2050

Heat Roadmap Europe

A low-carbon heating and cooling strategy

Review of heat saving technologies in industry

WP3: Developing a baseline for the heating and cooling systems within the EU

D3.4 background report

May, 2017

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 695989.

Authors: Cathelijne Rutten, Utrecht University
Tobias Fleiter, Fraunhofer Institute for Systems and Innovation Research
Matthias Rehfeldt, Fraunhofer Institute for Systems and Innovation Research
Robert Harmsen, Utrecht University

Reviewer: Ernst Worrell, Utrecht University

Contact: Robert Harmsen
Copernicus Institute of Sustainable development
Utrecht University
Heidelberglaan 2
3584 CS Utrecht
the Netherlands

E-mail: r.harmsen@uu.nl
Heat Roadmap Europe website: www.heatroadmap.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 695989. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the funding authorities. The

Table of Contents

1. Introduction

In Europe, there is a clear long-term objective to decarbonise the energy system, but it is currently unclear how this will be achieved in the heating and cooling sector. The Heat Roadmap Europe (HRE) project will enable new policies and prepare the ground for new investments by creating more certainty regarding the changes that are required. Heat Roadmap Europe is co-funded by the European Union, brings together 24 academic, industrial, governmental and civil society partners, and runs from 2016-2019.

The overall objective of the HRE project is to provide new capacity and skills for lead users in the heating and cooling sector including policymakers, industry, and researchers at local, national, and EU levels by developing the data, tools, and methodologies necessary to quantify the impact of implementing more energy efficiency measures on both the demand and supply sides of the sector.

This technical report is part of the work on developing a heating and cooling energy demand baseline up until 2050. The report focuses on the industry sector and reviews the available literature about heat saving options in the various industrial sectors.

The information collected is then used to benchmark techno-economic data currently used in the FORECAST model. The FORECAST model is applied to calculate the baseline scenario for the industrial sector. Further, the techno-economic data on heat saving options provide the starting point for the heat saving cost curves developed in work package 4.

In the following sections we first describe the approach used before we then discuss saving options and techno-economic data for the most relevant industrial processes and sub-sectors.

2. Methodology

2.1. Selection of processes and saving options

The selection of saving options which are investigated in this technology update are based on two selection criteria:

- Processes with the highest heating demand
- Saving options with the largest saving potential

2.1.1. Processes with the highest heating demand

Processes were selected by analyzing the results from the latest heating project run by FORECAST prior to the Heat Roadmap Europe Project (i.e. Mapping Heat Supply Europe). From these results, the total heating and cooling demand for each process in Europe in 2012 was compared. From the heating and cooling demand of those processes, only those with a heating and cooling demand of >40 TWh were selected for this technology data update.

This led to the selection of the following 11 processes:

- Aluminum, primary
- Ammonia
- Blast furnace
- Chemical pulp
- Clinker calcination dry
- Electric arc furnace
- Ethylene
- Meat processing
- Paper
- Rolled steel
- Sinter

Together, these processes represented 54% of the total heating and cooling demand in the Mapping Heat Supply Europe project. All saving options related to these processes were selected for inclusion in this document, except for saving options which had no connection to a reduction in heating/cooling demand (e.g. replacing hydraulic by electric machines in the injection molding process). These saving options were not included due to the focus on heating and cooling demand in the Heat Roadmap Europe project.

2.1.2. Saving options with the largest saving potential

The saving options were selected based on a saving potential which was approximated for every saving option in the following way:

$$Total\ saving\ potential, i\ [GJ] = Production, j\ [t] \cdot Specific\ fuel\ savings, i\ \left[\frac{GJ}{t}\right] + Production, j\ [t] \cdot Specific\ electricity\ savings, i\ [\frac{GJ}{t}]$$

In which *i* represents the individual saving options and *j* represents the process to which saving option *i* belongs. The production values for each process *j* were taken from FORECAST in which the most recent industrial production data were from 2012. For this year, production data of all countries were added together in order to find the total industrial production for Europe.

From this analysis, the saving options which were in the top 20% based on the magnitude of their total savings were selected for further analysis in this technology data update. In many cases, these savings options also overlapped with the processes with the highest heating demand. If saving options fell within the top 20% based on their saving potential but did not have a connection to a reduction in heating/cooling demand (e.g. replacing hydraulic by electric machines in the injection moulding process), they were not included in this document due to the focus on heating and cooling demand within the Heat Roadmap Europe project.

2.2. Technology data update

For the selection of processes and saving options made based on the methodology described above, an technology data update was performed for the parameters described below.

2.2.1. Specific energy consumption

For processes, the specific energy consumption used in FORECAST was evaluated and compared in light of the recent literature. Recent literature was defined as literature since 2012, when the last big update of technological data in FORECAST took place. Where possible, updates for the data used in FORECAST were proposed.

2.2.2. Specific saving potential

For saving options, specific saving potentials are evaluated and compared in light of recent literature. Where possible, updates for the data used in FORECAST were proposed.

2.2.3. Type of modification

The type of modification is defined for each saving option based on recent literature according to the following categories presented in Fleiter et al. (2012):

- Organizational measure: Changes to firms' routines like new responsibilities, e.g. dedicating personnel to energy, or instructions to switch-off equipment not being used.
- Add-on technology: Measures not having any functional impact on the process involved, e.g. insulating steam pipes.

- Technology replacement: Simple technology replacement in which one production technology is replaced with a similar, but more energy efficient alternative, e.g. replacement of an old throttle-controlled hydraulic press with an improved hydraulic press using a variable speed pump.
- Technology substitution: The adoption of different processes/components (e.g. replacement of a hydraulic drive with an electric motor. It implies a more disruptive change for the company and requires new know-how and routines to be established.

2.2.4. Diffusion

The phase of diffusion is defined for each saving options based on recent literature, or, if not available, on the historical diffusion data from FORECAST.

- Incubation (0%)
- Take-off (<15%)
- Linear (15-85%)
- Saturation (>85%)

2.2.5. Payback period

The payback period is defined for each saving options based on recent literature, or, if not available, on the payback period already used in FORECAST.

- Short (<2 years)
- Medium (2-4 years)
- Long (5-8 years)
- Very long (>8 years)

2.3. References

- Fleiter, T., Hirzel, S., & Worrell, E. (2012). The characteristics of energy-efficiency measures–a neglected dimension. *Energy Policy*, *51*, 502-513.

3. Pulp, paper and printing

3.1. Chemical pulp

Table 2.1: FORECAST process data

Chemical pulp	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
	12.7		2.3		15.0
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	1	0	

Specific energy consumption

Chemical pulping represents the most common method for producing wood pulp, with kraft and sulphite pulping with shares of 80% and 10% of the world pulp production, respectively (JRC, 2015). The data regarding the SEC of chemical pulping from literature are presented in Table 2.2. Since the data in Table 2.2 are in line with the SEC for chemical pulping in FORECAST, the F**ORECAST data are considered to be in line with the recent literature.**

Table 2.2: Specific energy consumption for chemical pulp from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Comment	Reference
10 - 14	2.2 - 2.9	Kraft pulping	JRC (2015)
7.5 - 16.5	2.0 - 3.24	Sulphite pulping	JRC (2015)
14.5		Current average energy consumption	Pettersson & Harvey (2012)
10		Current BAT levels or energy-efficient mill 10 years from now	Pettersson & Harvey (2012)

3.1.1. Black liquor gasification

Table 2.3: FORECAST data for black liquor gasification

Specific saving potential [GJ/t]	
Fuels	0
Electricity	2
Historic diffusion [%]	
1990	-
2000	-
2004	0
2007	0
Diffusion limit [%]	80

Specific investment cost [€/t]	404.8
Specific O&M costs [€/a · t]	4.67
Estimated payback time	7.32
Annual reduction investment [%]	-1.80
Annual reduction O&M [%]	0.00
Lifetime	
Calculatory	10
Real	20
Market entry	2020

Specific saving potential

Black liquor gasification is a technology that is still under development and is not expected to become commercialized on a large scale before 2020 (Harvey & Peterson, 2012). Even though several references since 2012 have mentioned technological or even economic data for BLG (e.g. Harvey & Petterson, 2012; JRC 2015), most of these are based on data from older references such as (Larson et al., 2003; Larson et al., 2007; Larson et al., 2009; Kam, 2003; Consonni et al. 2009; Grigoray, 2009). It appears no new (transparent) technological or economic data have come to light since 2012.

In the study by Harvey & Petterson (2012), the installation of a BLGCC cycle is compared to a reference situation with a recovery boiler. They do so for a reference mill with a steam demand of 14.5 GJ/ADt, which represents a mill at current average consumption levels, and 10 GJ/ADt which represents a mill at current BAT levels or an energy-efficient mill 10 years from now. In these cases the specific electricity saving potential ranges between 1.43 GJ/t and 2.64 GJ/t for 10 and 14.5 GJ/ADt respectively (for the derivation of these data see Table 2.4). Table 2.5 represents an overview of the specific saving potentials for black liquor gasification from literature. Since BLG technology has not developed much since 2012, there is not a lot of new data. The data from the European Commision (2015) and Harvey & Petterson (2012) **suggest that the current data in FORECAST can be considered representative**

Table 2.4: Resulting technology data for BLG from Pettersson & Harvey (2012)

		14.5 GJ/ADt	**10 GJ/ADt**
Electricity production reference case	MW	10	35
Electricity production BLG case	MW	71	68
Incremental electricity production	MW	61	33
	GWh*	534.4	289.1
	PJ	1.92	1.04
	GJ/t	2.64	1.43

Table 2.5: Specific saving potentials for black liquor gasification from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
-	1.44	JRC (2015)
-	1.43-2.64	Pettersson & Harvey (2012)

Type of modification

Characterizing the type of modification required for the implementation of BLG is not straightforward. At this point, the adoption of BLG technology is mainly relevant to exclusively displace the boiler in a pulp mill and in this way, produce more electricity. However, in the near future, the complete retrofit of a pulp mill to a biorefinery with a range of production may become more economically attractive. It is expected, that if a few technical problems can be solved such as corrosion and causticizing, BLG-motor fuel plants could be successfully commercialized within 10 years (Bajpai, 2014).

To this end, the type of modification for BLG can be characterized as either a technology **replacement** (replacing conventional boilers with BLG technology) **or technology substitution** (retrofitting a pulp mill to a biorefinery).

Diffusion

A review of the literature since 2012 demonstrates that black liquor gasification has seen a stagnation in development. Even though pilot research is ongoing, the technology has been unable to reach take-off and plans to build a full-scale demonstration plant in Sweden were cancelled in 2012 (Dahlquist, 2013). A lack of economic data is hindering the implementation of black liquor gasification since no stakeholders want to take the risk for the initial implementation of the technology (Dahlquist, 2013). The technology is therefore still in the **incubation phase (0%)** of diffusion. Furthermore, some technical problems remain. At this point, a mill's performance must be higher than 450,000 ADt/yr to achieve a favorable power efficiency for implementation, which only represented 12% of the mills in 2013 (JRC, 2015). This means that at this point, only a limited amount of pulp mills would be suitable for implementation even though the number of pulp mills with a capacity of more than 450,000 ADT/yr, as well as the numbers of boilers needing replacement, will continue to grow.

Payback period

The payback period for BLG in FORECAST as described in Table 2.3 is 7.32 years which can be described as a long (5-8 years) payback period based on the categories by Fleiter et al. (2012a). Since the technology is still in the incubation phase, there is high uncertainty regarding the economic feasibility of the technology. No recent, detailed or transparent data have been provided on the economics of BLG. Therefore, **the long payback period of 7.32 years from FORECAST is deemed representative.**

3.2. Mechanical pulp

Table 2.6: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Mechanical pulp	-2.0		7.9		5.9
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	1	0	

Specific energy consumption

The specific energy consumption of mechanical pulping depends on the pulping process, the wood species used and the quality of the pulp required for the end product (JRC, 2015). The data regarding the SEC of mechanical pulping from recent literature are presented in Table 2.7.

Table 2.7: Specific energy consumption for mechanical pulping from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Reference
	3.6 – 15.5	JRC (2015)

As can be seen from Table 2.7, there is a large range possible for the SEC of mechanical pulping. **However, since the data in FORECAST falls reasonably within the range from the literature, the data is considered realistic.** The numbers from the JRC (2015) do not consider heat recovery, which explains why FORECAST shows a negative SEC for fuels while this is not reflected in Table 2.7. However, the potential for heat recovery is discussed separately in section 2.2.1.

3.2.1. Heat recovery (TMP, GW)

Table 2.8: FORECAST data for heat recovery (TMP, GW)

Specific saving potential [GJ/t]	
Fuels	3.48
Electricity	0
Historic diffusion [%]	
1990	-
2000	-
2004	89
2007	92

Diffusion limit [%]	100
Specific investment cost [€/t]	35.87
Specific O&M costs [€/a · t]	0
Estimated payback time	1.15
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Table 2.9: Specific saving potentials for heat recovery (TMP, GW) from literature

Specific saving potential fuels (GJ/t)	**Specific saving potential electricity (GJ/t)**	**Reference**
3.2 – 5.5		Worrell (Personal communication, September/October 2016)
1.18 – 5.94		JRC (2015)

Specific saving potential

Limited data could be found on the specific saving potentials for heat recovery from thermomechanical pulping or groundwood pulping. The JRC (2015) has presented ranges for heat recovery as a share of the electricity consumption, but even when only the averages of these ranges are considered, the range remains very broad (see Table 2.7). Consultation with Ernst Worrell (person communication, September/October, 2016) brought to attention that the energy savings proposed in Table 2.8Table 2.9 are on the low side compared to the estimation from Worrell (Table 2.9). Even though the number from Table 2.9 couldn't be directly verified with recent literature, it is important to note that the specific energy consumption for the mechanical pulping process as a whole is already producing heat at 2 GJ/t. The saving option for heat recovery would cause further savings of 3.48 GJ/t. Combining these numbers together corresponds to the range presented by Worrell in Table 2.9 Since the combination of the specific saving potential presented in Table 2.8 and the production of heat presented in the specific energy consumption falls within the range as presented by Worrell in Table 2.9, **the FORECAST can be considered in line with recent literature**

Type of modification

Several options for heat recovery for TMP exist including: mechanical vapor recompression, direct contact heat exchangers, reboilers, thermal vapor recompression and heat pumps (IETD, 2016a). Therefore, most technological options for heat recovery can be considered **add-on technologies** with which a heat recovery unit is incorporated into the existing process.

