapeel.pdf

Aviko (2016). Toelichting Revisie milieuvergunning. Retrieved from https://planmonitoring.ruimtelijkinzichtlimburg.nl/ruimtelijke-plannen/default.asp?mode=download&folder=ATKKFF2%5C4RN673IR%5C&file=Overig-Toelichtingrevisiemilieuvergunning.pdf.

Aviko. (2019). Frequently Asked Questions. Retrieved from https://corporate.aviko.com/en/faq

Aviko Potato. (2019). Avikogroep en Cosun. Retrieved from https://www.avikopotato.nl/nl/over-aviko-potato/avikogroup-en-cosun

Baltussen, W., Dolman, M., Hoste, R., Janssens, S., Reijs, J., & Smit, A. (2016). Grondstofefficiëntie in de zuivel-, varkensvlees-, aardappel- en suikerketen. Wageningen: LEI Wageningen UR. Retrieved from http://edepot.wur.nl/368103

Berenschot, Energy Matters, CE Delft, Industrial Energy Experts. (2017). *Electrification in the Dutch process industry*. Retrieved from https://www.ce.nl/publicaties/download/2278.

Berenschot, CE Delft, ISPT. (2015). *Power to products*. Retrieved from https://www.topsectorenergie.nl/sites/default/files/uploads/Eindrapport_Power_to_Products_externe_link.pdf.

Biind.nl. (2018, December 18). De aardappelen van CelaVita verwarmen het zwembad van Wezep. Retrieved from https://www.biind.nl/artikel/de-aardappelen-van-celavita-verwarmen-het-zwembad-van-wezep

Boerderij.nl. (2018, June 6). Amper meer frites ondanks forse investeringen. Retrieved from https://www.boerderij.nl/Akkerbouw/Achtergrond/2018/6/Amper-meer-frites-ondanks-forse-investeringen-292639E/

Boerderij.nl. (2019, April 30). Aviko moet blijven investeren in groeimarkt. Retrieved from https://www.boerderij.nl/Akkerbouw/Achtergrond/2019/4/Aviko-moet-blijven-investeren-in-groeimarkt-420761E/

capitalmind. (2019, January). Growth continues for the Dutch food industry: the top-10 achieve more than 10 percent revenue growth. Retrieved from https://capitalmind.com/wp-content/uploads/2019/01/Capitalmind-Fab-40-Food-2015-Final.pdf

Carlini, M., Mosconi, E. M., Castellucci, S., & et al. (2017). An Economical Evaluation of Anaerobic Digestion Plants Fed with Organic Agro-Industrial Waste. Energies. Retrieved from https://www.mdpi.com/1996-1073/10/8/1165

Carmen, W. (2014, April 24). Material Handling Forum. Retrieved from https://www.erim.eur.nl/fileadmin/centre_content/material_handling_forum/Seminar_24_april_2014/Presentations/Agristo_-_Belang_duurzaamheid_en_uitgevoerde_acties.pdf

Centraal Bureau voor de Statistiek. (2019a). StatLine: Bedrijfsleven; arbeids- en financiele gegevens, per branche, SBI 2008. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81156ned/table?fromstatweb

Centraal Bureau voor de Statistiek. (2019b). Verkopen; industriële producten naar productgroep (ProdCom). Retrieved from CBS StatLine: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83115NED/table?ts=1565705732223

Centraal Bureau voor de Statistiek. (2020a). Akkerbouw en tuinbouw. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/navigatieScherm/thema?themaNr=35990.

Centraal Bureau voor de Statistiek (2020b). Landbouw; nationale rekeningen. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/navigatieScherm/thema?themaNr=83105.

Clark, S., Jung, S., & Lamsal, B. (2014). Food Processing: Principles and Applications. Chichester: John Wiley & Sons.

Colsen. (sd). PekaKroef partnership. Retrieved from https://www.colsen.nl/en/projects/pekakroef-partnership

Danish Energy Agency (Energistyrelsen). (2017). Technology data - renewable fuels: technology descriptions and projections for long-term energy system planning. Retrieved from https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

Danish Energy Agency (Energistyrelsen). (2020). Technology data – industrial process heat. Retrieved from https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-industrial-process-heat.

