Koninklijke
Vereniging van
Nederlandse
Papier- en
karton-
fabrieken

DECARBONISING THE STEAM SUPPLY OF THE DUTCH PAPER AND BOARD INDUSTRY

8/1/2018

Raising steam for paper and board industry without emitting carbon dioxide

The Dutch paper and board industry is an energy-intensive sector that is actively searching for possibilities to reduce greenhouse gas emissions and to become more sustainable. In the production processes, large amounts of steam are used for drying. In the long term, the paper and board industry may be able to implement breakthrough technologies that do not require any steam. This report focuses on the medium term (up to 2030) and aims to give an overview of options for decarbonisation of the steam supply.

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This report is summary of the results of both parties their research. Note however that ECN part of TNO and Lux Research are each only responsible for the content of their own respective work, as presented in their individual reports.

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SAMENVATTING

De Nederlandse papier- en kartonindustrie is een energie-intensieve sector die actief op zoek is naar mogelijkheden om de uitstoot van broeikasgassen te verminderen en te verduurzamen. In de productieprocessen worden grote hoeveelheden stoom gebruikt om te drogen. Op lange termijn kan de papier- en kartonindustrie mogelijk doorbraaktechnologieën toepassen waar geen stoom voor nodig is. Dit rapport richt zich op de middellange termijn (tot 2030) en heeft als doel een overzicht te geven van mogelijkheden voor decarbonisatie van de stoomvoorziening.

De structuur van dit rapport

Dit rapport bestaat uit twee delen. Het eerste deel geeft een overzicht van gegevens over de papier- en kartonindustrie in Nederland in 2015. Dit deel bespreekt productieprocessen, materiaalverbruik, energieverbruik, energieproductie, broeikasgasemissies en productiekosten. Om dit overzicht te maken hebben de VNP, het KCPK en ECN part of TNO een dataset samengesteld met gedetailleerde gegevens over de Nederlandse papier- en kartonfabrieken.

Het tweede deel van het rapport bespreekt alternatieve technologieën voor de stoomvoorziening. Lux Research heeft een inventarisatie gemaakt van technologische opties die een één-op-één vervanging kunnen zijn van aardgasgestookte stoomketels die stoom produceren tot 200 ºC. De resultaten van Lux Research geven inzicht in de kosten en efficiëntie van deze technologieën en lichten toe waar deze technologieën ontwikkeld worden.

De mogelijke rol van deze alternatieve technologieën wordt besproken op basis van verwachte ontwikkelingen in het energiesysteem als geheel, zoals de ontwikkeling van energieprijzen, de elektriciteitsopwekking en de energie-infrastructuur.

De papier- en kartonindustrie in Nederland

In 2015 bestond ongeveer 68% van de productie van de Nederlandse papier- en kartonindustrie uit verpakkingsmateriaal (golfkarton, massief karton, vouwkarton), 28% uit grafisch papier (op basis van primaire vezels en gerecyclede vezels), en 4% uit sanitair papier.

Er waren 21 fabrieken met een totale productiecapaciteit van ongeveer 2.900 kton per jaar. De fabrieken realiseerden een gemiddelde bezettingsgraad van 92%. De jaarlijkse productie van de individuele fabrieken varieerde van 5.000 tot 600.000 ton per jaar. Grote fabrieken produceren meestal bulkproducten, terwijl kleinere fabrieken meestal meer gespecialiseerde producten maken. Op één na waren alle fabrieken onderdeel van een grotere ondernemingsgroep.

Papier en kartonproductie bestaat uit de productie en voorbereiding van de vezels, de vorming van papier en droging. Het thermisch drogen van het papier is verantwoordelijk voor het grootste deel van het stoomverbruik.

Dit rapport presenteert gegevens over energie en emissies in 2015:

- Tien fabrieken maakten gebruik van warmtekrachtkoppeling (WKK) om te voorzien in (een deel van) hun stoomvraag. Het totaal elektrisch vermogen van deze installaties was 217 MWe en het totaal thermisch vermogen 496 MWth. De totale brandstofinzet was 14,7 PJ.
- Het finaal verbruik van elektriciteit in de Nederlandse papier- en kartonindustrie was 4,6 PJ. De totale elektriciteitsopwekking met WKK-installaties was 4,1 PJ.
- Het totale verbruik van stoom/warmte was 12,5 PJ, waarvan 62% (7,8 PJ) geproduceerd werd met WKK-installaties.
- De totale ETS emissies van de papier- en kartonfabrieken in Nederland waren in 2015 1.054 kton CO2-eq.

Alternatieve technologieën voor stoomproductie

Lux Research heeft enkele van de meest veelbelovende technologie-opties geselecteerd die een één-op-één vervanging kunnen zijn voor aardgasgestookte stoomketels die stoom produceren met een temperatuur tot 200 ºC. Voor de geselecteerde technologieën heeft Lux Research data verzameld en inschattingen gemaakt van waarschijnlijke toekomstige eigenschappen.

De volgende technologieën zijn onderzocht:

- Terugwinning van restwarmte met een warmtepomp: Warmte uit de omgeving of een reservoir wordt met behulp van elektriciteit in temperatuur verhoogd.
- Directe elektrische verwarming: Met directe elektrische verwarming kan stoom worden geproduceerd. Dit verschilt niet veel van een elektrische ketel, maar dan op een grotere schaal en bij hogere temperatuur en druk.
- Verbranding van waterstof: De industrie kan waterstof inkopen en verbranden in plaats van aardgas.
- Elektrolyse: In plaats van de inkoop van waterstof kunnen bedrijven ter plekke waterstof maken met elektrolyse. De waterstof kan dan worden verbrand om de gewenste temperatuur te bereiken.
- WKK-systeem op basis van vergassing van biomassa: Biomassa wordt vergast en het gas wordt gebruikt als brandstof voor een warmtekrachtkoppelingseenheid.

Andere opties (zoals geothermie, restwarmte van nabije industrie en biogas) kunnen ook een belangrijke rol spelen in de decarbonisatie van de stoomvoorziening. Lux Research heeft de overwegingen ten aanzien van de selectie van de technologieën toegelicht. Geothermie is niet geselecteerd omdat het alleen toepasbaar is voor industrie op een geschikte locatie. De mogelijkheid om restwarmte van nabije industrie te gebruiken hangt af van de aanwezigheid van aanbieders van restwarmte. Biogas wordt als een algemeen haalbare optie gezien, maar de toegevoegde waarde van het selecteren van biogas is als beperkt gezien omdat er al veel studies over het gebruik van biogas beschikbaar zijn.