Diffusion

Heat recovery for thermomechanical pulping is applicable to any mill that uses pressurized refining, however, most modern TMP mills are already equipped with heat recovery systems (IETD, 2016a). This means that the technology can be considered to be in the **saturation (>85%)** of diffusion.

Payback period

The payback period for heat recovery in FORECAST as described in Table 2.8 1.15 years which can be described as a **short (<2 years) payback period** based on the categories by Fleiter et al. (2012a). Since the technology is already in the saturation phase, there is good certainty regarding the economic data of the technology.

3.3. Paper

Table 2.10: FORECAST process data

Paper	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
	5.5		1.9		7.4
	Heating [%]	Cooling [%]	Heating [%]	Cooling [%]	
	100	0	1	1	

Specific energy consumption

Papermaking consists of three separate stages: stock preparation, the wet and the dry end (IETPD, 2016b). However, large difference exist between papermills according to the type of feedstock used and grades produced (Laurijssen, 2013). The data for the SEC of papermaking from literature is presented in Table 2.11.

Table 2.11: Specific energy consumption for papermaking from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Reference
7.5 – 14.7		Laurijssen (2013)

Compared to the data in Table 2.11, the data in FORECAST seem to be on the low side. The combined fuel and electricity consumption actually falls below the range seen in Table 2.11. However, of the different types of paper, board paper (corrugated board/greyboard/folding boxboard) is the most produced (e.g., 1705 kt in 2007 in the Netherlands) followed by printing and writing paper (e.g. 924 kt in 2007 in the Netherlands) (Laurijssen, 2013). For board paper, the specific energy consumption presented by Laurijssen (2013) is 7.5 GJ/t, which could be **considered acceptably in line with the data in FORECAST**.

3.3.1. Efficient refiners

Table 2.12: FORECAST data for efficient refiners

Specific saving potential [GJ/t]	
Fuels	0
Electricity	0.118
Historic diffusion [%]	
1990	-
2000	-
2004	3
2007	5
Diffusion limit [%]	100
Specific investment cost [€/t]	14.17
Specific O&M costs [€/a · t]	0
Estimated payback time	4.01
Annual reduction investment [%]	-1.60
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2000

Table 2.13: Specific saving potentials for efficient refiners from literature

Specific saving potential fuels (GJ/t)	**Specific saving potential electricity (GJ/t)**	**Reference**
-	0.360	JRC (2015)

Specific saving potential

The BREF document by JRC (2015) gives the specific saving potential for the implementation of 'cutting edge refining technologies'. Table 2.13 shows that this number is quite high in comparison to the data in FORECAST. However, it is not clear from the BREF on which references this number has been based. However, since the pulp and paper industry is one of the sectors which is most extensively researched by Fraunhofer (see Fleiter et al., 2012) and the underlying assumptions behind the number from the JRC (2015) are not clear, **the FORECAST data can be considered to be in line with the recent literature.**

Type of modification

High efficiency refiners can be applied to new and existing plants using virgin pulp, depending on the raw material used and the paper properties required. It is mainly interesting for mills in which the refining plant if oversized or operated in an inefficient mode. However, the application of efficient refiners does require a substantial change in the process (JRC, 2015). For this reason, it can be considered characterized as **a technology replacement** option.

Diffusion

JRC (2015) describes that a few plants in Europe have installed new efficient refiners. Due to a limited number of plants having applied the technology, the technology can be characterized to be in a **take-off** (<15%) phase of diffusion.

Payback period

The payback period in for efficient refiners in FORECAST is 4.01 years as described in Table 2.12, which can be considered a **medium payback period** (Fleiter et al., 2012a). This can be considered representative for a technology in the take-off (<15%) phase of diffusion.

3.3.2. Optimization of refining

Table 2.14: FORECAST data for optimization of refining

Specific saving potential [GJ/t]	
Fuels	0
Electricity	0.075
Historic diffusion [%]	
1990	-
2000	-
2004	25
2007	30
Diffusion limit [%]	100
Specific investment cost [€/t]	0.64
Specific O&M costs [€/a · t]	0
Estimated payback time	0.28
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Table 2.15: Specific saving potentials for optimization of refining from literature

Specific saving potential fuels (GJ/t)	**Specific saving potential electricity (GJ/t)**	**Reference**
-	0.018 – 0.054	JRC (2015)

Specific saving potential

The specific electricity saving potential for the optimization of refining is described in Table 2.15 to range between 0.018-0.054 GJ/t. Interestingly, the data in in FORECAST is actually higher and thus falls outside the range from Table 2.15. However, since the pulp and paper industry is one of the sectors which is most extensively researched by Fraunhofer (see Fleiter et al., 2012) and the underlying assumptions behind the number from the JRC (2015) are not clear, **the FORECAST data can be to be considered in line with the recent literature.**

Type of modification

Optimizing the refiners can be carried out without significant investment in many cases since it mainly concerns changes to the operational mode of the existing refiner (JRC, 2015). Therefore, the technology can be characterized as an **organizational measure** in which the current technology used is optimized with regard to its energy use, without requiring significant technological changes.

Diffusion

According to JRC (2015), numerous plants in Europe (at least four in Germany) have optimized their refiner operating mode. The technology can therefore be characterized as somewhere between the **incubation (0%)** and **take-off phase (<15%)** of diffusion.

Payback period

Referring to the low investment required for the optimization for refining based on the data in FORECAST (Table 2.14) and the information given about the type of modification, it can be concluded that the payback period can be characterized as a **short payback period (<2 years)**.

3.3.3. Chemical modification of fibres

Table 2.16: FORECAST data for chemical modification of fibres

Specific saving potential [GJ/t]	
Fuels	0.185
Electricity	0.164
Historic diffusion [%]	
1990	-
2000	-
2004	0
2007	0
Diffusion limit [%]	81
Specific investment cost [€/t]	3.94
Specific O&M costs [€/a · t]	3
Estimated payback time	1.1
Annual reduction investment [%]	-1.10

Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2015

Specific saving potential

Specific data for the saving potential of the chemical modification of fibers in papermaking cannot be found in recent literature. Therefore, the data regarding the specific saving potential of this technology in FORECAST **cannot be updated based on the recent literature**.

Type of modification

The idea behind the chemical modification of fibers in papermaking is to influence other binding effects in fibers besides the conventional method of focusing on hydrogen bonds (Fleiter et al., 2012b). Since it constitutes a (partial) substitution of conventional refining technology, which is only one part of the entire papermaking process, it can be considered a **technology replacement** option.

Diffusion

The technology is highly experimental and its technical feasibility has not yet been proven even though market entry is expected in the coming years (Fleiter et al., 2012b). Therefore, the technology is still in the **incubation phase (0%)** of diffusion.

Payback period

The payback period for chemical modification of fibers is uncertain since the technology is still in the experimental phase of development and therefore, potential electricity savings are uncertain at this point in time. Furthermore, cost benefits resulting from reduced pulp costs and increased productivity are also uncertain at this point. The payback period currently applied in FORECAST is 1.1 years which can be considered a short (<2 years) payback period. It could be questioned whether such a short payback period is realistic for a technology which is currently not technically feasible. For this reason, **the investment cost is updated in order to reflect a payback period of 4 years**, a medium (2-4 year) payback period which is deemed to be more realistic for such a novel technology. To reflect that these novel technologies may become cheaper in the future, even though initial investment costs may be high for these technologies, **the annual reduction of investment is doubled**. Furthermore, **the market entry is delayed to 2025** to reflect the fact that the technology has not currently entered the market yet, but that commercialization is expected to be achieved in the coming years (Fleiter et al., 2012). The proposed update is presented in Table 2.18.

Table 2.17: Proposed updated FORECAST data chemical modificatino of fibers

Specific investment costs [€/t]	14.35
Estimated payback time	4
Annual reduction investment [%]	-2.20
Market entry	2025

3.3.4. Steam box

Table 2.18: FORECAST data for a steam box

Specific saving potential [GJ/t]	
Fuels	0.18
Electricity	0
Historic diffusion [%]	
1990	-
2000	-
2004	62
2007	64
Diffusion limit [%]	80
Specific investment cost [€/t]	3.94
Specific O&M costs [€/a · t]	0
Estimated payback time	2.43
Annual reduction investment [%]	-0.50
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	15
Market entry	-

Specific saving potential

Interestingly, the specific saving potentials for a steam box in Table 2.18 and Table 2.19 are the same. Therefore, the **FORECAST data is consistent with the recent literature** and does not need to be updated.

Table 2.19: Specific saving potentials for a steam box from literature

Specific saving potential fuels (GJ/t)	**Specific saving potential electricity (GJ/t)**	**Reference**
0.18		JRC (2015)

Type of modification

A steam box preheats water to reduce its viscosity, improving dewatering efficiency and allowing higher dry contents to be attained in the press section (Fleiter et al., 2015b). As a result of this, less water needs to be evaporated in the dryer section. Since it simply preheats the water, it can be considered an **add-on technology**.

Diffusion

Steam boxes are common in modern paper mills (Fleiter et al., 2012b) which is also reflected in the historical diffusion data from FORECAST in Table 2.18. Based on this information, the technology can be considered to be in the **saturation phase of diffusion (>85%)**, if only the papermaking machines are considered for which it is applicable (80% according to the diffusion limit in FORECAST).

Payback period

According to the data in FORECAST, the payback period for a steam box is 2.43 years which can be considered a medium payback period (2-4 years). Since it is a proven technology which is already in the saturation (>85%) phase of diffusion, the **payback period from FORECAST can be considered realistic** for such a technology.

3.3.5. Shoe press

Table 2.20: FORECAST data for a shoe press

Specific saving potential [GJ/t]	
Fuels	0.48
Electricity	0
Historic diffusion [%]	
1990	-
2000	-
2004	56
2007	56.7
Diffusion limit [%]	81
Specific investment cost [€/t]	27.45
Specific O&M costs [€/a · t]	0
Estimated payback time	6.35
Annual reduction investment [%]	-1.10
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Specific saving potential

The specific fuel saving potential for a shoes press is presented in Table 2.21. However, compared to the data in FORECAST the specific saving potential in Table 2.21 seems to be on the high side. However, since the pulp and paper industry is one of the sectors which is most extensively researched by Fraunhofer (Fleiter et al., 2012), **the FORECAST data can be considered to be in line with the recent literature.**

Table 2.21: Specific saving potentials for shoes press from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.72	-	JRC (2015)

Type of modification

A shoes press is integrated into the paper machine's press section to improve dewatering of the paper web by an increased pressing surface between the two rollers (Fleiter et al., 2012b). It entails a substitution of the conventional short nip presses (JRC, 2015). Therefore, it can be characterized as a **replacement technology**.

Diffusion

The shoe press can be applied to both new and existing paper machines and for most paper grades, provided that sufficient space is available and that the construction permits the higher weight of a shoe press (JRC, 2015). The shoes press for paper machine had its market entry around the 1990s and since 1997, all new high-speed paper machines include shoe presses. The technology can therefore be considered to be in the **linear (15-85%) phase of diffusion**, which is in line with the diffusion parameters as they are currently present in FORECAST.

Payback period

According to the JRC (2015), a typical payback period for a shoe press in a press rebuild is about 2.5 years, which can be considered a medium payback period (2-4 years). This is lower than the 6.35 years which is currently used in FORECAST (see table Table 2.20), which would be considered a long payback period (5-8), according to the categories defined by Fleiter et al. (2012a). For such a proven technology, the payback period could be considered on the high side but this is difficult to verify since there is limited data available on the economics of the technology. However, since the pulp and paper industry is one the industries which is most extensively researched by Fraunhofer, **the FORECAST data can be considered to be in line with the recent literature.**

3.3.6. New drying techniques

Table 2.22: FORECAST data for new drying techniques

Specific saving potential [GJ/t]	
Fuels	0.667
Electricity	0
Historic diffusion [%]	
1990	-

2000	-
2004	0
2007	0
Diffusion limit [%]	100
Specific investment cost [€/t]	79.14
Specific O&M costs [€/a · t]	0
Estimated payback time	13.19
Annual reduction investment [%]	-1.80
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2015

Specific saving potential

Drying the paper web is the most energy-consuming process in papermaking. Various new drying concepts exist, however, much uncertainty still exists concerning their saving potentials and market entry (Fleiter et al., 2012b). When comparing the data from Laurijssen (2013) to FORECAST, it seems like the data from FORECAST are on the low side. However, this can be explained by the fact that the number from Laurijssen is based on the theoretical heat savings possible due to optimization actions of the drying section in papermaking. The data in FORECAST therefore fall below this maximum, theoretical saving potential and represent a more realistic saving potential.

In light of the assumptions behind the work of Laurijssen (2013), the data in FORECAST are deemed to be a realistic saving potential for the implementation of new drying techniques and are therefore **considered to be up to date**.

Table 2.23: Specific saving potentials for new drying techniques from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
1.3		Laurijssen (2013)

Type of modification

Different drying techniques are being researched at the moment including steam/air impingement drying, condensing belt drying and impulse drying. Therefore, this may also imply different impacts on the production process for these different techniques. However, for most of these new technologies, a retrofit of the drying section of the papermaking process is required (Laurrijsen, 2013). Therefore, in general, the application of new drying techniques can be considered **substitution technologies**.

Diffusion

At this point, most of the new drying techniques mentioned in the section above are not economically viable (Fleiter et al., 2012b; Laurijssen, 2013). Most conventional paper machines still use the conventional method contact drying with steam heated cylinder (Laurijssen, 2012). Furthermore, even if economic viability of new drying techniques would be achieved, the diffusion would take a long time, since the dryer of a paper machine typically has a lifetime of 20-40 years (Fleiter et al., 2012b). Therefore, all the new drying techniques mentioned can be considered to be in an **incubuation (0%) of diffusion**, which is in line with the diffusion parameters which are currently used in FORECAST (Table 2.23).

Payback period

The new drying techniques mentioned in this section, are not economically viable yet and are still in a very early stage of diffusion. Therefore, there is much uncertainty regarding the payback period for this saving option. This uncertainty is increased by the fact that the saving option describes different types of possible drying techniques. At this point, it is not clear which drying section will become most common in the future. The payback period which is currently used in FORECAST described a **very long (<8 years) payback time** of 13 years. This seems realistic since the technologies are still very experimental at this point in time.