Danish Technological Institute. 2014. Biogas upgrading: Evaluation of methods for H_2S removal. Retrived from https://www.teknologisk.dk/_/media/60599_Biogas%20upgrading.%20Evaluation%20of%20methods%20for%20H2S%20removal.pdf.

de Gelderlander. (2019, June 17). Loonsverhoging van 5,5 procent voor Aviko-personeel. Retrieved from https://www.gelderlander.nl/bronckhorst/loonsverhoging-van-5-5-procent-voor-aviko-personeel~a3936962/

Dickson, M.H. & Fanelli, M. (2013). *Geothermal Energy: Utilization and Technology*. Routledge.

Dolman, M.A., Jukema, G.D., Ramaekers, P. (eds.) (2019). *De Nederlandse landbouwexport in 2018 in breder perspectief.* Wageningen, Wageningen Economic Research, Rapport 2019-001.

Engie. (2016, March). Aardappelverwerker Aviko: Dagelijks 480 ton friet invriezen. Retrieved from https://koudetechniek.engie-services.nl/referenties/detail/dagelijks-20-ton-friet-per-uur-invriezen/

European Commission. (2019). Waste heat recovery for industrial heat intensive processes: Periodic Reporting for period 1 - Hot chips. Retrieved from https://cordis.europa.eu/project/rcn/215864/reporting/en

European Commission. (sd). CLB - Demonstration of a closed loop blanching system for the potato processing industry. Opgeroepen op October 1, 2019, van http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=2864&docType=pdf

Eurostat. (2019, September 23). Manufactured goods (PRODCOM). Retrieved from https://ec.europa.eu/eurostat/web/prodcom/data/database

Eurostat. (2019, May 20). The EU potato sector. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php/The_EU_potato_sector_-_statistics_on_production,_prices_and_trade

Eurostat. (sd). PRODCOM - statistics by product. Opgeroepen op September 23, 2019, van https://ec.europa.eu/eurostat/web/prodcom/data/database

FAOSTAT. (2019). Crops and livestock products - data. Opgeroepen op 09 23, 2019, van http://www.fao.org/faostat/en/#data/TP

FarmFrites. (2016). Sustainability report 2016. Retrieved from http://sustainabilityreport.farmfrites.com/

FarmFrites. (2018). Sustainability Report 2018. Opgeroepen op September 6, 2019, van https://sustainabilityreport2018.farmfrites.com/2/

Fauster, T., Schlossnikl, D., Rath, F., Ostermeier, R., Teufel, F., Toepfl, S., & Jaeger, H. (2018). Impact of pulsed electric field (PEF) pretreatment on process performance of industrial French fries production. Journal of Food Engineering, 16-22.

FreshPlaza.com. (2018, August 23). Dutch harvest 2018: small potatoes require better sorting. Retrieved from https://www.freshplaza.com/article/2199981/dutch-harvest-2018-small-potatoes-require-better-sorting/

GEA Engineering. (2017, January 27). Efficient refrigeration; a foundation for sustainable food production. Retrieved from https://www.gea.com/en/technology-talks/efficient-refrigeration-a-foundation-for-sustainable-food-production.jsp

Gigler, J., & Weeda, M. (2019). Topsector Energie. Retrieved from "Outlines of Hydrogen Roadmap": https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/20180514%20Roadmap%20Hydrogen%20TKI%20Nieuw%20Gas%20May%202018.pdf

In 't Groen, B., De Vries, C., Mijnlieff, H., & Smekens, K. (2019). CONCEPTADVIES SDE++ 2020 Geothermie. Retrieved from https://www.pbl.nl/sites/default/files/downloads/pbl-2019-conceptadvies-sde-plus-plus-2020-geothermie_3692.pdf.

Jannsens, S.R.M., Hoste, R., Baltussen, W.H.M., and Bunte, F.H.J. (2011). *Handelsrelaties in de aardappel- en varkenssector: De relatie tussen aanbieder en afnemer.* LEI, Wageningen UR, LEI rapport 2011-077.

Joint Research Centre. (2018). Best Available Techniques (BAT) Reference Document in the Food, Drink and Milk Industries: Final Draft (October 2018). European Commission.

Keijbets, J. (2008). Potato Processing for the Consumer: Developments and Future Challenges. Potato Research, 271-281.