Discussie

Het doel dat is gesteld voor het Nederlandse Klimaatakkoord is om in 2030 een reductie van de nationale broeikasgasemissies te bereiken van 49% (ten opzichte van 1990). De huidige Europese ambitie is om in 2050 een reductie van 80 tot 95% te bereiken. Dergelijke reductiedoelstellingen kunnen alleen worden bereikt door grote veranderingen in het Nederlandse energiesysteem.

De rol van elektrificatie

In dit rapport zijn drie technologieën onderzocht die kunnen bijdragen aan elektrificatie van de stoomvoorziening van de industrie: warmtepompsystemen, directe elektrische verwarming en elektrolyse.

Elektrificatie door middel van elektrische warmtepompen kan leiden tot significante energie-efficiëntieverbeteringen vergeleken met aardgasketels. Onderzoek- en ontwikkelingsinspanningen zijn er op gericht om de kapitaalkosten te verlagen en de uitgangstemperaturen te verhogen.

Elektrificatie door middel van weerstandsverwarming of elektrolyse leidt niet tot substantiële energie-efficiëntieverbeteringen, maar kan toch resulteren in emissiereductie in combinatie met CO2-vrije elektriciteitsopwekking.

De eerste fase van elektrificatie kan plaatsvinden met hybride systemen. Dergelijke systemen kunnen gebruik maken van zonne- en windenergie die anders verloren zou gaan door curtailment.

De rol van waterstof

Vergeleken met elektriciteit heeft waterstof enkele voor- en nadelen. Het is gemakkelijker om waterstof op te slaan en met hoge dichtheid te transporteren. De productie van waterstof uit elektriciteit kan helpen om overschotten van zonne- en windenergie te benutten.

Een nadeel is dat het energieverbruik toeneemt omdat de ketenefficiëntie doorgaans lager is. Het gebruik van waterstof maakt meestal aanzienlijke aanpassingen bij energieverbruikers en veranderingen aan de infrastructuur noodzakelijk.

De technologie om waterstof te gebruiken en te produceren is al beschikbaar (bijvoorbeeld elektrolyse en waterstofbranders), maar deze technologieën zijn vaak nog niet concurrerend met de bestaande (fossiele) alternatieven.

De rol van biomassa

Biomassa heeft veel toepassingen in de energieproductie- en energieverbruikssectoren. Het kan worden gebruikt voor de productie van warmte, waterstof, elektriciteit, biobrandstoffen en voor specifieke industriële processen.

Vanuit een lange-termijn perspectief kan het gebruik van biomassa in de industrie logisch zijn, in het bijzonder omdat biomassa in combinatie met CCS kan leiden tot negatieve emissies. CCS is echter alleen toepasbaar bij voldoende schaalgrootte, zoals bij grote industriële puntbronnen of industriële agglomeraties.

Het gebruik van biomassa in de industrie in plaats van fossiele brandstoffen maakt het mogelijk om de CO2-uitstoot te verminderen. Het is echter wel van groot belang om de duurzaamheid van de biomassa te garanderen en de hoeveelheid broeikasgassen die vrijkomt in de keten te beperken.

De rol van geothermie

De industrie heeft maar beperkte ervaring met geothermie. In de diepe ondergrond is een grote hoeveelheid warmte beschikbaar. De mate waarin deze warmte kan worden toegepast in de industrie hangt af van de locatie en mogelijke neveneffecten. Geothermie speelt vaak een rol in kosten-optimale oplossingen voor diepe decarbonisatie van de industrie.

De rol van restwarmte

Industriële locaties kunnen restwarmte van andere industrie benutten als de restwarmteleverancier dichtbij genoeg is en warmtedistributie-infrastructuur aanwezig is. In clusters van industriële activiteit is het vaak mogelijk om aanbod en vraag van restwarmte bij elkaar te brengen. De industrie kan ook restwarmte leveren aan andere sectoren.

Algemene conclusie

Dit rapport bespreekt veelbelovende opties voor één-op-één vervanging van aardgasgestookte stoomketels in de industrie. Het biedt geen compleet overzicht van decarbonisatie van de stoomvoorziening.

Het succes van dergelijke technologieën is afhankelijk van toekomstige ontwikkelingen in het energiesysteem en energiebeleid, die vaak onzeker zijn. Er kunnen aanpassingen nodig zijn aan de energie opwekking, distributie en infrastructuur. Het zal niet zo zijn dat er één technologische oplossing is die in alle gevallen kan worden toegepast.

De klimaatuitdaging voor de energie-intensieve industrie is groot. Om de uitdaging succesvol aan te gaan is het essentieel om beter inzicht te krijgen in de huidige productiemethodes en de mogelijke verduurzamingsopties voor de Nederlandse industrie. Om hierover meer duidelijkheid te scheppen is samenwerking met de industrie essentieel.

SUMMARY

The Dutch paper and board industry is an energy-intensive sector that is actively searching for possibilities to reduce greenhouse gas emissions and to become more sustainable. In the production processes, large amounts of steam are used for drying. In the long term, the paper and board industry may be able to implement breakthrough technologies that do not require any steam. This report focuses on the medium term (up to 2030) and aims to give an overview of options for decarbonisation of the steam supply.

The structure of this report

This report consists of two parts. The first part gives an overview of data on the paper and board industry of the Netherlands in 2015. This part discusses production processes, material consumption, energy consumption, energy production, greenhouse gas emissions and production costs. To obtain this overview, the VNP, the KCPK and ECN part of TNO have compiled a dataset with detailed information on the Dutch paper and board mills.

The second part of the report discusses alternative technologies for the steam supply. Lux Research has made an inventory of technology options for a drop-in replacement for natural-gas fired steam boilers that produce steam of up to 200 ºC. The results of Lux Research give insights into the costs and efficiencies of these technologies and explain where these technologies are being developed.

The possible role of these alternative technologies is discussed, based on expected developments in the energy system as a whole, such as the developments of energy prices, electricity generation and energy infrastructure.