3.3.7. Heat recovery

Table 2.24: FORECAST data for heat recovery

Specific saving potential [GJ/t]	
Fuels	1.07
Electricity	0
Historic diffusion [%]	
1990	-
2000	-
2004	45
2007	50
Diffusion limit [%]	100
Specific investment cost [€/t]	13.81
Specific O&M costs [€/a · t]	0
Estimated payback time	1.43
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Specific saving potential

Heat recovery from papermaking is a general saving option which describes a total potential for heat recovery from the papermaking process including waste heat from refiners, grinders, the dryer section and the effluent water (Fleiter et al., 2012b). When comparing the data from Laurijssen (2013) to FORECAST, the data in FORECAST are somewhat lower than the data presented by Laurijssen (2013) (Table 2.25). This makes sense, since the data from Laurijssen (2013) represent a theoretical maximum potential for energy savings from heat recovery.

Table 2.25: Specific saving potentials for heat recovery from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
1.3		Laurijssen (2013)

Considering the theoretical nature of the potential presented Laurijssen (2013), the **FORECAST data are deemed realistic based on the recent literature.** Since the data in FORECAST are somewhat lower, they are assumed to present a more realistic saving potential than the optimal theoretical number presented by Laurijssen (2013).

Type of modification

Heat recovery from papermaking does not describe very specific technologies but rather gives an overall potential for the recovery of waste heat in the papermaking process, including for example the external use of heat for district heating or optimizing and replacing heat exchangers (Fleiter et al., 2012b). Since most of the technologies included will be aimed at using existing waste heat, it could be concluded that most technologies included can be considered **add-on technologies**, even though it may also include **technology replacement options** which replace conventional technology with one including waste heat recovery,

Diffusion

The recovery of waste heat is already common practice in the pulp and paper industry even though most plants still show significant potential for further waste heat savings, especially for the use of low temperature heat (Fleiter et al., 2012b). For this reason, the practice of heat recovery can be considered to be in the **linear (15-85%) phase of diffusion**, which is also reflected in the diffusion parameters currently used in FORECAST (Table 2.25).

Payback period

The payback period currently used in FORECAST is a **short (<2 years) payback period** of 1.43 years. Since the pulp and paper industry is one of the sectors which is most extensively researched by Fraunhofer (Fleiter et al., 2012b), and many waste heat recovery options already quite economically viable, such a payback period can be deemed realistic.

3.4. References

- Blum et al. (2009), Revision of best available technique reference document for the pulp & paper industry: use of energy saving techniques. UBA Germany (Federal Environmental Agency Germany) and PTS München.
- Dahlquist, E. (Ed.). (2013). Technologies for converting biomass to useful energy: combustion, gasification, pyrolysis, torrefaction and fermentation. CRC Press.
- Fleiter, T., Hirzel, S., & Worrell, E. (2012a). The characteristics of energy-efficiency measures–a neglected dimension. *Energy policy*, *51*, 502-513.
- Fleiter, T., Fehrenbach, D., Worrell, E., & Eichhammer, W. (2012b). Energy efficiency in the German pulp and paper industry–A model-based assessment of saving potentials. *Energy*, *40*(1), 84-99.
- IETD (2016a), Heat recovery in thermo-mechanical pulping, Retrieved from:
- http://ietd.iipnetwork.org/content/heat-recovery-thermo-mechanical-pulping
- IETD (2016b), Papermaking. Retrieved from:
- http://ietd.iipnetwork.org/content/papermaking
- JRC (2015), Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). Retrieved from:
- http://eippcb.jrc.ec.europa.eu/reference/BREF/PP_revised_BREF_2015.pdf
- Laurijssen, J. (2013). Energy use in the paper industry. An assessment of the improvement potentials at different levels. Dissertation, Utrecht University.
- Consonni, S., Katofsky, R. E., & Larson, E. D. (2009). A gasification-based biorefinery for the pulp and paper industry. *Chemical Engineering Research and Design*, *87*(9), 1293-1317.
- Grigoray, O. (2009). Gasification of black liquor as a way to increase power production at kraft pulp mills.
- KAM (2003). KAM-report A100, final report from the ecocyclic pulp mill programme. Stockholm, Sweden: STFI.
- Larson, E. D., Consonni, S., Katofsky, R., Iisa, K., & Frederick, J. W. (2007). Gasification-based biorefining at kraft pulp and paper mills in the United States. In Proceedings of the 2007 TAPPI International Chemical Recovery Conference (pp. 303-313).
- Larson, E. D., Consonni, S., & Katofsky, R. E. (2003). A Cost-Benefit Assessment of Biomass Gasification Power Generation in the Pulp and Paper Industry: Final Report. Princeton University.
- Larson, E. D., Consonni, S., Katofsky, R. E., Lisa, K., & Frederick Jr, W. J. (2009). An assessment of gasification-based biorefining at kraft pulp and paper mills in the United States, Part B: Results. Tappi Journal, 8(1), 27-35.

- Pettersson, K., & Harvey, S. (2012). Comparison of black liquor gasification with other pulping biorefinery concepts–systems analysis of economic performance and CO 2 emissions. Energy, 37(1), 136-153.
- Spachman, J. (2007). Not Just Hot Air. Paper Age, May/June 2007.

4. Iron & steel

4.1. Coke oven

Table 3.1: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Coke oven	3.2		0.1		3.3
	Heating [%]	Cooling [%]	Heating [%]	Cooling [%]	
	100	0	0	0	

Specific energy consumption

Data regarding the specific energy consumption of a coke oven are presented in Table 3.2.

Table 3.2: Specific energy consumption for papermaking from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Reference
6.54		Pardo & Moya (2013)
3.5 - 5		IEA (2007)

The number from Pardo & Moya (2013) seems quite high compared to the number in FORECAST, even though the assumptions behind this number from Pardo & Moya (2013) are not made clear. However, if the number from FORECAST is compared to older literature such as IEA (2007), also presented in Table 3.2, the number in FORECAST seems more reasonable, even if it is still on the low side. A possible explanation for this is that the number in FORECAST is based on research which is mostly focused on the German iron & steel industry which may be considered quite efficient to other European countries (Arens, 2016). Overall, the number **can be considered acceptably in line with the literature**.

4.1.1. Coke dry quenching

Table 3.3: FORECAST data for coke dry quenching

Specific saving potential [GJ/t]	
Fuels	1.02
Electricity	0.03
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0

Diffusion limit [%]	100
Specific investment cost [€/t]	40
Specific O&M costs [€/a · t]	0
Estimated payback time	3.97
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	30
Market entry	1990

Specific saving potential

Several references have discussed the specific saving potentials for coke dry quenching. First of all, it should be noted that all specific saving potentials from Table 3.4 are higher than FORECAST. Furthermore, Ernst Worrell (personal communication, 2016), Hasanbeigi et al. (2013) and Pardo & Moya (2013) display highly similar saving potentials between 1.4-1.463 GJ/t. The number from the U.S. EPA (2012) is slightly higher but this might be explained by the fact that this is a derived number. U.S. EPA (2012) gives a steam recovery rate of 0.55 GJ/t for coke dry quenching and an additional reduced coke consumption in blast furnaces of 0.28 GJ/t due to a better coke quality. The steam recovery rate is converted to a specific fuel saving potential by dividing it with an efficiency of 40% which represents an average steam engine. This leads to the number represented in Table 3.4, but it should be noted that this derivation makes the number more uncertain.

Table 3.4: Specific saving potentials for coke dry quenching from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
1.4	-	Personal communication with Ernst Worrell (September/October, 2016)
1.655	-	U.S. Enviromental Protection Agency (2012)
1.41	-	Hasanbeigi et al. (2013)
1.463	-	Pardo & Moya (2013)

Since the literature show such consistent data for coke dry quenching for three of the references, it is proposed to **update the data in FORECAST according to these references** by taking the average of the specific saving potentials by Pardo & Moya (2013), Ernst Worrell (personal communication, 2016) and Hasanbeigi et al. (2013).

Type of modification

At the end of the coke production process, hot coke comes out of the coke oven. The conventional technology is to cool this hot coke directly in a wet quenching system with large amounts of water which evaporates in a cooling tower. In dry quenching, the coke is cooled by circulating nitrogen in a cooling chamber which recovers energy which can be used to generate high pressure steam (Pardo & Moya, 2013). The installation of coke dry quenching is based on a retrofit of the coke oven (EPA, 2012). However, characterizing the technology is not very straightforward in this case. On the one hand, technology can be considered a **replacement technology** in which wet quenching is replaced with a more energy-efficient variant. On the other hand, it may considered a **substitution technology** since it will probably require new know-how and routines in the facility in order to operate the new system.

Diffusion

Coke dry quenching has been widely diffused in China and Japan, however, its diffusion has been lacking in the U.S. and Europe. Arens & Worrell (2014) explain that for Germany specifically, several coke dry quenching plants have been installed in the past, however, diffusion has dropped to 0% after shutting down of these plants. It is however not clear from literature what has caused this lack of diffusion. Overall, this information leads to the conclusion that the technology can considered to have moved back to the **incubation (0%) phase of diffusion** (in Europe).

Payback period

Since no new literature has been published on the techno-economic status of coke dry quenching, the payback period is highly uncertain. The payback period currently used in FORECAST is 4 years (Table 3.3), which represents a **medium payback period**. Since the technology is currently not applied in Europe but has been in highly diffused in Asia, this payback period can be considered representative.

Table 3.5: Proposed updated FORECAST data for coke dry quenching

Specific saving potential [GJ/t]	
Fuels	1.424
Electricity	-

4.2. Blast furnace

Table 3.6: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Blast furnace	11.6		0.6		12.2
	Heating [%]	Cooling [%]	Heating [%]	Cooling [%]	
	100	0	0	0	

Specific energy consumption

Blast furnaces are used to produce iron by reducing iron-bearing materials with hot gas (EPA, 2012). Data regarding the specific energy consumption of this process are presented in Table 3.7.

Table 3.7: Specific energy consumption for blast furnaces from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Reference
12.31		Pardo & Moya (2013)

The number from Pardo & Moya (2013) is very similar to that presently used in FORECAST (Table 3.6). The SEC used in FORECAST can therefore be **considered in line with the existing literature**.

4.2.1. Top gas recycling

Table 3.8: FORECAST data for top gas recycling

Specific saving potential [GJ/t]	
Fuels	1.665
Electricity	0.03
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	50
Specific investment cost [€/t]	80
Specific O&M costs [€/a · t]	0
Estimated payback time	5.04
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	

Calculatory	10
Real	20
Market entry	2020

Specific saving potential

Specific saving potentials for top gas recycling are scarce in literature since it is a developing technology which is not commercially applied yet. Compared to the one reference from Table 3.9, the figure in FORECAST seems to be on the high side.

Table 3.9: Specific saving potentials for top gas recycling from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
1.226		Pardo & Moya (2013)

However, even though a blast furnace will consume less coke when using top gas recycling, it should be noted that the top gas will not be available for other purposes such as electricity generation. Consequently, extra energy may be needed to compensate for this. Besides, extra oxygen will need to be injected into the furnace to reduce the N_2 levels in the furnace. Therefore, there will also be more electricity required for the production of oxygen (Ernst Worrell, personal communication September/October 2016). Currently, top gas recovery turbines which generate electricity using the top gas, are much more common and can generate up to 0.13-0.18 GJ/t.

Considering the information provided above, it chosen to add the more conventional top gas recovery turbine as a saving option to FORECAST, this is discussed in section Top gas recovery turbine. Other than that, the **specific fuel saving potential is lowered** to the one described in Pardo & Moya (2013) and **dismiss the electricity saving** based on the information above, which leads to the proposed update for FORECAST presented in Table 3.10.

Type of modification

Based on the considerations presented in the section about the specific saving potential of top gas recycling, it becomes clear that the saving option will have a big impact on the production process of iron and therefore has a high level of complexity. For this reason, the technology can be considered a **substitution technology**.

Diffusion

As mentioned above, top gas recycling is a developing technology which is not commercially applied yet. Its technical and economic viability has not been proven at this point and it is only expected to become relevant in the medium term (Pardo & Moya, 2013). For this reason, top gas recycling can be considered in the **incubation (0%) phase of diffusion** at this point.

Payback period

Because the technology is still in the incubation (0%) phase of development, its economic data are very uncertain at this point. In FORECAST, currently, a payback period of 5.04 years is used which is a **long (5-8) payback period** based on the categories of Fleiter et al. (2012). Even though it is difficult to evaluate the payback period at this point in time, a long payback period can be considered realistic for such a novel technology.

Table 3.10: Proposed updated FORECAST data for top gas recycling

Specific saving potential [GJ/t]	
Fuels	1.226
Electricity	-

4.2.2. Top gas recovery turbine

Table 3.11: Proposed FORECAST data for top gas recovery turbine

Specific saving potential [GJ/t]	
Fuels	0
Electricity	0.0951
Historic diffusion [%]	
1990	-
2000	-
2004	63
2007	64
Diffusion limit [%]	100
Specific investment cost [€/t]	3
Specific O&M costs [€/a · t]	0.48
Estimated payback time	3
Annual reduction investment [%]	-0.5
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	1979

Based on the findings from section 3.2.1, it has been decided to add top gas recovery turbine as a saving option to FORECAST. Top gas recovery turbines are a proven way to produce electricity by using the high-pressure top gas leaving the blast furnace (Arens & Worrell, 2014). The proposed data for import into FORECAST are presented in Table 3.11. Data have been collected based on a review of the recent literature on this subject. The data from Table 3.11

have been derived using information from U.S. EPA (2012), Arens & Worrell (2014) and Pardo & Moya (2013) and personal communication with experts within Fraunhofer ISI.

4.2.3. Measure package

Table 3.12: FORECAST data for measure package

Specific saving potential [GJ/t]	
Fuels	0.3
Electricity	0
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	50
Specific investment cost [€/t]	8
Specific O&M costs [€/a · t]	0
Estimated payback time	2.96
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2010

Unfortunately this saving option could not be reviewed because it is unclear from Fleiter et al. (2013) which measures are included in this option.

4.2.4. Optimization top gas usage

Table 3.13: FORECAST data for optimization top gas usage

Specific saving potential [GJ/t]	
Fuels	0.49
Electricity	0.01
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	50
Specific investment cost [€/t]	5
Specific O&M costs [€/a · t]	0

Estimated payback time	1.06
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2010

It could not be deduced from Fleiter et al. (2013) what is included in this saving option. Due to this lack of clarity, the saving option cannot be reviewed at this point in time.