Kiremko Food Processing Equipment. (2019). "Drum dryer (flakes)". Retrieved from Kiremko: https://www.kiremko.com/en_US/subprocessinglines/subprocessitem/40-drum-dryer-flakes.html

LambWeston. (2018). Sustainability Report 2017-2018. Retrieved from https://www.lambweston.eu/sustainability/uploads/file/262/LWM_SustainabillityReport_2018_Summary_UK.pdf

LambWeston. (2019a). Kantoren. Retrieved from https://www.lambweston.eu/nl/offices

LambWeston. (2019b). LambWeston / Meijer completes acquisition potato division Oerlemans Foods. Retrieved from https://www.lambweston.eu/news/lamb-weston-meijer-completes-acquisition-potato-division-oerlemans-foods

LambWeston. (2019c). The Sustainable Seven. Retrieved from https://www.lambweston.eu/sustainability/the-sustainable-seven.html

LambWeston. (sd). Water: The Broader Context. Retrieved from https://www.lambweston.eu/sustainability/the-sustainable-seven/water.html

Lensink, S., & Pisca, I. (2020). Eindadvies basisbedragen SDE++ 2020. Den Haag: Planbureau voor de Leefomgeving. Retrieved from https://www.pbl.nl/sde/publicaties

Lucinschi, V. & van den Bovenkamp, H. (2020). Personal communication, Kuipers.

Marsidi, M. (2018a). Energy.nl. Industrial Mechanical Vapour Recompression (MVR) Technology Factsheet.

Marsidi, M. (2018b). Energy.nl. Industrial high-temperature heat pump Technology Factsheet.

Marsidi, M. (2019). Energy.nl. Retrieved from Industrial electric boiler Technology Factsheet: https://energy.nl/wp-content/uploads/2018/12/Technology-Factsheet-Electric-industrial-boiler-1.pdf

Masanet, E., Worrell, E., Graus, W., & Galitsky, C. (2008). Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry: An ENERGY STAR Guide for Energy and Plant Managers. Lawrence Berkeley National Laboratory.

McCain. (2019a). Our Business & Brands. Retrieved from https://www.mccain.com/about-us/our-business-brands/

McCain. (2019b). Resource Efficient Operations. Retrieved from https://www.mccain.com/sustainability/resource-efficient-operations/

Nederlandse Aardappel Organisatie. (2019, 20 September). Verwerkingcijfers. Retrieved from https://nao.nl/nl/markt/verwerking-cijfers

Nederlandse Emissieautoriteit. (2019). Emissiecijfers ETS. Retrieved from https://www.emissieautoriteit.nl/onderwerpen/rapportages-en-cijfers-ets/emissiecijfers-ets

New food magazine. (2014, October 27). Current advances in food freezing. New food magazine. Opgeroepen op March 16, 2020, van https://www.newfoodmagazine.com/article/15079/current-advances-food-freezing/

Noothout, P., de Beer, J., Quant, M., & Blok, K. (2019). Verkenning uitbreiding SDE+ met industriële opties; Inschatting van subsidie-intensiteit van geselecteerde technologieën en evaluatie van knelpunten. Navigant.

NRC.nl. (2019, April 1). De gemeente, de bewoners en de Patatweg. Retrieved from https://www.nrc.nl/nieuws/2019/04/01/de-gemeente-de-bewoners-en-de-patatweg-a3955242

Nursanto, A. (2017). Design and Cost Evaluation of Anaerobic Bioreactor for Industrial Waste. University of Stavanger. Retrieved from https://pdfs.semanticscholar.org/addc/33c2dbe731d1fa5dfd88db8abbb53df55c57.pdf

Orehov, D. (2019, January 8). Exclusive - Sorting: Going Optical is the Way Forward. Retrieved from PotatoBusiness: https://www.potatobusiness.com/process/exclusive-sorting-going-optical-is-the-way-forward/

Peka Kroef. (2019a). About Peka Kroef. Retrieved from https://www.pekakroef.com/en/about-peka-kroef/peka-kroef/

Peka Kroef. (2019b). Production. Retrieved from https://www.pekakroef.com/en/about-peka-kroef/sustainability-2/production/

PepsiCo. (2017). Sustainability Reporting. Retrieved from https://www.pepsico.com/sustainability/Sustainability-Reporting

PepsiCo. (2019). Ons Bedrijf. Retrieved from http://www.pepsico.nl/ons-bedrijf/pepsico-nederland

Pereira, R., & Vicente, A. (2010). Environmental impact of novel thermal and non-thermal technologies in food processing. Food Research International, 1936-1943.