The paper and board industry in the Netherlands

In 2015, about 68% of the Dutch paper and board production consisted of packaging paper (corrugated board, solid board and folding boxboard), 28% of graphic paper (based on virgin and recovered fibre), and 4% of sanitary paper.

There were 21 mills with a combined production capacity of approx. 2,900 kton per year. The mills realised an average capacity utilization of 92%. The annual production capacity of the individual mills ranged from 5,000 to 600,000 tons per year. Large mills typically produce bulk products, whereas smaller mills tend to produce more specialized products. Except for one, all of the paper mills are part of a larger corporate group.

Paper and board production consists of the production and preparation of the fibres, formation of the paper, and drying. The thermal drying of the paper accounts for most of the steam use.

This report presents figures on energy and emissions in 2015:

- Ten paper mills used combined heat and power (CHP) installations to cover (part of) their steam demand. The total electrical capacity of these installations was 217 MWe and the total thermal capacity was 496 MWth. The total fuel input was 14.7 PJ.
- The final electricity consumption in the Dutch paper and board industry was 4.6 PJ. The total electricity generation by CHP installations was 4.1 PJ.
- The total consumption of steam/heat was 12,5 PJ of which 62% (7.8 PJ) was produced by CHP installations.
- The total ETS emissions of the paper and board plants in the Netherlands in 2015 amounted to 1,054 kton CO2-eq.

Alternative technologies for steam production

Lux Research has selected some of the most promising technology options for a drop-in replacement for natural-gas fired steam boilers that produce steam of up to 200 ºC. For the selected technologies, Lux Research has collected data and made estimations regarding their likely future performance.

The following technologies have been studied:

- Heat pump recovering waste heat: Heat from the environment or a reservoir is raised to a higher temperature level using electricity.
- Direct electric heating: Steam can be raised using direct electric heating. This is not much different from an electric kettle, just operating on a much larger scale and at higher temperatures and pressures.
- Hydrogen combustion: The industry could buy hydrogen and burn that instead of natural gas.
- Electrolysis: Rather than buying hydrogen, companies could generate hydrogen on-site using electrolysis and then burn the hydrogen to generate the desired temperature.
- Biomass gasification based CHP system: Biomass is gasified and the gas is used to run a CHP unit.

Other options (such as geothermal energy, waste heat from nearby industry and biogas) can play an important role in decarbonisation of the steam supply as well. Lux Research has explained the considerations for the technology selection. Geothermal energy has not been selected as it is only applicable to industry that is located in a suitable place. The possibility to use waste heat from nearby industry depends on the availability of suppliers of waste heat. Biogas is considered to be a viable option, but the added value of selecting biogas was considered to be limited, as there are already many studies on using biogas.

Discussion

The goal that has been set for the Dutch Climate Agreement is to reach a reduction of the national emission of greenhouse gases by 49% in 2030 (compared to 1990). The current European ambition is to reach a reduction of 80 to 95% in 2050. Such reduction targets can only be reached through major changes in the energy system of the Netherlands.

The role of electrification

This report has looked into three technologies than can contribute to electrification of the steam supply of the industry: heat pump systems, direct electric heating and electrolysis.

Electrification using electrical heat pumps can give rise to significant energy efficiency improvements compared to natural gas boilers. Research and development efforts are ongoing to reduce the capital expenditures and to increase the output temperatures.

Electrification using resistors or electrolysis does not lead to substantial energy efficiency improvements, but can still result in emission reduction when combined with CO2-free electricity generation.

The first phase of electrification may take place using hybrid systems. Such systems can use the solar and wind energy that would otherwise be lost through curtailment.

The role of hydrogen

Compared to electricity, hydrogen has some advantages and some disadvantages. It is easier to store hydrogen and to transport it with high energy density. Production of hydrogen from electricity can help to make use of surpluses of solar and wind energy.

A disadvantage is that the energy consumption increases because the chain efficiencies are typically lower. The use of hydrogen usually requires considerable measures on the side of the energy consumers and changes to infrastructure.

The technology to use and produce hydrogen is already available (e.g. electrolysis, hydrogen burners), but these technologies are often not yet competitive with the current (fossil) alternatives.

The role of biomass

Biomass has many applications in the energy production and in the energy demand sectors. It can be used for the production of heat, hydrogen, electricity, biofuels and for specific industrial processes.

From a long-term perspective, the large scale use of biomass in the industry can be logical, especially because biomass in combination with CCS can result in negative emissions. However, CCS can only be applied when the scale is sufficiently large, such as at large industrial point sources or industrial agglomerations.

The use of biomass in the industry instead of fossil fuels offers the possibility to reduce CO2-emissions. It is however very important to guarantee the sustainability of the biomass and to limit the greenhouse gas emissions in the supply chain.

The role of geothermal energy

The industry has only limited experience with geothermal energy. A large amount of heat is available in the deep underground. The extent to which this heat can be used in the industry depends on the location and possible side effects. Geothermal energy often plays a role in cost-optimal solutions for deep decarbonisation of the industry.

The role of waste heat

Industrial locations can use waste heat from other industry when the waste heat supplier is nearby enough and heat distribution infrastructure is available. In clusters of industrial activity it is often possible to match supply and demand of waste heat. The industry can also deliver waste heat to other sectors.

General conclusion

This report discusses promising drop-in replacements for natural-gas fired steam boilers in the industry. It does not provide a complete overview of technological options for decarbonisation of the steam supply.

The success of such technologies is dependent on future developments in the energy system and energy policies, which are often uncertain. Changes may be required to energy generation, distribution and infrastructure. There will not be one technological solution that can be applied in all cases.

The climate challenge for the energy-intensive industry is large. In order to meet the climate challenge, a better overview of the current production methods and possible sustainable improvement options for the Dutch industry is vital. To bring more clarity to these issues, cooperation with the industry is essential.


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INTRODUCTION

The Dutch paper and board industry is an energy-intensive sector that is actively searching for possibilities to reduce greenhouse gas emissions and to become more sustainable. In the production processes, large amounts of steam are used for drying. In the long term, the paper and board industry may be able to implement breakthrough technologies that do not require any steam. This report focuses on the medium term (up to 2030) and aims to give an overview of options for decarbonisation of the steam supply.