4.2.5. Waste heat recovery blast furnace slag

Table 3.14: FORECAST data for waste heat recovery blast furnace slag

Specific saving potential [GJ/t]	
Fuels	0.49
Electricity	0.01
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	80
Specific investment cost [€/t]	50
Specific O&M costs [€/a · t]	0
Estimated payback time	10.62
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2020

Specific saving potential

Compared to the specific saving potentials for waste heat recovery from blast furnace slag from literature in Table 3.15, the figure that is currently used in FORECAST seems on the high side even though the difference is not unreasonable. Furthermore the number from Table 3.15 is only an estimate, since the technology it not yet commercially applied due to technical difficulties which influence the slag quality (U.S. EPA, 2012). Related to this, if the waste heat is recovered from the slag, the properties of the slag change in such a way that the slag could not be used as a low carbonat component in cement clinker (Ernst Worrell, personal communication September/Otcober 2016).

Table 3.15: Specific saving potentials for waste heat recovery blast furnace slag from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.35	-	U.S. EPA (2012)

Based on the information provided above, **the FORECAST data is considered to be up to date with the recent literature.**

Type of modification

In general, it can be concluded that recovering waste heat from blast furnace slag re-uses an energy stream which could otherwise remain unused in the process. In this light, the technology could be described as an **add-on energy efficiency technology**. However, it remains important to keep in mind that, as mentioned above, in the case that the blast furnace slag would otherwise be used as a low-carbon component in clinker, waste heat recovery is not possible.

Diffusion

As mentioned above, waste heat recovery from blast furnace slag is currently not being applied commercially due to technical problems (U,S. EPA, 2012). Due to this, the technology can be considered to be in its **incubation (0%) phase of diffusion**, which is also reflected in the diffusion parameters currently used in FORECAST (Table 3.14).

Payback period

At this point, the application of waste heat recovery from blast furnace slag is not commercial and several technical problems still need to be solved before this can take place (U.S. EPA, 2012). Therefore, there is large uncertainty regarding the economic parameters of this technology. Currently, the payback period used in FORECAST is a **very long (<8 years) payback time** of 10.62 years. This seems realistic since both the technical and economic viability of the technology are not certain at this point in time.

4.3. Sinter

Table 3.16: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Sinter	2.2		0.1		2.3
	Heating [%]	Cooling [%]	Heating [%]	Cooling [%]	
	100	0	0	0	

Specific energy consumption

Data regarding the specific energy consumption of sintermaking are presented in Table 3.2.

Table 3.17: Specific energy consumption for sinter from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Reference
1.55		Pardo & Moya (2013)
2 - 3		IEA (2007)

The number from Pardo & Moya (2013) seems quite low compared to the number in FORECAST, even though the assumptions behind this number from Pardo & Moya (2013) are not made clear. However, if the number from FORECAST is compared to older literature such as IEA (2007), also presented in Table 3.19, the number in FORECAST seems more reasonable. In this comparison, the number of FORECAST is on the low side but might be explained by the fact that the number in FORECAST is based on research which is mostly focused on the German iron & steel industry which may be considered quite efficient to other European countries (Arens, 2016). Overall, the number can be **considered acceptably in line with the recent literature.**

4.3.1. Gas recirculation

Table 3.18: FORECAST data for gas recirculation

Specific saving potential [GJ/t]	
Fuels	0.19
Electricity	0.01
Historic diffusion [%]	
1990	0
2000	0
2004	12.5
2007	12.5
Diffusion limit [%]	100
Specific investment cost [€/t]	6
Specific O&M costs [€/a · t]	0
Estimated payback time	2.99
Annual reduction investment [%]	0.0
Annual reduction O&M [%]	0.0
Lifetime	
Calculatory	10
Real	20
Market entry	1990

Specific saving potential

Table 3.19 shows the saving potential for gas recirculation in sinter production from recent literature.

Table 3.19: Specific saving potentials for gas recirculation from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.387	-	Pardo & Moya (2013)

The saving potential in Table 3.19 is higher than the data used in FORECAST. Pardo & Moya (2013) describe that generally, two systems can be used for the recovering of energy from the sintering process. Firstly, by returning exhaust gas from the sinter bed to the sinter bed (gas recirculation) and secondly, by recovering energy from the hot sintered ore at the end of the sinter bed using a sintered ore cooling system and using this energy to generate steam. Their number represents an overall estimation for the saving potential for these kind of systems.

In comparison to the number in Table 3.19, the figures in FORECAST seem to be on the low side. Since the data from Moya & Pardo (2013) closely resembles the saving option currently described by FORECAST, **the data can be updated based on these numbers**. This update has been validated by communication with Ernst Worrell (2016).

Table 3.20: Proposed updated FORECAST data for gas recirculation

Specific saving potential [GJ/t]	
Fuels	0.387
Electricity	-

Type of modification

Based on the description of gas recirculation in the previous section, it can be concluded that gas recirculation is aimed at using existing waste heat, which would otherwise be released in the exhaust gas of the system. To this end, gas recirculation technology can be considered an **add-on technology** since it does not significantly impact the production process itself. However, since it in unclear from literature to what extent retrofitting is necessary in order to implement sinter gas recirculation, the technology could also be **replacement technology**.

Diffusion

Gas recirculation can be applied in new plants while existing plants can be retrofitted to include the technology (EPA, 2012). No data could be found in recent literature regarding the actual diffusion of the technology. Based on the data used in FORECAST, the technology was in the take-off phase of diffusion (<15%) in 2007 with a diffusion rate of 12.5%. Due to the reasonable payback period of the technology (see next section) and the fact that the technology is based on quite conventional waste heat recovering technology, it is be expected that the technology will have now moved on to the **linear phase of diffusion (15-85%).**

Payback period

EPA (2012) estimated the payback period at 2.8 years for a specific retrofitted facility in the Netherlands, which represents a **medium payback period (2-4 years)**. This is in line with the payback period currently used in FORECAST which is 2.99 years (Table 3.18), which can therefore be deemed a realistic payback period based on the recent literature.

4.4. Rolled steel

Table 3.21: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Rolled steel	2.4		0.6		3.0
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	10%	0	

Specific energy consumption

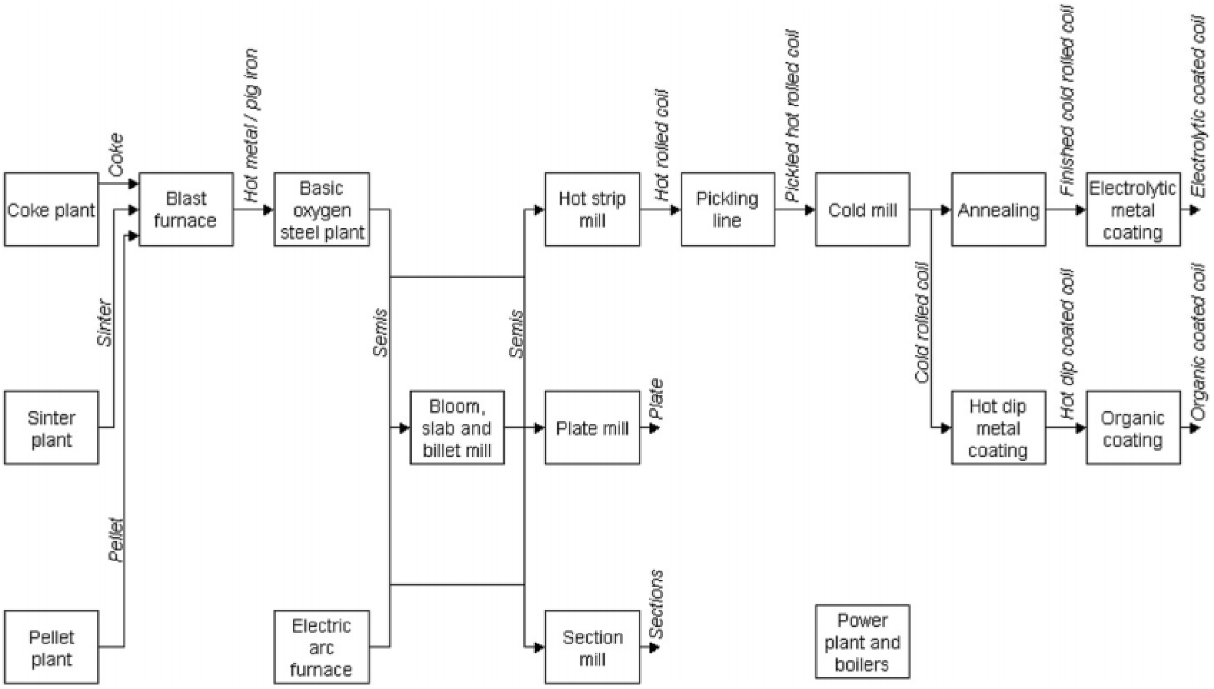
The process of rolling steel may in- or exclude many different processes, depending on the system boundaries applied, which is illustrated by the data in Table 3.22 and Figure 1.

Table 3.22: Specific energy consumption for rolled steel from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Comment	Reference
1.78		Boom, slab and billet mill	Pardo & Moya (2013)
1.70		Hot strip mill	Pardo & Moya (2013)
1.91		Plate mill	Pardo & Moya (2013)
1.83		Section mill	Pardo & Moya (2013)
0.22		Pickling line	Pardo & Moya (2013)
0.74		Cold mill	Pardo & Moya (2013)
1.09		Annealing	Pardo & Moya (2013)
1.49		Hot dip metal coating	Pardo & Moya (2013)
2.62		Electrolytic metal coating	Pardo & Moya (2013)
0.758		Organic coating	Pardo & Moya (2013)

A combination of the specific energy consumption presented in Table 3.22 should represent the specific energy consumption used in FORECAST. However, at this point, it is not clear what rolling/finishing processes are included in the SEC currently used in FORECAST and how these are weighted. However, to create some type of context to evaluate the number of FORECAST in, it has been deduced from the Steel Statistics Yearbook 2016 that hot rolled products represent the majority of steel-based products in Europe (World Steel Association, 2016).

Figure 1: Current pathways for iron & steel production in Europe (from Hasanbeigi et al., 2013)



If this taken to comprise the specific energy consumption of a boom, slab and bill mill and a hot strip mill as presented in Table 3.22, the total specific energy consumption would be 3.48 GJ/t based on literature. This is somewhat higher than in FORECAST, however, a possible explanation for this is that the number in FORECAST is based on research which is focused on the German iron & steel industry which may be considered quite efficient compared to other European countries (Arens, 2016). Therefore the number in FORECAST can be considered **acceptably in line with literature at this time.**

4.4.1. Waste heat recovery from rolling

Table 3.23: FORECAST data for waste heat recovery from rolling

Specific saving potential [GJ/t]	
Fuels	0.45
Electricity	0.1

Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	60
Specific investment cost [€/t]	8
Specific O&M costs [€/a · t]	0
Estimated payback time	1.13
Annual reduction investment [%]	0.0
Annual reduction O&M [%]	0.0
Lifetime	
Calculatory	10
Real	20
Market entry	2010

Specific saving potential

Several reference since 2012 have discussed energy efficiency in the iron and steel sector. Table 3.24 shows the saving potentials for waste heat recovery from rolling for these references.

Table 3.24: Specific saving potentials for waste heat recovery from rolling from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.3 – 0.7	0 – 0.011	U.S. Environmental Protection Agency (2012)
0.3 – 0.74	-0.0006 – 0.011	Hasanbeigi et al. (2013)

The data from the different references in Table 3.24 are very similar since the data from Hasanbeigi et al. (2013) is based on data from the U.S. Environmental Protection Agency (2012). Both references are based on the saving potential for using recuperative burners to transfer heat from the outgoing exhaust gas to preheat the incoming combustion air. Recuperative burners therefore represent a specific form of waste heat recovery from rolling. The data from FORECAST is based on systems which preheat the combustion air with regenerative technology in general. The range of specific fuel savings from FORECAST seem in line which the range of data from table Table 3.24. The FORECAST is therefore **in line with the recent literature.**

Type of modification

Based on the description of waste heat recovery from rolling in the previous section, it can be concluded that this technology is aimed at re-using the existing waste heat, which would otherwise be released in the exhaust gas of the system. To this end, waste heat recovery from rolling can be considered an **add-on technology** since it does not significantly impact the production process itself.

Diffusion
The use of recuperative burners is described to be common at many hot rolling facilities by EPA (2012). However, in FORECAST, the diffusion parameters applied imply that the technology is still in the **incubation (0%) phase of diffusion.** From recent literature, new data or insights regarding the diffusion of the technology in practice could not be found.

Payback period
EPA (2012) give an estimated payback period for the application of recuperative burners in hot rolling mills of 1.8 years, which can be considered a **short payback period (<2).** This payback period is in line with the payback period currently used in FORECAST of 1.13 years (Table 3.22).

4.4.2. Thin slab or strip casting

Table 3.25: FORECAST data for thin slab or strip casting

Specific saving potential [GJ/t]	
Fuels	0.9
Electricity	0.3
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	40
Specific investment cost [€/t]	0
Specific O&M costs [€/a · t]	0
Estimated payback time	-
Annual reduction investment [%]	0.0
Annual reduction O&M [%]	0.0
Lifetime	
Calculatory	10
Real	20
Market entry	2015

Specific saving potential
Thin slab casting and strip casting are both forms of continuous casting (U.S. Environmental Protection Agency, 2012). Several systems for thin slab casting and strip casting are presented by the U.S. Environmental Protection Agency (2012) and the range of saving potentials for

these systems are presented in Table 3.26. The data by Hasanbeigi et al. (2013) are presented per tonne of crude steel and are therefore not suitable for comparison to FORECAST.

Table 3.26: Specific saving potentials for thin slab or strip casting from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
1 - 2	0.32 – 0.55	U.S. Environmental Protection Agency (2012)
0.05 (per tonne of crude steel)	0.151 (per tonne of crude steel)	Hasanbeigi et al. (2013)

The numbers in FORECAST are relatively similar to the range of data by the U.S. Environmental Protection Agency (2012), however, they could be **considered on the low side.** In consultation with Ernst Worrell (personal communication , September/October 2016), the data in Table 3.27 are proposed.

Type of modification

Thin slab or strip casting integrate the casting and hot rolling of steel into one process step, thereby reducing the need to reheat the steel before rolling it (EPA, 2012). Therefore, the technology can be considered to have a big influence on the production process, requiring new know-how and routines to be established. For this reason, the technology can be characterized as a **substitution technology** according to the categories by Fleiter et al. (2012a).