PotatoPro.com. (2011, August 14). Aardappelindustrie Nederland verwerkt record hoeveelheid aardappelen. Retrieved from https://www.potatopro.com/news/2011/aardappelindustrie-nederland-verwerkt-record-hoeveelheid-aardappelen

PotatoPro.com. (2017, October 31). Potato Production (food) in the Netherlands up 27 percent, exceeds 4 million tonnes. Retrieved from https://www.potatopro.com/news/2017/potato-production-food-netherlands-27-percent-exceeds-4-million-tonnes

PotatoPro.com. (2017, January 22). Sustainability Report: Potato Processor Lamb Weston / Meijer continues to innovate. Retrieved from https://www.potatopro.com/news/2017/sustainability-report-potato-processor-lamb-weston-meijer-continues-innovate

PotatoPro.com. (2018, December 29). Biogas from potato waste cuts greenhouse gas emissions Cavendish Farms French Fry Plant. Retrieved from https://www.potatopro.com/news/2018/biogas-potato-waste-cuts-greenhouse-gas-emissions-cavendish-farms-french-fry-plant

PotatoPro.com. (2018, February 8). Excellent performance in 2017 for Aviko - the potato processing subsidiary of Cosun. Retrieved from https://www.potatopro.com/news/2018/excellent-performance-2017-aviko-potato-processing-subsidiary-cosun

PotatoPro.com. (2018, July 10). Pulsed Electric Field in Potato Processing: Impact on Sustainability. Retrieved from https://www.potatopro.com/news/2018/pulsed-electric-field-potato-processing-impact-sustainability

PotatoPro.com. (2019a). Companies: Aviko. Retrieved from https://www.potatopro.com/companies/aviko

PotatoPro.com. (2019b). Companies: Farm Frites. Retrieved from https://www.potatopro.com/companies/farm-frites

Procesverbeteren.nl. (2015). "Aviko Rixona verbetert tot in de vezels." Retrieved from https://www.procesverbeteren.nl/TPM/Aviko_Rixona_TPM.php.

RaboBank Group. (2019, March). World Potato Map 2019. Retrieved from https://research.rabobank.com/far/en/sectors/regional-food-agri/world_potato_map_2019.html?qsl_reqcnt=1

Rijksdienst voor Ondernemend Nederland. (2013). MJA Sectorrapport 2012: Aardappelverwerkende industrie. Utrecht.

Rijksdienst voor Ondernemend Nederland. (2016). MJA Sectorrapport 2015: Aardappelverwerkende industrie. Utrecht.

Rijksdienst voor Ondernemend Nederland. (2018). Nederlandse lijst van energiedragers en standaard CO2 emissiefactoren, versie januari 2018. Retrieved from https://www.rvo.nl/sites/default/files/2018/03/Nederlandse%20energiedragerlijst%202018.pdf

Rijksdienst voor Ondernemend Nederland. (2019a). Aardappelverwerkende industrie MJA. Opgeroepen op January 3, 2020, van https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-besparen/mja3-mee/stand-van-zaken/resultaten-sector-t/m2017/aardappelverwerkende-industrie-mja

Rijksdienst voor Ondernemend Nederland. (2019b). Maatregellijsten MJA3. Retrieved from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-besparen/mja3-mee/tools/maatregellijsten

Royal Cosun. (sd). Aviko's improved blanching measure. Retrieved from Cosun.com: https://www.cosun.com/getdoc/89385dda-6c07-4e80-a1f0-9b0ec62a80fd/Closed-Loop-Blanching.aspx

Somsen, D. (2004). Production yield analysis in food processing: Applications in the French fries and the poultry-processing industries. Wageningen: Wageningen University and Research. Retrieved from http://edepot.wur.nl/121537

Somsen, D., Capelle, A., & Tramper, J. (2004). Manufacturing of par-fried French-fries: Part 2: Modelling yield efficiency of peeling. Journal of Food Engineering, 199-207.

Swedish Gas Technology Centre Ltd (SGC). 2012. *Basic Data on Biogas*. SGC, Malmö.

The Explorer. (sd). World-class technology for waste heat recovery. Retrieved from https://www.theexplorer.no/solutions/Tocircle-World-class-technology-for-waste-heat-recovery/

TOMRA. (2013, July 9). Succesverhaal Aviko, Nederland. Retrieved from https://www.tomra.com/nl-nl/sorting/food/case-studies/aviko

TOMRA. (2014, November 27). Success Story Kadi, Switzerland. Retrieved from https://www.tomra.com/en/sorting/food/case-studies/kadi

Uslu, A. (2018). Technology Factsheet: Biomass Steam Boiler for Industry > 5 MWth. Energy.nl. Retrieved from https://energy.nl/wp-content/uploads/2019/09/Biomass-steam-boiler-for-industry-more-than-5-MWth.pdf

van Asseldonk, M. and van der Meer, R. (2016). *Coping with price risks on Dutch farms.* LEI, Wageningen UR, LEI Report 2016-054.