The energy transition requires completely new approaches. The industry is willing to invest in new methods of production, but is hindered by a lack of insight into developments in the energy system as a whole. There is also uncertainty about characteristics of technologies that are in an early stage of development. These uncertainties make it difficult to determine which technological options are the most attractive and how the limited financial resources for development can best be spent.

This report consists of two parts. The first part gives an overview of information on the paper and board industry of the Netherlands in 2015, which discusses production processes, material consumption, energy consumption, energy production, greenhouse gas emissions and production costs. To obtain this overview, the VNP, the KCPK and ECN part of TNO have compiled a dataset with detailed information on the Dutch paper and board mills.

The second part of the report discusses alternative technologies for the steam supply. Currently, boilers and combined heat and power (CHP) installations are generally used to produce steam. Lux Research has made an inventory of alternatives that may contribute to decarbonisation in the medium term. The results of Lux Research give insights into the costs and efficiencies of these technologies and explain where these technologies are being developed.

The possible role of these alternative technologies is discussed, based on expected developments in the energy system as a whole, such as the developments of energy prices, electricity generation and energy infrastructure.

THE PAPER AND BOARD INDUSTRY IN THE NETHERLANDS

The Dutch paper and board mills produce different end products, use various input materials and are also different in their energy consumption and production.

This chapter provides an overview of information on the Dutch paper and board industry for the year 2015, with respect to:

- Product categories and production capacities;
- Production processes, specific energy consumption and material use;
- Energy consumption, energy production and greenhouse gas emissions;
- Investments, market prices of materials and operating and maintenance costs.

Methodology for data collection

For this report, ECN part of TNO, the Royal Association of Dutch Paper and Paperboard (VNP) and the Knowledge Centre for Paper and Cardboard (KCPK) have compiled a dataset with information about the Dutch paper and board industry. Most of the data have been obtained from an existing dataset of the VNP containing data on capacities, energy, materials and emissions in 2015. The data has been gapfilled and corrected, and, in some cases, aggregated and rounded off to prevent confidentiality issues.

Product categories and production capacities

The Dutch paper and board industry produces different types of paper and board, each with their own characteristics (e.g. in terms of thickness and strength). These characteristics determine the possibilities for application.

In 2015, about 68% of the Dutch paper and board production consisted of packaging materials (corrugated board, solid board and folding boxboard), 28% of graphic paper (based on virgin and recovered fibre), and 4% of sanitary paper.

Product categories

For the data collection, the types of paper and board produced in the Netherlands were categorized as follows :

- Graphic paper: The high quality of printing and writing paper used in e.g. magazines requires primary fibre pulp. The quality is related to the end product, as consumers demand a certain whiteness and brightness. This type is dominated by chemical pulping because of the requirement for a high level of brightness and good strength;
- Graphic paper made from recovered paper: Similar to graphic paper but produced from recovered paper. Mainly used for applications such as leaflets;
- Corrugated board: Corrugated board can consist of different combinations of layers of sheets produced from recovered pulp, mechanical pulp and chemical pulp. In the

Netherlands mainly recovered pulp is used. This type of paper has a wide variety of applications but is mostly used for packaging;

- Solid board: Solid board consists of 100% recovered paper and has multiple applications e.g. book covers and food plates. Because of its applications, it does not require deinking;
- Folding boxboard: Folding boxboard can consist of different types of fibres and is typically used as packaging material of various food products. In the Netherlands this paper grade consists of recovered paper and mechanical pulp. Because of its application, the outer layer needs to be representative; the layers therefore undergo either deinking steps or bleaching;
- Sanitary paper: Sanitary paper can be produced from primary fibre or recovered fibre, and is used to produce e.g. toilet paper and tissues. The primary fibre is generally from chemical pulp. Sanitary paper needs to be strong, absorbent and soft.

Production and production capacities

Figure 1 shows the production capacity per product type in 2015. The product types that take the largest shares of the production capacity are corrugated board (37%), solid board (25%), graphic paper (20%) and graphic paper from recovered paper (10%).

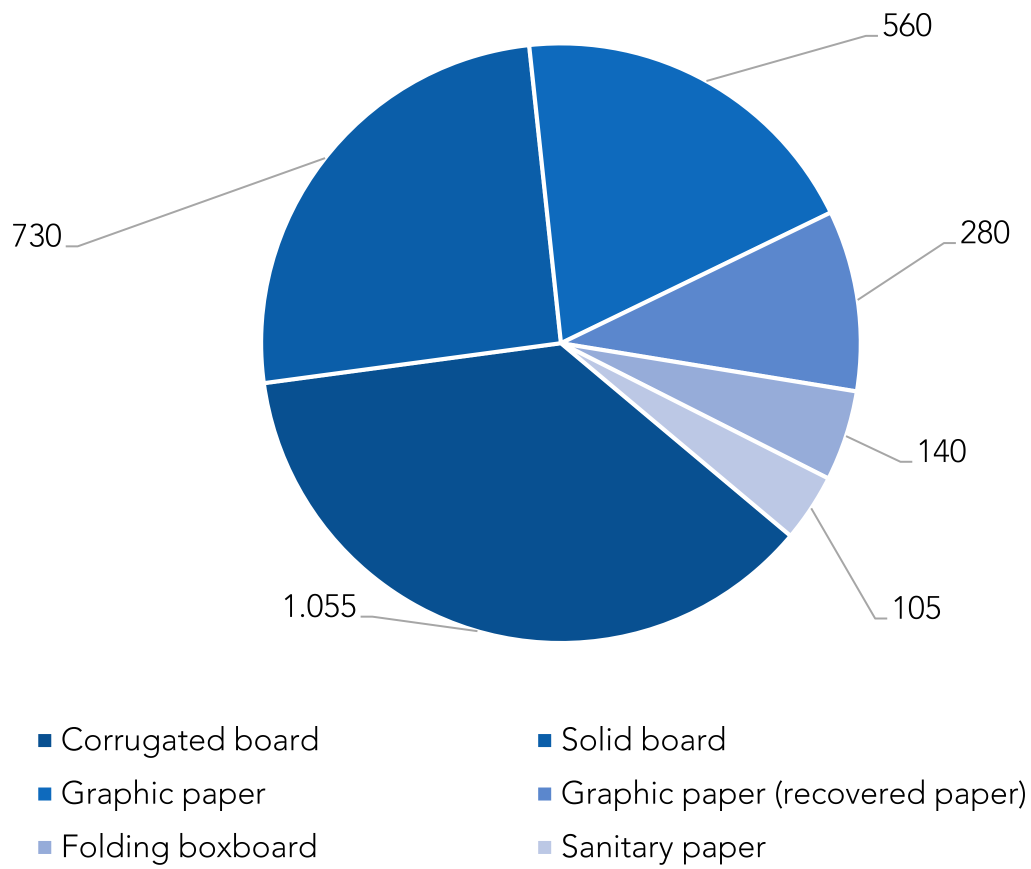


Table 1: The number of mills, paper machine capacity, production and the number of paper machines by product type in 2015 (source: adapted VNP data)

The production volumes, the number of mills and the number of paper machines are presented in Table 1. In 2015, there were 21 mills with a total production capacity of approx. 2,900 kton per year. The mills realised an average annual capacity utilization of 92%.