Diffusion

Thin slab or strip casting has been applied in several plants worldwide. However, several technical constraints limit the diffusion of the technology. Even though no recent literature can be found on the diffusion, it is expected that the technology is still in the **incubation (0%) phase of diffusion**. Most likely, the technology will only become viable for certain shapes while for others, it is likely that the technology may create delays in operation and increased operating costs even though potentially much energy can be saved (EPA, 2012).

Payback period

According to EPA (2012), the estimated payback period for thin slab casting is 3.3 years, which can be considered a medium payback period (2-4 years). In FORECAST, currently no data regarding the economic data or payback period are included (Table 3.25). However, based on recent literature, **no economic data could be found to update FORECAST**. Based on the status of diffusion of the technology, it can be concluded that the payback period presented by the EPA (2012) is quite low for a technology of which the economic viability has not been proven with certainty.

Table 3.27: Proposed updated FORECAST data for thin slab or strip casting

Specific saving potential [GJ/t]	
Fuels	1.0
Electricity	0.45

4.5. Electric arc furnace

Table 3.28: FORECAST process data

<table>
<tr><td rowspan="4">Electric arc furnace</td><td colspan="2">SEC fuels [GJ/t]</td><td colspan="2">SEC electricity [GJ/t]</td><td>Total [GJ/t]</td></tr>
<tr><td colspan="2">1</td><td colspan="2">2.3</td><td rowspan="3">3.3</td></tr>
<tr><td>Heating [%]</td><td>Cooling [%]</td><td>Heating [%]</td><td>Cooling [%]</td></tr>
<tr><td>100</td><td>0</td><td>95</td><td>0</td></tr>
</table>

Specific energy consumption

The share of EAF steel in production has been growing, because of its higher operational flexibility compared to the blast furnace route. Nonetheless, about 20% of the energy input for melting scrap in an EAF is wasted in the form of waste heat (Pardo & Moya, 2013). Table 3.29 shows the specific energy consumption for electric arc furnaces from literature.

Table 3.29: Specific energy consumption for electric arc furnaces from literature

Specific fuel consumption (GJ/t)	**Specific electricity consumption (GJ/t)**	**Comment**	**Reference**
2.51			Pardo & Moya (2013)

The number from Pardo & Moya (2013) seems quite low compared to the number in FORECAST, even though the assumptions behind this number from Pardo & Moya (2013) are not made clear. However, the number in FORECAST is based on an extensive literature review on the specific energy consumption of electric arc furnaces (Arens, 2016). Therefore, **the number in FORECAST can be considered representative.**

4.5.1. Heat recovery

Table 3.30: FORECAST data for heat recovery

Specific saving potential [GJ/t]	
Fuels	0.15
Electricity	0.37

Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	100
Specific investment cost [€/t]	16
Specific O&M costs [€/a · t]	0
Estimated payback time	1.28
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2010

Specific saving potential

The specific saving potentials from literature for heat recovery from electric arc furnaces are presented in Table 3.31. Table 3.31 represents figures from the U.S. Environmental Protection Agency (2012), Hasanbeigi et al. (2013) and Pardo & Moya (2013) which appear to be reasonably in line with the data from FORECAST. However, these data all represent a specific form of waste heat recovery for the EAF, namely scrap preheating by using hot furnace gases. However, personal communication with Worrell has found that waste heat recovery in general can lead to much higher energy savings which are also represented in Table 3.31.

Table 3.31: Specific saving potentials for heat recovery from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
	0.016 – 0.22	U.S. Enviromental Protection Agency (2012)
	0.22	Hasanbeigi et al. (2013)
	0.288	Pardo & Moya (2013)
0.3	1	Worrell (personal communication, September/October 2016)

According to personal communication with Ernst Worrell (September/October 2016), the numbers seem on the low side, if the saving options is meant to represent the total amount of waste heat which can be recovered from an EAF. However, looking at the literature, the main form of waste heat recovery that is actually implemented in EAFs is scrap preheating (U.S. Department of Energy, 2008), even though the theoretical potential may be higher. However, since data on any specific technologies found for recovering this remaining waste heat for

EAFs cannot be found in the recent literature, **the current FORECAST data can be considered representative.**

Type of modification

Heat recovery from an electric arc furnace does not describe very specific technologies but rather gives an overall potential for the recovery of waste heat in the EAF process. Since most of the technologies included will be aimed at using existing waste heat, it could be concluded that most technologies included can be considered **add-on technologies**, even though it may also include **technology replacement** options which replace conventional technology with one including waste heat recovery,

Diffusion

As mentioned with regard to the specific energy consumption of EAFs, about 20% of energy input to an EAF is currently being wasted in the form of waste heat (Pardo & Moya, 2013). This implies that the recovery of waste heat from EAFs is still limited at this point in time, which is reflected in the diffusion parameters currently used in FORECAST (Table 3.30). For this reason, the practice of waste heat recovery from EAFs can be considered to be in **the incubation (0%) phase of diffusion.**

Payback period

The payback period currently used in FORECAST is a short (<2 years) payback period of 1.28 years, which is quite low for a technology which has not been commercially applied and is still in the incubation (0%) phase of diffusion. However, because of the novelty of waste heat recovery in electric arc furnaces, there **is no adequate economic data available to evaluate this payback period from FORECAST.**

4.6. References

- Arens, M., & Worrell, E. (2014). Diffusion of energy efficient technologies in the German steel industry and their impact on energy consumption. *Energy*, *73*, 968-977.
- Arens, M. (2016). Technological change and industrial energy efficiency. Dissertation: Copernicus Institute of Utrecht University, the Netherlands.
- Fleiter, T., Schlomann, B., & Eichhammer, W. (2013). Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien: Einsparpotenziale, Hemmnisse und Instrumente. T. Fleiter (Ed.). Fraunhofer-Verlag.
- Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., & Xu, T. (2013). A bottom-up model to estimate the energy efficiency improvement and CO 2 emission reduction potentials in the Chinese iron and steel industry. *Energy*,*50*, 315-325.
- IETD (2016). Coke dry quenching. Retrieved from:
- http://ietd.iipnetwork.org/content/coke-dry-quenching

- Pardo, N., & Moya, J. A. (2013). Prospective scenarios on energy efficiency and CO 2 emissions in the European iron & steel industry. *Energy*, *54*, 113-128.
- U.S. Department of Energy (2008), Waste heat recovery: Technology and opportunities in U.S. Industry.
- https://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf
- U.S Environmental Protection Agency (2012). Available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry. Retrieved from: https://www.epa.gov/sites/production/files/2015-12/documents/ironsteel.pdf on 10-10-2016
- World steel association (2016). Steel Statistical Yearbook. *World Steel Association, Brussels*.

5. Non-ferrous metals

5.1. Primary aluminum

Table 4.1: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Primary aluminum	5.2		53.6		58.8
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	5	0	

Specific energy consumption

The production of primary aluminum is mainly based on the use of electricity for the electrochemical reduction of alumina by the Hall-Héroult process (Kermeli et al., 2013). The specific energy consumption for this process found in literature is presented in Table 4.2.

Table 4.2: Specific energy consumption for primary aluminum production from literature

Specific fuel consumption (GJ/t)	**Specific electricity consumption (GJ/t)**	**Reference**
	53.3	Kermeli et al. (2013)

Kermeli et al. (2013) only discuss the electricity consumption for the production of primary aluminum production, which represents the majority share of energy use in this process. This specific electricity consumption presented in Table 4.2, is very similar to that currently applied in FORECAST. Therefore, the **current FORECAST data can be considered up to date.**

5.1.1. Inert anodes

Table 4.3: FORECAST data for inert anodes

Specific saving potential [GJ/t]	
Fuels	0
Electricity	3.6
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	100
Specific investment cost [€/t]	1011.64
Specific O&M costs [€/a · t]	0
Estimated payback time	9.37

Annual reduction investment [%]	-1.10
Annual reduction O&M [%]	0.00
Lifetime	
Calculatory	2
Real	2
Market entry	2010

Specific saving potential

Specific data for the saving potential of inert anodes are scarce in literature. Furthermore, the number from Springer & Hasanbeigi (2016) is an approximation made based on information from this reference that inert anodes can give 3-4% energy savings within a modified Hall-Héroult cell compared to a conventional Hall-Héroult cell (which is said to use 47 GJ/t for the BAT). This information however, is based on data from the U.S. Department of Energy from 2007.

Table 4.4: Specific saving potentials for inert anodes from literature

Specific saving potential fuels (GJ/t)	**Specific saving potential electricity (GJ/t)**	**Reference**
-	1.645	Springer & Hasanbeigi (2016)

The data in the recent literature is scarce and uncertain. Therefore, **the FORECAST cannot be updated at this point in time.**

Type of modification

Inert anodes represent an alternative to the carbon anodes currently used in the Hall-Héroult process. An ideal inert anode would be chemically nonreactive, would not be consumed by the electrolysis reaction and would thus have the same lifetime as the smelting cell (Springer & Hasanbeigi, 2016). Inert anodes could be easily installed in existing Hall-Héroult cells and would not require large changes in the smelter infrastructure. However, since regular access to the cells to replace the anodes would no longer be necessary, the cells could be sealed more effectively and therefore operational efficiency could be improved (Springer & Hasanbeigi. 2016). Therefore, the technology could be considered a **replacement technology** in which carbon anodes are replaced with the more energy-efficient alternative of inert anodes.

Diffusion

Even though inert anodes seem a promising alternative to carbon anodes, a major barrier to their development is finding cost-efficient anode materials that do not corrode in the reaction solvent (Springer & Hasanbeigi, 2016). Even though plans for pilot projects were made in the past, there is no indication that these pilots have actually taken place and new literature on the subject is very limited. The technology is therefore still in its **incubation (0%) of diffusion.**

Payback period

There are still major technical and economic barriers for the implementation of inert anodes (Springer & Hasanbeigi, 2016). Since the technology is not commercially applied yet, the techno-economic data of this technology are very uncertain. However, the economic viability is expected due to the lack of progress in the field in recent years. The payback period currently used in FORECAST is a **very long (<8 years) of 9.37 years.** This is deemed realistic when the context of the technology described above is taken into account. However, in order to reflect that the technology has currently not entered the market yet and is not expected to do so soon, the market entry is delayed to 2030.

Table 4.5: Proposed updated FORECAST data for inert anodes

Market entry	2030

5.1.2. Wetted cathode

Table 4.6: FORECAST data for wetted cathode

Specific saving potential [GJ/t]	
Fuels	0
Electricity	7.34
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	100
Specific investment cost [€/t]	299.84
Specific O&M costs [€/a · t]	0
Estimated payback time	1.36
Annual reduction investment [%]	-1.10
Annual reduction O&M [%]	0.00
Lifetime	
Calculatory	8
Real	8
Market entry	2010

Specific saving potential

As is the case for inert anodes, specific data for the potential energy savings from wetted cathode are scarce in literature. The number from Springer & Hasanbegi (2016) is an approximation based on information from this reference that a wetted cathode can give energy savings of about 20% in a modified Hall-Héroult cell compared to a conventional Hall-Héroult cell (which is said to use 47 GJ/t for the BAT). However, this information is based on an old reference from 2007 and new literature regarding the techno-economic performance of this technology could not be found.

Table 4.7: Specific saving potentials for wetted cathode from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
-	9.4	Springer & Hasanbeigi (2016)

The data in the recent literature is scarce and uncertain. Therefore, **the FORECAST cannot be updated at this point in time.**

Type of modification

In short, a wetted cathode represents a completely wetted cell lining which is inert to the cell bath and which would allow molten aluminum to be drained out of the anode-cathode spacing (Springer & Hasanbeigi, 2016). The application of wetted cathode is technically complex and would require a significant redesign of the Hall-Héroult cell. Therefore, it can be considered a **substitution technology**.

Diffusion

The application of wetted cathodes faces several technical problems, including a smaller anode-cathode distance and lower voltage operation (Springer & Hasanbeigi, 2016). Even though the technology was first piloted as far back as the 1960s, the development has stagnated and no indication of commercial application of the technology can be found in literature. Therefore, the technology is still in the **incubation (0%) phase of diffusion.**

Payback period

There are still major technical barriers for the implementation of wetted cathodes (Springer & Hasanbeigi, 2016). Since the technology is not commercially applied yet, the techno-economic data of this technology are very uncertain. However, the economic viability is expected to be limited due to the lack of progress in the field in recent years. The payback period currently used in FORECAST is a short (<2 years) of 1.36 years. However, since there are no economic data available at this point, the **payback period cannot be evaluated based on recent literature.**

5.1.3. PFPB

Table 4.8: FORECAST data for PFPB

Specific saving potential [GJ/t]	

Fuels	0
Electricity	2.52
Historic diffusion [%]	
1990	31
2000	57
2004	89
2007	89
Diffusion limit [%]	100
Specific investment cost [€/t]	141.63
Specific O&M costs [€/a · t]	0
Estimated payback time	1.87
Annual reduction investment [%]	-1.10
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	1980

Specific saving potential

The conversion of CWPB, SWPB, VSS and HSS cells into state-of-the-art PFPB cells is a widespread development (Kermeli et al, 2015). Currently, VSS and HSS cells are hardly applied in Europe anymore (Ernst Worrell, personal communication September/October 2016). Therefore the specific saving potential to PFPB cells should primarily be based on the conversion of CWPB and SWPB cells which can save 6,.2 GJ/t and 2.88 GJ/t, respectively.

Table 4.9: Specific saving potentials for PFPB from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
-	3.8	Kermeli et al. (2015); Ernst Worrell (personal communication, September/October 2016)

Based on personal communication with Ernst Worrell (September/October, 2016), it is **proposed to use a weighted average of the energy savings for CWPB (30%) and SWPB (70%)** cells which is presented in Table 4.10.

Type of modification

Traditional types of cells (e.g. CWPB, SWPB, VSS, HSS) can be upgraded to PFPB (Kermeli et al., 2013). However, from the current literature, it is not clear what type of modification is required to convert more traditional types cells to PFPB technology. Most likely, it can be considered a **replacement technology** in which the traditional cells are replaced with the more energy-efficient PFPB technology.

Diffusion

As mentioned in the section about the specific saving potential, the application of PFPB cells is widespread in Europe and it is actually the main type of cell applied in primary aluminum production (Kermeli et al., 2013). Therefore, the technology is already in the **saturation (>85%) of diffusion** in Europe.