van Berkel, A., & Hernandez, J. (2018). Taking the C out of steam. Lux Research.

van der Boom, N. (2019). "Groeiplannen Farm Frites liggen gevoelig." Retrieved from https://www.boerenbusiness.nl/akkerbouw/artikel/10881940/groeiplannen-farm-frites-liggen-gevoelig.

van Loon, W. (2005). Process innovation and quality aspects of French fries. Retrieved from http://edepot.wur.nl/121683

Vereniging voor de Aardappelverwerkende Industrie (VAVI). (2019a). De Nederlandse aardappelverwerkende industrie. Retrieved from https://vavi.nl/nl/de-nederlandse-aardappelverwerking/

Vereniging voor de Aardappelverwerkende Industrie (VAVI). (2019b). Downloads - Verwerkingscijfers. Retrieved from https://vavi.nl/nl/downloads/

Vereniging voor de Aardappelverwerkende Industrie (VAVI). (sd). Beeldbank. Opgeroepen op January 3, 2020, van https://vavi.nl/nl/beeldbank/

Vlam.be. (2019). Agristo NV. Retrieved from https://exporteursdatabank.vlam.be/en/exporter/438/agristo-nv

Wageningen University & Research. (2018). De aardappelketen in beeld. Wageningen University & Research. Retrieved from https://www.agrimatie.nl/PublicatiePage.aspx?subpubID=2525&themaID=3577&sectorID=3534

Wageningen University & Research. (2019, November 20). Prijzen: Prijsontwikkeling consumptieaardappelen en uien. Retrieved from Agrimatie - informatie over de agrosector: https://www.agrimatie.nl/ThemaResultaat.aspx?subpubID=2232&themaID=2263&indicatorID=3155

Walker, C., Beretta, C., Sanjuán, N., & Hellweg, S. (2018). Calculating the enregy and water use in food processing and assessing the resulting impacts. International Journal of Life Cycle Assessment, 824-839.

Wallays, C. (2014), "Agristo – Missie – Visie – Waarden," Material Handling Forum, 24 April 2014. Opgeroepen op June 15, 2020 van https://www.erim.eur.nl/fileadmin/centre_content/material_handling_forum/Seminar_24_april_2014/Presentations/Agristo_-_Belang_duurzaamheid_en_uitgevoerde_acties.pdf.

Waterstromen. (2020a). "AWZI Lomm." Retrieved from https://waterstromen.nl/awzi%20lomm.

Waterstromen. (2020b). "AWZI Olburgen." Retrieved from https://waterstromen.nl/awzi%20olburgen.

Witteveen+Bos. (2015). "Notitie : onderzoek stikstofdepositie." Vergunningaanvraag Aviko Steenderen nieuwe vrieshuis. Retrieved from https://docplayer.nl/26144759-Afbeelding-2-1-locatie-aviko-en-nabijgelegen-natura-2000-gebied-rijntakken.html.

Wu, H., Jouhara, H., Tassou, S., & Karayiannis, T. (2010). Modelling of energy flows in potato crisp frying processes. Applied Energy.

Xiao, H.-W., Pan, Z., & et al. (2017). Recent developments and trends in thermal blanching - A comprehensive review. Information processing in Agriculture, 101-127.

Appendix A

A.1 Methodology for energy intensity estimations

In order to estimate final energy intensity of production in the Dutch potato processing sector, several literature sources were used, and estimates adapted to the Dutch situation. Masanet et al. in the 2008 report, “Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry,” provide bottom-up estimates of energy consumption for several processed fruit and vegetable products, including frozen potato products. Walker et al., in a 2018 article, “Calculating the energy and water use in food processing and assessing the resulting impacts,” also take a life cycle assessment approach to estimate the energy consumption for frozen French fries as well as for potato flakes production. Masanet et al. (2008) base their energy intensity estimates on literature, while Walker et al. use bottom-up calculations based on data from specific facilities.

Walker et al. has been chosen as the main source, as it is more recent and more detailed, and provides estimates for flakes as well as frozen potato products. However, Masanet et al. has also been used for electricity consumption estimates for cooling, freezing, and packaging, where Walker et al. did not include the same level of detail.

Values from these two sources have been combined and transformed to primary energy terms based on a 1.1 factor from steam to natural gas and 2.5 from electricity to primary energy. These values were then scaled on an annual basis to the process efficiency improvements reported in the MJA3 reports published by RVO for the Dutch potato processing sector.