Product type	Number of mills	Paper machine capacity (kton/yr)	Production (kton/year)	Number of paper machines
Corrugated board	4	1,055	992	22[1]
Solid board	7	730	655	11
Graphic paper	6	560	510	10
Graphic paper from recovered paper	1	280	252	1
Folding boxboard	1	140	133	1
Sanitary paper	2	105	97	4
Total	**21**	**2,870**	**2,639**	**49**

The annual production capacity of the individual mills ranged from 5,000 to 600,000 tons per year (see Table 2). Large mills typically produce bulk products, whereas smaller mills tend to produce more specialized products. Except for one, all of the paper mills are part of a larger corporate group.

Table 2 Production sites in the paper and board industry in 2015 (source: adapted VNP data)

Product category	Name of production site	Corporate group	Town/locality	(ton/year)
Corrugated board	DS Smith Paper De Hoop Mill	DS Smith	EERBEEK	350,000
	Huhtamaki Nederland BV	Huhtamaki	FRANEKER	35,000
	Papierfabriek Doetinchem B.V.	Papierfabriek Doetinchem B.V.	DOETINCHEM	70,000
	Smurfit Kappa Roermond Papier B.V.	Smurfit Kappa	ROERMOND	600,000
Folding boxboard	Mayr-Melnhof Eerbeek B.V.	Mayr Melnhof	EERBEEK	140,000
	Crown Van Gelder B.V.	Andlinger Company	VELSEN	240,000

[1] Note that this figure cannot be compared directly to the other categories, as it includes the machines of a paper mill that has a very different production process.

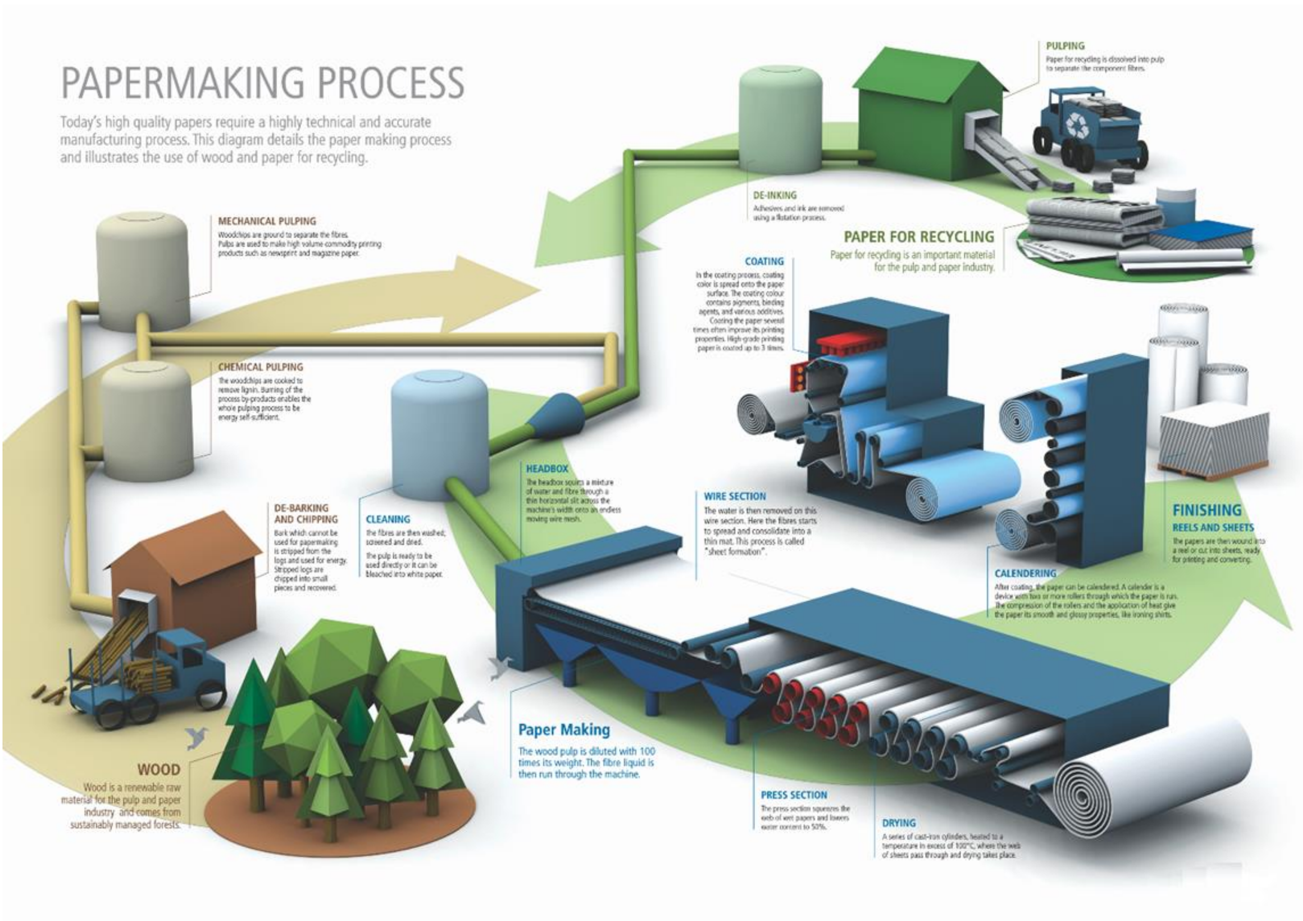
Graphic paper	Marsna Paper B.V.	Marsna	MEERSSEN	5,000
	Papierfabriek Schut B.V.	Exacompta Clairefontaine SA	HEELSUM	5,000
	Sappi Maastricht BV	Sappi	MAASTRICHT	280,000
	VHP Ugchelen B.V.	VHP	UGCHELEN	5,000
	W.A. Sanders Coldenhove Holding B.V.	Neenah	EERBEEK	25,000
Graphic paper from recovered paper	Parenco B.V.	H2 Equity Partners	RENKUM	280,000
Sanitary paper	SCA Hygiene Products Cuijk B.V.	Essity	KATWIJK A/D MAAS (NB)	60,000
	Van Houtum Holding B.V.	WEPA	SWALMEN	45,000
Solid board	Eska Graphic Board Hoogezand	Andlinger Company	HOOGEZAND	170,000
	Eska Graphic Board Sappemeer	Andlinger Company	SAPPEMEER	110,000
	Smart Packaging Solutions B.V.	VPK Packaging Group	LOENEN	70,000
	Solidus Solutions Board B.V. loc. Bad Nieuweschans	Solidus Solutions	BAD NIEUWESCHANS	120,000
	Solidus Solutions Board B.V. locatie Coevorden	Solidus Solutions	COEVORDEN	110,000
	Solidus Solutions Board B.V. locatie Hoogkerk	Solidus Solutions	HOOGHERK	90,000
	Solidus Solutions Board B.V. locatie Oude Pekela	Solidus Solutions	OUDE PEKELA	60,000