Payback period

The application of PFPB cells is widespread and represents major energy benefits (Kermetli et al., 2013). This is reflected in the **short (<2 years) payback time** currently used in FORECAST of 1.87 years, which is therefore deemed realistic.

Table 4.10: Proposed updated FORECAST data for PFPB

Specific saving potential [GJ/t]	
Fuels	-
Electricity	3.8

5.1.4. Optimization electrolysis control

Table 4.11: FORECAST data for optimization electrolysis control

Specific saving potential [GJ/t]	
Fuels	0
Electricity	3.6
Historic diffusion [%]	
1990	0
2000	0
2004	27
2007	27
Diffusion limit [%]	100
Specific investment cost [€/t]	-188.11
Specific O&M costs [€/a · t]	65
Estimated payback time	-4.37
Annual reduction investment [%]	-2.30
Annual reduction O&M [%]	-2.40
Lifetime	
Calculatory	5
Real	5
Market entry	2003

Specific saving potential

Kermeli et al. (2015) give an overall specific saving potential (Table 4.12) for the optimization of cell operation which is described as follows: *"With the further improvement of pot control and point-feeding systems in existing PFPB cells, the occurrence of anode effects can be reduced, while the electrolytic bath will be better controlled resulting in more optimal operating conditions".*

The figure given by Kermeli et al. (2015) therefore seems to encompass more measures than just the optimization of the electrolysis control, considering the number in FORECAST is much lower. The figure by Kermeli et al. (2015) can be considered to be a more general representation of optimization of the electrolytic cell and therefore a combination of two saving options in FORECAST, optimization electrolysis control and the optimization cell design (described in section 4.1.5 below).

Since the combined specific saving potential for optimization of electrolysis control (3.6 GJ/t) and optimization of cell design (2.52 GJ/t) from FORECAST is comparable to the overall figure of 7.2 GJ/t in Kermeli et al. (2015), the **FORECAST data can be considered in line with the recent literature.**

Table 4.12: Specific saving potentials for optimization electrolysis control from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
	7.2*	Kermeli et al. (2015)

*Represents a generalized number for the specific saving potential for optimization of the electrolytic cell, this is elaborated on below.

Type of modification

The optimization of electrolysis control as described in Kermeli et al. (2015) is based on the renovation of PFPB cells related to electrolysis. However, from the current literature, it is not clear what type of modification is required to achieve this optimization. Most likely, it is a **substitution technology** which substitutes conventional PFPB technology with more energy-efficient options related to the electrolysis control.

Diffusion

According to the data used in FORECAST, the technology was diffused in 27% of the primary aluminum production processes in 2007 (Table 4.11). This would imply that the technology is in a **linear (15-85%) stage of diffusion**. These findings could not be supported from the recent literature on primary aluminum production but are deemed reasonable.

Payback period

There is a lack of data on the economic viability of renovating PFPB cells (Kermeli et al., 2015). Therefore, the payback period for this measure is quite uncertain. In FORECAST, the payback period for this measure is negative due to negative specific investment costs. This seems contradictory with Kermeli et al. (2015) which implies that at least some investment are required for the renovation of PFPB cells (e.g. for the optimizing pot control). When these are checked against the work of Cebulla (2011), who has reviewed the saving options for the primary aluminum sector in 2011, the specific O&M costs there are noted to be 252.0 €/t against 65 €/t actually used in FORECAST. When these specific O&M costs are reflected in FORECAST, the **estimated payback period becomes 1.31 years** which is deemed more realistic for this saving option. The proposed update for the FORECAST data based on Cebulla (2011) is presented in Table 4.13.

Table 4.13: Proposed updated FORECAST data for optimization electrolysis control

Specific O&M costs [€/t]	252.0
Payback period	1.31

5.1.5. Optimization cell design

Table 4.14: FORECAST data for optimization cell design

Specific saving potential [GJ/t]	
Fuels	0
Electricity	2.52
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	100
Specific investment cost [€/t]	236.05
Specific O&M costs [€/a · t]	0
Estimated payback time	3.12
Annual reduction investment [%]	-1.10
Annual reduction O&M [%]	0
Lifetime	
Calculatory	6
Real	6
Market entry	2012

Specific saving potential

Kermeli et al. (2015) give an overall specific saving potential for the optimization of cell operation, which is described as follows: *"With the further improvement of pot control and point-feeding systems in existing PFPB cells, the occurrence of anode effects can be reduced, while the electrolytic bath will be better controlled resulting in more optimal operating conditions".*

The figure given by Kermeli et al. (2015) therefore seems to encompass more measures than just the optimization of cell design, considering the number in FORECAST is much lower. However, the figure by Kermeli et al. (2015) can be considered to be a more general represented of optimization of the electrolysis cell and therefore a combination of two saving options in FORECAST, optimization electrolysis control and the optimization cell design (described in section 4.1.4 above).

Since the combined specific saving potential for optimization of electrolysis control (3.,6 GJ/t) and optimization of cell design (2.52 GJ/t) from FORECAST is comparable to the overall figure of 7.2 GJ/t in Kermeli et al. (2015), the **FORECAST data can be considered in line with the recent literature.**

Table 4.15: Specific saving potentials for optimization cell design control from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
	7.2*	Kermeli et al. (2015)

*Represents a generalized number for the specific saving potential for optimization of the electrolytic cell, this is elaborated on below.

Type of modification

The optimization of cell operation as described in Kermeli et al. (2015) is based on the renovation of PFPB cells. However, from the current literature, it is not clear what type of modification is required to achieve this optimization. Most likely, it is a **substitution technology** which substitutes conventional PFPB technology with more energy-efficient options related to the cell design.

Diffusion

According to the data used in FORECAST, the technology was had not been diffused at all in 2007 (Table 4.11). This would imply that the technology is in a **incubation (0%) stage of diffusion.** These findings could not be supported from the recent literature on primary aluminum production but are deemed reasonable.

Payback period

There is a lack of data on the economic viability of renovating PFPB cells (Kermeli et al., 2015). Therefore, the payback period for this measure is quite uncertain. In FORECAST, the payback period for this measure is a **medium (2-4 years) payback period of** 3.12 years.

5.2. References

- Cebulla (2011). Energieeffizienz in der Aluminiumindustrie. Eine techno-ökonomische Analyse prozesstechnischer Einsparoptionen. Fraunhofer ISI, Karlsruhe.

- Springer, C., & Hasanbeigi, A. (2016). Emerging Energy Efficiency and Carbon Dioxide Emissions-Reduction Technologies for Industrial Production of Aluminum. Ernest Orlando Lawrence Berkeley National Laboratory, June 2016. Retrieved from:
- https://eta.lbl.gov/sites/all/files/publications/06-06-16_lbl_ceg_aluminum_ee_techs.pdf
- Kermeli, K., ter Weer, P. H., Crijns-Graus, W., & Worrell, E. (2015). Energy efficiency improvement and GHG abatement in the global production of primary aluminium. *Energy Efficiency*, *8*(4), 629-666.

6. Non-metallic minerals

6.1. Clinker calcination - dry

Table 5.1: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Dry clinker calcination	3.5		0.1		3.6
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	0	0	

Specific energy consumption

The production of dry clinker calcination is based on three main processes: kiln feed preparation, clinker production and finish grinding (Worrell et al., 2013) The specific energy consumption for this process found in literature is presented in Table 5.2.

Table 5.2: Specific energy consumption for dry clinker calcination from literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Comment	Reference
3.95	0.26	U.S.	Worrell et al. (2013)

The data from Table 5.2 are very similar to those used in FORECAST (Table 5.1). The numbers from literature are slightly higher than those in FORECAST, however, the difference is minimal. Furthermore, the literature is specifically focused on the U.S. which possibly explains the difference. **The specific energy consumption used in FORECAST can therefore be considered in line with literature.**

6.1.1. Waste heat use for material preheating

Table 5.3: FORECAST data for waste heat use for material preheating

Specific saving potential [GJ/t]	
Fuels	0.18
Electricity	0.002
Historic diffusion [%]	
1990	-
2000	-
2004	55
2007	56
Diffusion limit [%]	-
Specific investment cost [€/t]	6.04

Specific O&M costs [€/a · t]	0.05
Estimated payback time	3.77
Annual reduction investment [%]	-0.70
Annual reduction O&M [%]	0.00
Lifetime	
Calculatory	10
Real	20
Market entry	-

Specific saving potential

Waste heat use for material preheating is presumed to refer to the installation of a (multi-stage) preheater kiln. More specifically, this means that older, long dry kilns are replaced with multi-stage preheater kilns. This also includes the option to increase the number of preheater stages within these kilns to present even further energy savings. The number in Table 5.4 therefore presents the specific fuel savings for the combination of these two options (conversion of a long dry kiln to a preheater kiln and increase of preheater stages) from Worrell et al. (2013).

Table 5.4: Specific saving potentials for waste heat use for material preheating from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.814 – 1.628	-	Worrell et al. (2013)

Since the specific saving potential found for this saving option is much larger in Worrell et al. (2013) than in FORECAST, it proposed to increase the specific fuel saving potential in FORECAST. In light of the large difference between the two references and the uncertainty regarding the assumptions behind the original data in FORECAST, it is **proposed to update the specific fuel savings in FORECAST according to the average of the range presented in Worrell et al. (2013).** Since the specific electricity saving currently used in FORECAST is so marginal, it is proposed to delete this.

Type of modification

The conversion of older kilns is mainly attractive when the old kiln needs replacement and a new kiln would be too expensive (Worrell et al., 2013). It requires the installation of new preheaters and will have a positive influence on the productivity of the process, due to a higher degree of pre-calcination as the feed enters the kiln. Also, the kiln length may be shortened by 20-30% thereby reducing radiation losses. As the capacity increases, the clinker cooler may have to be adapted to cool the large amounts of clinker (Worrell et al., 2013). Overall, it can be considered a **replacement technology** in which older kilns are replaced by more efficient ones.

Diffusion

The conversion of older kilns has already been taking place in Europe in the last years (Worrell et al., 2013). According to the diffusion parameters in FORECAST, 56% of the kilns used waste heat for material preheating in 2007. This means the technology is in **the linear (15-85%) stage of diffusion.**

Payback period

The payback period for this technology used in FORECAST is a **medium (2-4 years) payback period** of 3.77 years which is deemed realistic for a technology in the linear stage of diffusion.

Table 5.5: Proposed updated FORECAST data for waste heat use for material preheating

Specific saving potential [GJ/t]	
Fuels	1.221
Electricity	-

6.1.2. Precalcination

Table 5.6: FORECAST data for precalcination

Specific saving potential [GJ/t]	
Fuels	0.28
Electricity	0
Historic diffusion [%]	
1990	-
2000	-
2004	25
2007	27
Diffusion limit [%]	-
Specific investment cost [€/t]	10.84
Specific O&M costs [€/a · t]	0.01
Estimated payback time	4.32
Annual reduction investment [%]	-2.30
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Specific saving potential

The addition of a precalciner is described in the ENERGYSTAR guide from Worrell et al. (2013), from which the specific saving potential is presented in Table 5.7.

Table 5.7: Specific saving potentials for precalcination from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.140-0.628	-	Worrell et al. (2013)

The specific saving potential in FORECAST falls within the range from Worrell et al. (2013), however, it seems to be on the low side. In consultation with Ernst Worrell (personal communication, September/October 2016) it is therefore **proposed to update the numbers in FORECAST** to the average of the range presented in Table 5.8.

Type of modification

The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption. Even though as many features of the existing plant will be used, existing plants will need to be converted in order to accommodate the increased production capacity (Worrell et al., 2013). The technology can be considered a **replacement technology** since the old and new technologies are similar, but adding a precalciner makes the process more energy-efficient.

Diffusion

Adding or retro-fitting precalciners has taken place in several plants in Europe, including Germany, Italy and Switzerland (Worrell et al., 2013). This is reflected in the diffusion parameters in FORECAST, which indicate that 27% of the dry clinker calcination production processes in Europe in 2007 had applied precalciners. Even if this number has increased since 2007, the technology can be assumed to in the **linear phase (15-85%) of diffusion.**

Payback period

The payback period for the addition/retrofit of a precalciner is estimated at 4.32 years in FORECAST, which represents a **medium (2-4 years) payback period**. Since it is a technology in the linear phase (15-85%) of diffusion, this seems a realistic payback period.

Table 5.8: Proposed updated FORECAST data for precalcination

Specific saving potential [GJ/t]	
Fuels	0.45
Electricity	0

6.1.3. Efficient clinker cooler

Table 5.9: FORECAST data for efficient clinker cooler

Specific saving potential [GJ/t]	
Fuels	0.2

Electricity	-0.005
Historic diffusion [%]	
1990	-
2000	-
2004	10
2007	13
Diffusion limit [%]	-
Specific investment cost [€/t]	4.41
Specific O&M costs [€/a · t]	0.025
Estimated payback time	2.71
Annual reduction investment [%]	-2.30
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Specific saving potential

The conversion efficient clinker cooler technology is described in Worrell et al. (2013) as being the conversion of older types of coolers (shaft, rotary, planetary, travelling) to at least grate coolers (since even more modern 4th and 5th generation cooler technologies are being developed). Furthermore, there is also an option to optimize the grate cooler with regard to heat recovery. The range presented in Table 5.10 represents the combination of these two saving options (conversion to grate cooler technology and optimization of heat recovery/upgrade of clinker cooler) from Worrell et al. (2013).

Table 5.10: Specific saving potentials for efficient clinker cooler from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.34 – 0.44	(-0.027) – (-0.012)	Worrell et al. (2013)

The specific saving potential found for this saving option is larger in Worrell et al. (2013) than in FORECAST. In light of the uncertainty regarding the assumptions behind the original data in FORECAST and in consultation with Ernst Worrell (personal communication, September/ October 2016), it is **proposed to update the specific fuel savings in FORECAST** according to the average of the range presented in Worrell et al. (2013) (Table 5.11).

Type of modification

The required reconstruction for converting cooler technology to more energy efficient technology may include installing new exhaust fans, shortening the kiln and new cooler filters (Worrell et al., 2013). Therefore, some adaptation of the production process is required for this saving option. Overall, the technology may be considered a **substitution technology** in which old types of coolers are replaced with similar, but more energy-efficient types of coolers.