These scaled intensities were then transformed back into final energy terms, providing an overall final energy intensities for the sector for frozen potato products (mainly French fries) and potato flakes. The scaled intensity for frozen potato products was then also differentiated for chilled potato products and crisps, based on the process steps needed for each product. For crisps, energy associated with post-frying refrigeration and freezing steps was excluded, and for chilled products, energy associated with freezing was excluded. For potato flakes, we have also adjusted the energy intensity to account for the fact that Aviko Rixona, the main producer of potato flakes in the Netherlands, does not use steam peeling. (DutchTecSource.com, 2016)

See the table below for a summary of these results, compared to the original sources.

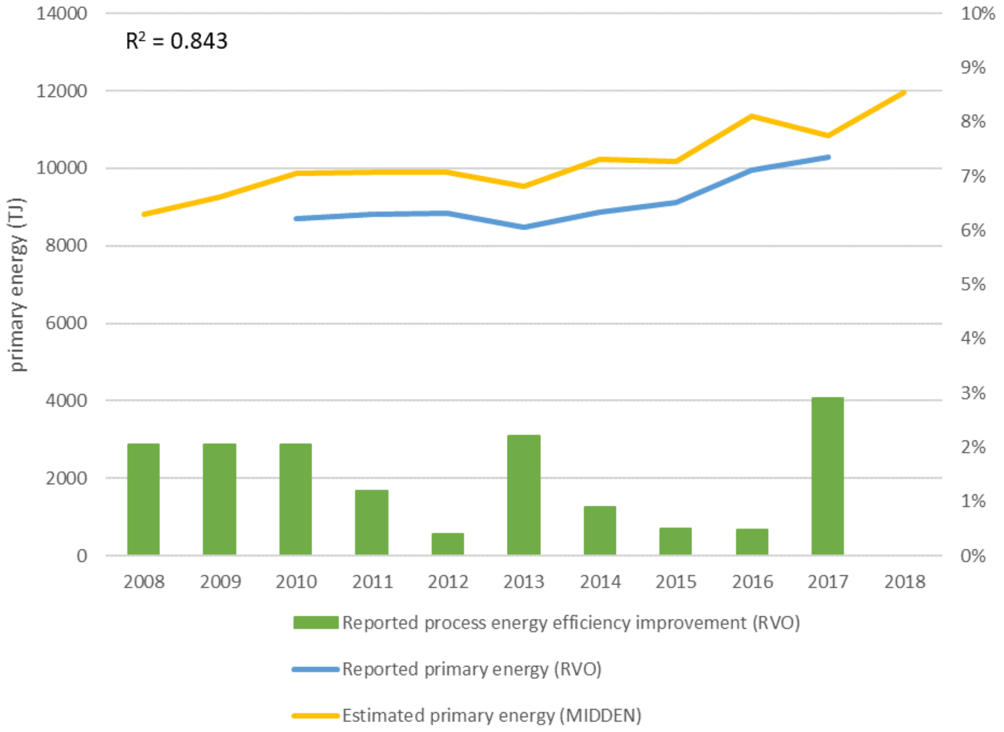
Table A1. Energy intensity (kJ/kg) of potato processing

Source	Frozen potato products	Chilled potato products	Potato flakes	Crisps/ potato chips
Walker et al. (2018)	4.84	-	7.32	-
Masanet et al. (2008)	3.01	-	-	-
MIDDEN estimate for 2017	3.39	2.99	18.7	2.98

Note: Masanet et al. original values given as Btu/lb. Major difference in Walker et al. and Masanet et al. values for frozen potato products comes from frying energy consumption. Walker et al. values for potato flakes refer to a specific plant, which utilises reject materials from other processing lines to complement the raw potato inputs, contributing to a lower overall energy intensity per unit of final product.

Because only primary energy use is reported to RVO, there is no comparison for the estimated final energy consumption or energy intensity estimates. However, the resulting primary energy intensity estimates, applied to relevant reported production levels, give a reasonable approximation of total primary energy use. The results have an r-squared value of 0.839 compared with the reported primary energy use from RVO reporting. See the figure below for a comparison of reported primary energy consumption with estimates based on the methodology described here.

Figure A1. Comparison of estimated and reported primary energy values



Note: Process energy efficiency values for 2008 through 2010 are estimated based on the stated 12.5% improvement in 2011 over 2005, and 2016 value is estimated based on reported 8.4% improvement in 2016 over 2012. The primary energy values reported here include only the 15 sites that are covered by MJA3 for comparable coverage, though the remaining sites are included elsewhere in the report.