Production processes, energy consumption and material use

Paper and board production consists of the production and preparation of the fibres, formation of the paper, and drying. The thermal drying of the paper accounts for most of the steam use. The specific electricity consumption varies much more between paper types than the specific steam consumption. Depending on the required quality and characteristics of the end-product, each paper and board type uses a different set of material inputs.

Production processes

The production process consists of the production of pulp (from wood or recovered paper), and the production of paper or board. In the Netherlands, there is, with the exception of one mill, no pulp production from wood. The pulp is produced from either recovered paper or from imported virgin fibre. Therefore, the energy consumption in the Dutch paper and board industry is almost exclusively due to paper and board production processes.



For virgin fibres the preparation step consists mainly of refining of the fibres to create the required characteristics of the fibres for the paper or board product. For pulp produced from recovered paper, cleaning steps are required to remove unwanted elements (plastics, ash etc.) and, in some cases, de-inking and dispersion steps to remove inkt.

The pulp (~1% dry matter content) is then spread over the wire to form paper. After the press section, in which water is mechanically removed, the pulp (with now a dry matter content of ~50%) is guided over hot cylinders for thermal removal of the remaining water. For some products a coating is applied after the (pre) drying section to increase the strength or to improve the writability of the product. In the case of applying a coating, the paper, or board, is dried again using another set of cylinders (after-drying section).

There are different types or qualities of steam. We distinguish here between two types based on the pressure or temperature level:

- Low and medium temperature steam

This is steam with temperatures up to 200°C and pressures up to 15 barg

- High temperature steam

This is steam with higher temperatures than 200°C

Low and medium temperature steam represents approximately 75% of the energy used as steam in industry. This type of steam is used in sectors as diverse as pulp and paper, food and nutrition, fine chemicals, and textiles. High temperature steam is much more prevalent in the energy sector. This type of steam is used in steam turbines for electricity generation for example. In the manufacturing industry it is used for mechanical drive trains (and the effluent low-pressure steam for heating) and for heating high temperature processes such as cracking.

The energy transition calls for a drop-in carbon free alternative

Steam boilers are thus still an indispensable energy resource for many industrial processes and will remain to be so for the foreseeable future. It will be impossible to reach the goals of the COP-21 agreement (UNFCC, 2015) without addressing CO2 emissions from steam boilers. Steam as an energy carrier is usually embedded in the core production process by means of heat exchangers and nozzles. Switching to another energy carrier (e.g. electric heating) in the process means replacing most or all or the equipment and reinventing the production process. These represent considerable costs and a very high risk to product quality and cost price.

For this reason, it is desirable to have a drop-in replacement for just the steam boiler. That way, the bulk of the manufacturing process can remain the same; only the boiler needs to be replaced.

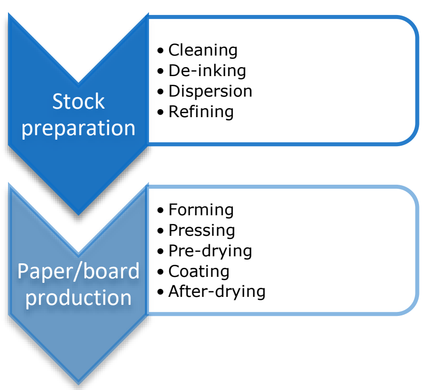


FIGURE 1: STEPS IN THE PAPER AND BOARD PRODUCTION PROCESS

Steam is used to attain the required dry matter content of the end product. The steam temperature varies between 150 and 180°C (see Table 3). The steam is typically produced using a boiler or a combined heat and power (CHP) installation.

Table 3: Overview of used steam temperature per paper type (source: adapted VNP data)

Company name	Steam temperature drying section (max) [°C]	Steam pressure drying section (max) [barg]
Corrugated board	180	10
Graphic paper	150	5
Sanitary paper	165	7
Solid board	180	10
Folding boxboard	180	10
Graphic paper made from recovered paper	150	5

Specific energy consumption

Analysis of the data shows that the process step with the highest energy consumption is the drying step. The specific energy consumption for the drying step generally varies between 3.6 and 6.2 GJ/ton, and depends on the dry matter content of the pulp before going into the drying section, the need for coating, and the amount of energy recovery from the heat coming out of the drying section (Laurijssen, 2013). After evaporation of the water, the energy (in the form of waste heat) is only partially recovered via heat exchangers, due to a lack of application possibilities.

The specific electricity consumption varies much more between paper types than the specific steam consumption, as can be seen in Figure 2. The specific electricity consumption in the stock preparation can be high if (for quality reasons) deinking and dispersion is required, as is the case for graphic paper produced from recovered paper, and for sanitary paper.