Diffusion

The grate cooler is the modern variant of efficient clinker cooler technology and is used in almost all modern kilns. Replacement of planetary coolers by grate coolers is also common (Worrell et al., 2013). The diffusion parameters in FORECAST represent the assumption that 13% of the dry clinker calcination processes in 2007 had applied modern cooler technology. Since grate coolers are applied in most modern kilns, it would be expected that the diffusion would be at least in the **linear (15-85%) phase of diffusion**. In this light, the diffusion used in FORECAST would seem om the low side. However, it is possible that the technology data in FORECAST represent even other/newer concepts of clinker coolers than grate coolers.

Payback period

The payback period for the efficient clinker cooler technology is 2.71 years in FORECAST which can be considered a **medium (2-4 years) payback period.** However, since it not clear exactly what kind of technologies are represented by this saving option, the payback period cannot be adequately evaluated at this point.

Table 5.11: Proposed updated FORECAST data for efficient clinker cooler

Specific saving potential [GJ/t]	
Fuels	0.39
Electricity	-0.020

6.1.4. Optimized burning

Table 5.12: FORECAST data for optimized burning

Specific saving potential [GJ/t]	
Fuels	0.18
Electricity	0.007
Historic diffusion [%]	
1990	-
2000	-
2004	6
2007	10
Diffusion limit [%]	-
Specific investment cost [€/t]	4.50
Specific O&M costs [€/a · t]	0.9
Estimated payback time	4.84
Annual reduction investment [%]	-2.30
Annual reduction O&M [%]	0

Lifetime	
Calculatory	10
Real	15
Market entry	-

Specific saving potential

Optimized burning is discussed as a saving option in Worrell et al. (2013) under kiln combustion system improvements and its specific saving potentials are presented in Table 5.14.

Table 5.13: Specific saving potentials for optimized burning from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.070 – 0.372	0	Worrell et al. (2013)

From the range presented in Table 5.14, it can be concluded that the saving potential in FORECAST falls within this range, however, it seems to be on the low side. In consultation with Ernst Worrell (personal communication, September/October 2016) it is therefore proposed to **update the numbers in FORECAST** to the average of the range presented in Table 5.13 and delete the electricity saving as represented in FORECAST since it is so marginal (Table 5.14).

Table 5.14: Proposed updated FORECAST data for optimized burning

Specific saving potential [GJ/t]	
Fuels	0.221
Electricity	-

Type of modification

Optimized burning addresses problems such as poorly adjusted firing, incomplete fuel burn-out with high CO formation and combustion with excess air (Worrell et al., 2013). Optimizing combustion can be achieved with different approaches. Therefore, this saving option can represent different specific adjustments to the combustion process. In general, since optimizing combustion will not impact the production process, but will mainly save energy through more efficient combustion, the technology can be considered an **add-on technology**.

Diffusion

From recent literature, it is unclear how many kilns have currently optimized their combustion processes. The diffusion parameters in FORECAST show the assumptions that only 10% of the dry clinker calcination production processes had applied optimized burning in 2007 (Table 5.12), which means that optimized burning is still in the **take-off (<15%) stage of diffusion** even though this cannot be validated with the recent literature.

Payback period

The payback period used in FORECAST, which is 4.84 years, represents a **medium (2-4 years) payback period**. This can be considered consistent with the diffusion parameters used in FORECAST which is representative for a technology in the take-off (<15%) stage of diffusion.

6.1.5. Low carbonat cement types

Table 5.15: FORECAST data for low carbonat cement types

Specific saving potential [GJ/t]	
Fuels	1
Electricity	0.02
Historic diffusion [%]	
1990	-
2000	-
2004	2
2007	2
Diffusion limit [%]	-
Specific investment cost [€/t]	80.50
Specific O&M costs [€/a · t]	0
Estimated payback time	8.39
Annual reduction investment [%]	-2.30
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	2025

Specific saving potential

Low carbonat cement types represent the option to use decarbonated feedstock material (such as electric arc furnace slag, granulated blast furnace slag, fly ash and cement kiln dust). In Worrell et all. (2013), several of such novel substitution feedstocks and their saving potential are discussed. The range presented in Table 5.16 is therefore based on a combination of the following saving options from Worrell et al. (2013): steel slag in clinker (10 % substitution), fly ash or blast furnace slag (15% substitution), cement kiln dust in clinker, calcareous oil share in clinker (8% substitution) and reduction of the lime saturation factor. However, even when the specific saving potentials for all these substitution feedstocks are combined, the data in FORECAST remains more favorable. This can be explained by the fact that this includes the implementation of the Celitement feedstock (patented by KIT) as a low carbonat cement option with has shown a favourable balance of substances and energy in their experiments by KIT and Fraunhofer and which implies such savings are possible.

Table 5.16: Specific saving potentials for waste heat use for low carbonat cement types from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.686 – 0.709	(-0.081) – (-0.039)	Worrell et al. (2013)

Since the FORECAST data are based on a patented process by Fraunhofer itself, the **FORECAST data can be considered up to date** for this saving option.

Type of modification

The application of new cement types, and especially Celitement, represents a very innovative technology, which will have a large impact on the production process. Therefore, the technology can be considered a **substitution technology.**

Diffusion

Applying low carbonat cement types is a very innovative technology, which becomes clear from the explanation for the specific saving potential. Therefore, the technology is still in the **incubation (0%) stage of diffusion**, which is also represented in the diffusion parameters in FORECAST.

Payback period

Due to the novelty of this technology, there is large degree of uncertainty in the techno-economic performance of this technology in the future. At this point, it is therefore expected that the technology will have a long payback period. This is correctly represented by the payback period used in FORECAST which is 8.39 years which can be considered a **very long payback time (<8 years)** and is therefore deemed realistic for this technology.

6.2. Container glass

Table 5.17: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Container glass	5.8		1.4		7.2
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	4	6	

Specific energy consumption

The production container glass mainly requires energy for the melting of glass. The range of energy consumption encountered within the sector is very large, since flaconnage has a much higher SEC than mainstream bottles and jars (JRC, 2013). The specific energy consumption for container glass from literature, presented in Table 5.18, represents the results of a survey from 2009. It represents the mean specific energy consumption across all product types, in which only the mid-90th percentile of the data from the survey are taken into account.

Table 5.18: Specific energy consumption for container glass literature

Specific fuel consumption (GJ/t)	**Specific electricity consumption (GJ/t)**	**Reference**
7.70		JRC (2013)

The specific fuel consumption represented in Table 5.18 is in line with the specific energy consumption currently used in FORECAST (Table 5.17) and therefore, **FORECAST can be considered in line with the recent literature** for the production of container glass.

6.2.1. Increased cullets

Table 5.19: FORECAST data for increased cullets

Specific saving potential [GJ/t]	
Fuels	1.30
Electricity	0
Historic diffusion [%]	
1990	-
2000	-
2004	47
2007	47
Diffusion limit [%]	85
Specific investment cost [€/t]	28.02
Specific O&M costs [€/a · t]	0.84
Estimated payback time	2.58
Annual reduction investment [%]	-1.0
Annual reduction O&M [%]	-1.0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Specific saving potential

Ernst Worrell (personal communication, September/October 2016) has indicated that 1.3 GJ/t as presented in Table 5.19 seems high in light of a specific energy consumption for fuels of 5.8 GJ/t. This implies, in his opinion, that the baseline already includes the presence of cullets to some extent in the SEC and that therefore, either the savings potential should go down of the SEC should go up. However, the IEA (2007) states that as a general rule the increased use of cullets from 0 to 100% may reduce the furnace energy consumption from 5.2 to 4.0 GJ/t which would therefore seem in line with the data in FORECAST.

Table 5.20: Specific saving potentials for increased cullets from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
1.2		JRC (2013)

Since the data in FORECAST do not seem to differ significantly from the information in the literature, it can be considered **in line with recent literature.**

Type of modification

Increasing the share of cullets (recycled glass) reduces the specific energy consumption of glass production. In container glass, cullet use can vary from 10% to over 90% (Worrell, 2008). However, the non-homogeneity of glass colors and contaminants and impurities mixed with recycled glass present problems for manufacturers (Worrell, 2008). However, overall, the increased use of cullets can be considered an **add-on technology** in which energy savings are achieved by using a different feedstock in the glassmaking process.

Diffusion

In the E.U. specifically, a 2003 reference mentions an average cullet use in container glass production of 60% (Worrell, 2008). The increased use of cullets is therefore a saving option which is already quite common in Europe. This is in line with the diffusion parameters in FORECAST which represent increased cullet use in 47% of container glass production in 2007. The technology is therefore in its **linear (15-85%) phase of diffusion.**

Payback period

Since, the technology is already quite common in Europe, it is expected that the payback period of using an increased share of cullets will be reasonable. This is confirmed by the payback period used in FORECAST which is 2.58 years, representing a **medium (2-4 years) payback period.**

6.3. Bricks

Table 5.21: FORECAST process data

	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
Bricks	1.4		0.2		1.6
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	0	0	

Specific energy consumption

There is limited new literature on the specific energy consumption of brick production. However, there is some older literature which can be used to validate the specific energy consumption in FORECAST (Table 5.22).

Table 5.22: Specific energy consumption for brickmaking literature

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Reference
2.3		IEA (2007)

The number in Table 5.22 represents a the specific energy consumption of a modern tunnel kiln, which is the most widely accepted kiln type (IEA, 2007). Compared to FORECAST, the SEC in FORECAST seems on the low side. However, since the reference from IEA (2007) is quite outdated, it can be deemed realistic that the specific energy consumption has decreased in the last decade. Since the difference is not very large, the **FORECAST data can be considered representative.**

6.3.1. Energy management system

Table 5.23: FORECAST data for energy management system

Specific saving potential [GJ/t]	
Fuels	0.35
Electricity	0.0019
Historic diffusion [%]	
1990	-
2000	-
2004	2
2007	3
Diffusion limit [%]	-
Specific investment cost [€/t]	14.46
Specific O&M costs [€/a · t]	0
Estimated payback time	4.51
Annual reduction investment [%]	-1.10
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	15
Market entry	-

Table 5.24: Specific saving potentials for an energy management system for bricks from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
0.185	0.002	Fleiter et al. (2013)

No new recent literature could be found on the potential energy savings from energy management systems in the production of bricks. However, consultation with Ernst Worrell (person communication, September/October, 2016) brought to attention that the energy savings proposed in table 14.1 are quite high. When compared to older data for this saving option (presented in table 14.2) which were previously used in FORECAST, the specific fuel saving potential has increased with 0.165 GJ/t. However, Ernst Worrell (personal communication, September/October 2016) has indicated that using controls usually only leads to about 10% of energy savings from the specific energy consumption (which would in this case be 0.14 GJ/t). In light of the findings above, it **proposed to lower the saving potential** for this saving option according to the data previously used in FORECAST.

Type of modification

Using an energy management system implies changing how energy is managed by implementing an organization-wide energy manangement plan. Therefore, this saving options can be considered an **organizational measure** which does not make technological changes to the process.

Diffusion

According to the diffusion parameters currently used in FORECAST, the saving option is in the **incubation (0%) of diffusion**. Since there is no recent literature on energy use in brick production, it is not possible to validate this at this point in time.

Payback period

The payback period for using an energy management system in brick production is currently set at 4.51 years in FORECAST, which is a **medium (2-4) payback period**. This can be considered quite long if the saving option is considered an organizational measure (see type of modification).

Table 5.25: Proposed updated FORECAST data for an energy management system

Specific saving potential [GJ/t]	
Fuels	0.185
Electricity	0.0019

6.4. References

- Fleiter, T., Schlomann, B., & Eichhammer, W. (2013). Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien: Einsparpotenziale, Hemmnisse und Instrumente. T. Fleiter (Ed.). Fraunhofer-Verlag.
- IEA (2007), Tracking Industrial Energy Efficiency and CO_2 Emissions. Retrieved from https://www.iea.org/publications/freepublications/publication/tracking_emissions.pdf
- JRC (2013), Best Available Techniques (BAT) Reference Document for the Manufacture of Glass. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). Retrieved from:
- http://eippcb.jrc.ec.europa.eu/reference/BREF/GLS_Adopted_03_2012.pdf
- Worrell, E. (2008). Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry. An ENERGY STAR Guide for Energy and Plant Managers. *Lawrence Berkeley National Laboratory*.
- Worrell, E., Kermeli, K., & Galitsky, C. (2013). Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making An ENERGY STAR® Guide for Energy and Plant Managers. Retrieved from:
- https://www.energystar.gov/sites/default/files/tools/ENERGY%20STAR%20Guide%20for%20the%20Cement%20Industry%2027_08_2013_Rev%20js%20reformat%2011192014.pdf

7. Food, beverages and tobacco

7.1. Meat processing

Table 6.1: FORECAST process data

Meat processing	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
	2.0		1.5		3.5
	Heating [%]	Cooling [%]	Heating [%]	Cooling [%]	
	100	0	5	61	

Specific energy consumption

The SEC in FORECAST is based on several sub-processes: cooling, cooking, brewing, smoking and packaging (Fleiter et al., 2013). However, the exact assumptions behind the SEC in FORECAST are not clear. These assumptions are expected to have a big influence on the SEC of meat processing since the process includes so many different types of products. For this reason, **the SEC cannot be updated at this point.**

7.1.1. Process optimization for cooling

Table 6.2: FORECAST data for process optimization for cooling

Specific saving potential [GJ/t]	
Fuels	0
Electricity	0.345
Historic diffusion [%]	
1990	-
2000	-
2004	-
2007	30
Diffusion limit [%]	100
Specific investment cost [€/t]	11.62
Specific O&M costs [€/a · t]	0
Estimated payback time	1.12
Annual reduction investment [%]	-0.50
Annual reduction O&M [%]	0
Lifetime	
Calculatory	3
Real	15
Market entry	2010

Specific saving potential

Specific data for the saving potential of process optimization for cooling in meat processing cannot be found in recent literature. Therefore, **the data in FORECAST cannot be updated based on the recent literature.**

Type of modification

The term process optimization implies computer-aided optimization reduce energy consumption of a process. In this light, process optimization of cooling can be considered an **organizational measure in** which the use of present technology is improved rather than a novel technology being added to the process.

Diffusion

There is no specific new data on process optimization for cooling in the meat processing industry. However, the diffusion parameters used in FORECAST (Table 6.2) show that 30% of the meat processing processes applied process optimization for cooling in 2007. Even if this share has increased in the last decade, it can be considered realistic that the technology will still be in the **linear (15-85%) stage of diffusion.**

Payback period

Since the optimization of cooling is considered mainly an organizational measure, it is expected that it will have a reasonably low payback period. The payback period used in FORECAST is 1.12 years which represents a **short (<2 years) payback period.** Even though this cannot be validated with data from more recent data, this is deemed realistic based on the diffusion and type of modification of the saving option.