Solid board and corrugated board production use relatively little electricity compared to their heat consumption, whereas sanitary paper and graphic paper made from recovered paper use a relatively large amount of electricity (mostly related to the energy required for the deinking steps of these mills).

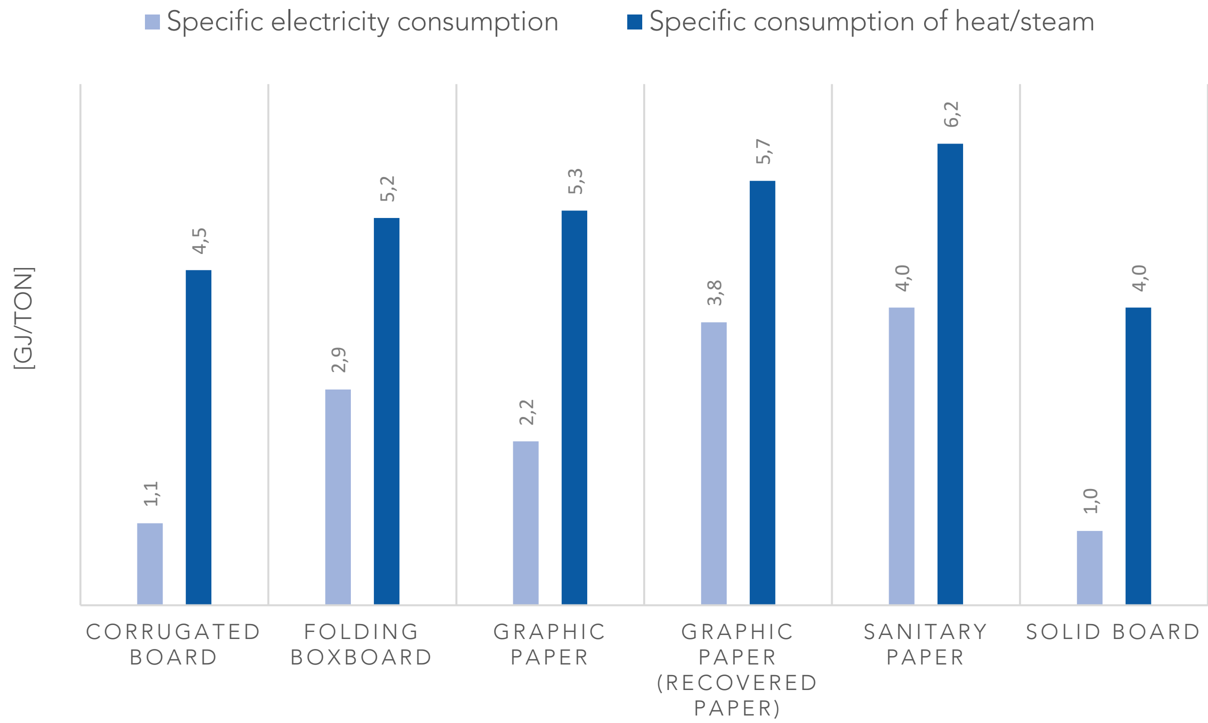


FIGURE 2 SPECIFIC ENERGY CONSUMPTION OF HEAT/STEAM AND ELECTRICITY PER PRODUCT TYPE IN 2015 (SOURCE: ADAPTED VNP DATA)

Material use

Depending on the required quality and characteristics of the end-product, each paper and board type uses a different set of material inputs (see Table 4). Graphic paper uses virgin pulp (chemical pulp) in order to obtain the required brightness, but also uses a large amount of filler material ($CaCO_3$). Folding boxboard also uses virgin fibre, but it uses mechanical pulp instead of chemical pulp. The other paper and board products are produced almost completely from recovered paper. Many mills also apply a coating to provide their product with strength or writability qualities. Especially maize or potato starch is utilized for coating.

TABLE 4: OVERVIEW OF MATERIAL CONSUMPTION PER PAPER TYPE IN 2015 (SOURCE: ADAPTED VNP DATA)

	Recovered paper	Virgin fibre	Other
Corrugated board	96%		4%
Folding boxboard	32%	61%	7%
Graphic paper		63%	37%
Graphic paper made from recovered paper	89%		11%

Sanitary paper	99%		1%
Solid board	100%		

Energy consumption, energy production and CO_2 emissions

Energy consumption

Steam/heat consumption and the final electricity consumption demonstrates large differences in scale between the mills. The bulk producing corrugated board and graphic paper mills (both virgin fibres and recovered paper based) have a significantly larger need for energy than the other mills. This is in stark contrast to the more specialized paper mills that produce a larger variety of products in much lower quantities.

Combined heat and power (CHP)

In 2015, ten paper mills used combined heat and power (CHP) installations to cover (part of) their steam demand. The total electrical capacity of these installations was 217 MW_e. The total fuel input was 14.7 PJ. The total electricity production was 4.1 PJ and the total steam/heat production was 7.8 PJ.