7.1.2. Heat pump integration

Table 6.3: FORECAST data for heat pump integration

Specific saving potential [GJ/t]	
Fuels	0.20
Electricity	0
Historic diffusion [%]	
1990	-
2000	-
2004	-
2007	0
Diffusion limit [%]	100
Specific investment cost [€/t]	8.22
Specific O&M costs [€/a · t]	0
Estimated payback time	4.54
Annual reduction investment [%]	-1.10

Annual reduction O&M [%]	0
Lifetime	
Calculatory	5
Real	10
Market entry	2010

Specific saving potential

The specific saving potential for fuels presented in Table 6.4. is quite high compared to the specific saving potential for fuels in FORECAST (Table 6.3). The number in Table 6.4 is based on the following information from Seck et al. (2013): "50% of final energy demand in meat industry can be provided by heat recovered by heat pumps". This has been interpreted as being 50% of the specific energy consumption used for heating only (considering both fuels and electricity), which gives the number represented in Table 6.4. The big difference can possibly be explained by the fact that the data in FORECAST is based on a reference from 2009 and the development in heat pumps has been significant since that time.

Table 6.4: Specific saving potentials for heat pump integration from literature

Specific saving potential fuels (GJ/t)	Specific saving potential electricity (GJ/t)	Reference
1.04		Seck et al. (2013)

The large difference between the data in FORECAST and the data in Table 6.4 suggest that the potential for heat pump integration in the meat processing industry may be **on the low side in FORECAST.** However, because of the large difference between the two numbers and to avoid overestimation, it is proposed, in consultation with Ernst Worrell (personal communication, September/October 2016) to take the average of the numbers of Table 6.3 and Table 6.4. In consideration of the increased electricity use due to the use of heat pumps, it can be deduced from the case study of the French food & drink industry by Seck et al. (2013) that, relatively speaking, 12% of the total achieved fuel savings in this case study are compensated for by increased electricity use. If this is applied to the specific fuel saving presented in Table 6.5, this gives an increased electricity use of 0.07 GJ/t.

Type of modification

The integration of heat pumps in the food & drink industry is based on recovering energy from the multitude of low-temperature waste heat sources in this industry (Seck et al., 2013). In this way, the integration heat pumps does not influence the production process itself but uses the waste heat from these processes. It can therefore be considered an **add-on technology.**

Diffusion

The development of heat pumps has been substantial in the last year, however, at this point heat pumps are not incorporated in the food processing industry at a large scale yet (Seck et al., 2013). This is reflected in the diffusion parameters currently used in FORECAST, which show the technology is still in the **incubation (0%) phase of diffusion.**

Payback period

Since the technology is not commercially applied on a large scale yet, it is expected that the payback period is significant. This is reflected in the payback period currently used in FORECAST which is 8.22 years which is a **very long (<8 years) payback period.**

Table 6.5: Proposed updated FORECAST data for heat pump integration

Specific saving potential [GJ/t]	
Fuels	0.62
Electricity	-0.07

7.2. References

- Fleiter, T., Schlomann, B., & Eichhammer, W. (2013). Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien: Einsparpotenziale, Hemmnisse und Instrumente. T. Fleiter (Ed.). Fraunhofer-Verlag.
- Seck, G. S., Guerassimoff, G., & Maïzi, N. (2013). Heat recovery with heat pumps in non-energy intensive industry: A detailed bottom-up model analysis in the French food & drink industry. Applied energy, 111, 489-504.

8. Chemical and petrochemical

8.1. Ethylene

Table 7.1: FORECAST process data

Ethylene	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
	35.9		0		35.9
	Heating [%]	Cooling [%]	Heating [%]	Cooling [%]	
	100	0	0	4	

The energy use in the production of ethylene is complex to analyze, since ethylene can be produced from the cracking of different feedstocks and there are also many by-products produced simultaneously. To this end, it is difficult to assign energy consumption to specific by-products or sub-processes. In the case of FORECAST, the energy use of the entire ethylene cracker is assigned to the production of ethylene. Main documents which are used for the estimation of energy saving potential of industrial technologies (BREF documents, Energy Star guides, EPA documents, etc.), have not been updated for the chemical industry since the last update in 2012. Furthermore, the updating of these saving options is complicated further by the complex and heterogenous structure of the chemical industry and ethylene production. General specific energy savings are difficult to quantify since individual systems can differ greatly with regard to raw materials, the existing degree of heat integration and different capacities and ages of the installations. Therefore, more specific literature is difficult to evaluate since it always requires a detailed look at the underlying assumptions. **For these reasons, the saving options for ethylene production cannot be updated within the timeline of this project.** Updating the data for ethylene production would require a more extensive, standalone investigation of energy use in ethylene production. What can be done, is to give an overview of the type of modification, the diffusion phase and payback period category based on the data already present in FORECAST. This information is presented in Table 7.2.

Table 7.2: Diffusion phase and payback period of the FORECAST saving options for ethylene

Saving option	Type of modification	Historical diffusion 2007	Diffusion phase	Payback period	Payback period category
Heat recovery	Add-on	58%	Linear	2.50	Medium
Utilization of flare gas	Add-on	68%	Linear	2.50	Medium
Heat integration of distillation columns	Replacement technology	15%	Linear	2.50	Medium
Modern control system	Add-on	68%	Linear	2.50	Medium

Integration of gas turbine	Replacement technology	0%	Incubation	2.50	Medium
Energy efficient compressors and refrigerators	Replacement technology	68%	Linear	2.50	Medium

8.2. Ammonia

Table 7.3: FORECAST process data

Ammonia	SEC fuels [GJ/t]		SEC electricity [GJ/t]		Total [GJ/t]
	11.3		0.5		11.8
	Heating [%]	**Cooling [%]**	**Heating [%]**	**Cooling [%]**	
	100	0	0	6	

Specific energy consumption

The specific energy consumption of ammonia production is a large part dependent on the feedstock used. In production processes based on the partial oxidation process, mainly coal and fuel oil are used as feedstock, while production processes based on the steam reforming process use natural gas. Table 7.4 presents the data about the SEC of ammonia production from recent literature.

Table 7.4: Specific energy consumption for ammonia production

Specific fuel consumption (GJ/t)	Specific electricity consumption (GJ/t)	Comments	Reference
10.93	0.29	Natural gas	Kermeli et al. (2013)
17.33	3.7	Coal	Kermeli et al. (2013)
16.13	0.7	Oil	Kermeli et al. (2013)
11.40	0.235	Weighted for Europe	Calculated based on data above and in text below.

The share of gas is 90% for Western Europe and 95% for Central European countries, with the rest of their ammonia production coming from oil (Kermeli et al., 2013). The production in 2010 was 11 Mt and 5.2 Mt in Western Europe and Central European countries, respectively. If these numbers are weighted accordingly, the specific energy consumption represented in the bottom of Table 7.4 is found. It can be concluded from these weighted average is very similar to the SEC in FORECAST and therefore, **the SEC in FORECAST can be considered up to date and in line with the recent literature.**

8.2.1. Efficiency package, synthesis gas section

Table 7.5: FORECAST data for efficiency package, synthesis gas section

Specific saving potential [GJ/t]	
Fuels	1.33
Electricity	0.07
Historic diffusion [%]	
1990	30
2000	50
2004	54
2007	56
Diffusion limit [%]	90
Specific investment cost [€/t]	38.70
Specific O&M costs [€/a · t]	1.93
Estimated payback time	3.18
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

Specific saving potential

The saving option as presented in FORECAST, represents a package of different measures which makes it difficult to evaluate this saving option. Based on Fleiter et al. (2013), it is expected that this saving option incorporate measures for both the steam reforming and partial oxidation process, including for steam reforming:

- Low-temperature desulfurization. This allows low-pressure steam to be used for heating the feed gas.
- Preheating the raw material/steam mixture and the air with waste heat from the primary or secondary reformer
- Reduction of the steam/carbon ratio
- Introduction of a modern gas turbine for air compression, the exhaust gas of which is introduced into the primary reformer (applies more to new plants)
- Optimization of the kiln burner in order to ensure an optimal distribution of the exhaust gas form the gas turbine over the burner.

- Switching on a catalytic adiabatic pre-reformer in combination with a suitable steam management system.
- Isothermal CO conversion (mainly for new installations)
- Optimization of CO2 capture by using more effective absorption media
- Membrane separation of the methane in the methanation stage
- Use of a liquid nitrogen scrubber for the purification of the synthesis gas.

Regarding partial oxidation, the following measures are included:

- Use of sulfur-resistant catalysts for CO conversion
- Use of a liquid nitrogen wash for the purification of the synthesis gas

The saving option has been implemented this way to represent modernizing of existing facilities. In these facilities, to a varying extent, the above-described measure have already been implemented. According to Fleiter et al. (2013), an estimate of the share of each measure is hardly possible due to a lack of published information. Therefore, an average value of the energy saving potential is represented in FORECAST with this saving option. However, this means that the **specific saving potential cannot be updated at this point of time** since this would require a much more detailed analysis of the underlying assumptions in FORECAST and how these could be updated.

Type of modification

Since the saving option includes a multitude of measures which improve the energy efficiency of the gas synthesis in ammonia production, it is **not possible to assign this saving option to a certain type of modification.** Fleiter et al. (2013) indicate that some of the measures included in this saving option are standard in the construction of new plants. However, whether measures are also suitable for retrofitting in existing installation will differ by measure and plant.

Diffusion

For this type of saving option, it is difficult to assign a certain phase of diffusion, since the option includes a range of different measures. Therefore, the phase of diffusion can only be assigned based on what is already used in FORECAST. In FORECAST, a diffusion of 56% in 2007 is used, which represents a **linear (15-85%) phase of diffusion.**

Payback period

Like for diffusion, it is difficult to assign a payback period to this saving option, since the option includes a range of different measures. Therefore, not too much importance should be attached to the payback period of this saving option. The payback period can only be evaluated in general based on the data already used in FORECAST. In FORECAST, a payback period of 3.18 years is used which represents a **medium (2-4 years) payback period.**

8.2.2. Efficiency package, ammonia synthesis

Table 7.6: FORECAST data for efficiency package, ammonia synthesis

Specific saving potential [GJ/t]	
Fuels	1
Electricity	0.07
Historic diffusion [%]	
1990	30
2000	50
2004	54
2007	57.3
Diffusion limit [%]	95
Specific investment cost [€/t]	25.44
Specific O&M costs [€/a · t]	1.27
Estimated payback time	2.59
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	20
Market entry	-

The saving option as presented in FORECAST, represents a package of different measures which makes it difficult to evaluate this saving option. Based on Fleiter et al. (2013), it is expected that this saving option includes the following measures:

- Indirect cooling of the ammonia synthesis reactor
- Recovery of hydrogen from the purge gas stream by cooling or membrane technology
- Use of small-grained catalysts in the ammonia reactor
- Use of a low-pressure or medium-pressure ammonia synthesis
- Use of a modern process control system to drive optimum operating points
- Recovery of the ammonia from the process condensate, e.g. by stripping
- Use of turbochargers in connection with steam turbines

The saving option has been implemented this way to represent modernizing of existing facilities. In these facilities, to a varying extent, the above-described measure have already been implemented. According to Fleiter et al. (2013), an estimate of the share of each measure is hardly possible due to a lack of published information. Therefore, an average value of the energy saving potential is represented in FORECAST with this saving option. However, this means that the **specific saving potential cannot be updated at this point of time** since this would require a much more detailed analysis of the underlying assumptions in FORECAST and how these could be updated.

Type of modification

Since the saving option includes a multitude of measures which improve the energy efficiency of the gas synthesis in ammonia production**, it is not possible to assign this saving option to a certain type of modification**. Fleiter et al. (2013) indicate that some of the measures included in this saving option are standard in the construction of new plants. However, whether measures are also suitable for retrofitting in existing installation will differ by measure and plant.

Diffusion

For this type of saving option, it is difficult to assign a certain phase of diffusion, since the option includes a range of different measures. Therefore, the phase of diffusion can only be assigned based on what is already used in FORECAST. In FORECAST, a diffusion of 57.3% in 2007 is used, which represents a **linear (15-85%) phase of diffusion.**

Payback period

Like for diffusion, it is difficult to assign a payback period to this saving option, since the option includes a range of different measures. Therefore, not too much importance should be attached to the payback period of this saving option. The payback period can only be evaluated in general based on the data already used in FORECAST. In FORECAST, a payback period of 2.59 years is used which represents a **medium (2-4 years) payback period.**

8.2.3. New plant (BAT)

Table 7.7: FORECAST data for new plant (BAT)

Specific saving potential [GJ/t]	
Fuels	3.7
Electricity	0.14
Historic diffusion [%]	
1990	0
2000	0
2004	0
2007	0
Diffusion limit [%]	67
Specific investment cost [€/t]	0
Specific O&M costs [€/a · t]	0

Estimated payback time	-
Annual reduction investment [%]	0
Annual reduction O&M [%]	0
Lifetime	
Calculatory	10
Real	40
Market entry	-

Specific saving potential

This measure is included in FORECAST to represent the situation in Germany in which the average age of an ammonia plant is 35 years old. Even though plants will be able to continue to run at this age for years, with increasing age and associated increase in maintenance costs, such plants will not be able to compete with new, modern systems and must then be decommissioned for economic reasons (Fleiter et al., 2013). This replacing of old plants with newer ones will represent a potential for large energy savings. However, since most references on this production process include feedstock energy in their data**, it is not possible to update this saving potential** without a very detailed analysis of the underlying assumptions.

Type of modification

Since this saving option represents the construction of entirely new plant with implementation of BAT, the saving option can be considered a **substitution technology.**

Diffusion

The saving option represents a completely new plant with implementation of BAT. At this point in time, there is no such plant constructed. Therefore, such a new BAT plant is still in the **incubation (0%) phase of diffusion.**

Payback period

The payback period for this option **cannot be evaluated at this point in time**, since there are no economic data present for this saving option in FORECAST.

8.3. References

- Fleiter, T., Schlomann, B., & Eichhammer, W. (2013). Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien: Einsparpotenziale, Hemmnisse und Instrumente. T. Fleiter (Ed.). Fraunhofer-Verlag.
- Kermeli, K., M. Corsten, W. Graus & E. Worrell (2013). Ammonia production. Energy Efficiency Technologies, Practices, Organizations and Programs. Utrecht University, May 2013 (internal document).