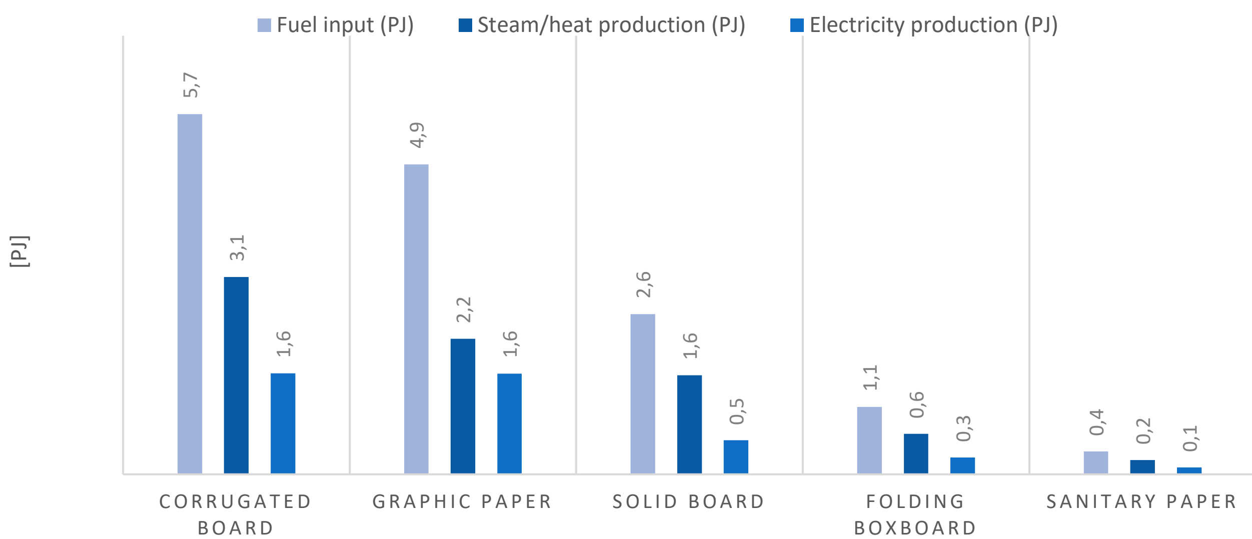


FIGURE 3 FUEL INPUT, STEAM PRODUCTION AND ELECTRICITY PRODUCTION OF CHP INSTALLATIONS IN 2015 (SOURCE: ADAPTED VNP DATA)

	Electrical CHP capacity [MW_e]	Thermal CHP capacity [MW_{th}]
Graphic paper	93	213
Corrugated board	84	131
Solid board	24	115
Folding boxboard	13	22
Sanitary paper	4	15
Graphic paper from recovered paper	0	0
Total	217	496

FIGURE 4 ELECTRICAL AND THERMAL CAPACITY OF CHP INSTALLATIONS IN THE PAPER AND BOARD INDUSTRY IN 2015 (SOURCE: ADAPTED VNP DATA)

According to Statistics Netherlands (CBS), in 2015 there were 25 CHP-installations in the Dutch paper and board industry with a total electrical capacity of 309 MW_e.[2] The Dutch paper and board industry has previously invested heavily in combined heat and power installations to meet their energy demand. Due to unfavorable gas and electricity prices, some of these have been decommissioned, and therefore no longer appear in the database of the VNP, but are still included in the statistics of CBS.

Final electricity consumption

The final electricity consumption in the Dutch paper and board industry was 4.6 PJ in 2015. The total electricity generation by CHP installations was 4.1 PJ. Part of the electricity produced by the CHP installations is sold to the grid.

For the product types 'Graphic paper' and 'Corrugated board', there are several mills whose production of electricity (by their CHP installations) exceeds their final electricity consumption. The net electricity consumption of these mills is negative.

[2] Source: Elektriciteit; productie en productiemiddelen, Statistics Netherlands (CBS) (preliminary data for 2015).

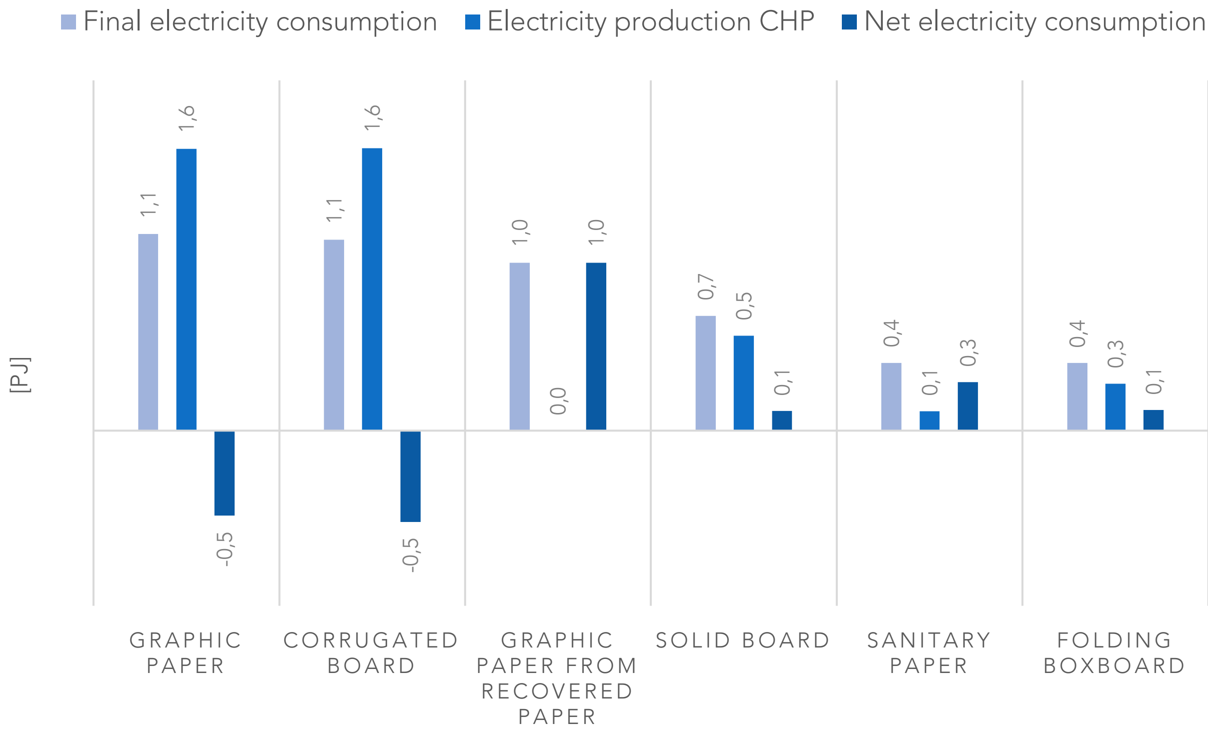


FIGURE 5 FINAL ELECTRICITY CONSUMPTION, ELECTRICITY PRODUCTION OF CHP AND NET ELECTRICITY CONSUMPTION PER PRODUCT TYPE IN 2015 (SOURCE: ADAPTED VNP DATA)

Steam/heat consumption

Figure shows the consumption of steam/heat per product type in 2015. The total consumption of steam/heat was 12.5 PJ of which 62% (7.8 PJ) was produced by CHP installations.

Most boilers and CHPs in the Dutch paper and board industry use natural gas to convert water into steam. One mill uses deinking sludge and biomass as fuel input. Aside for steam production, natural gas is also used for other forms of drying. Mills producing sanitary paper blow hot air against the paper in the drying section. There is one mill producing a type of packaging board that does not use any cylinders but uses mostly hot air for the drying of its products.

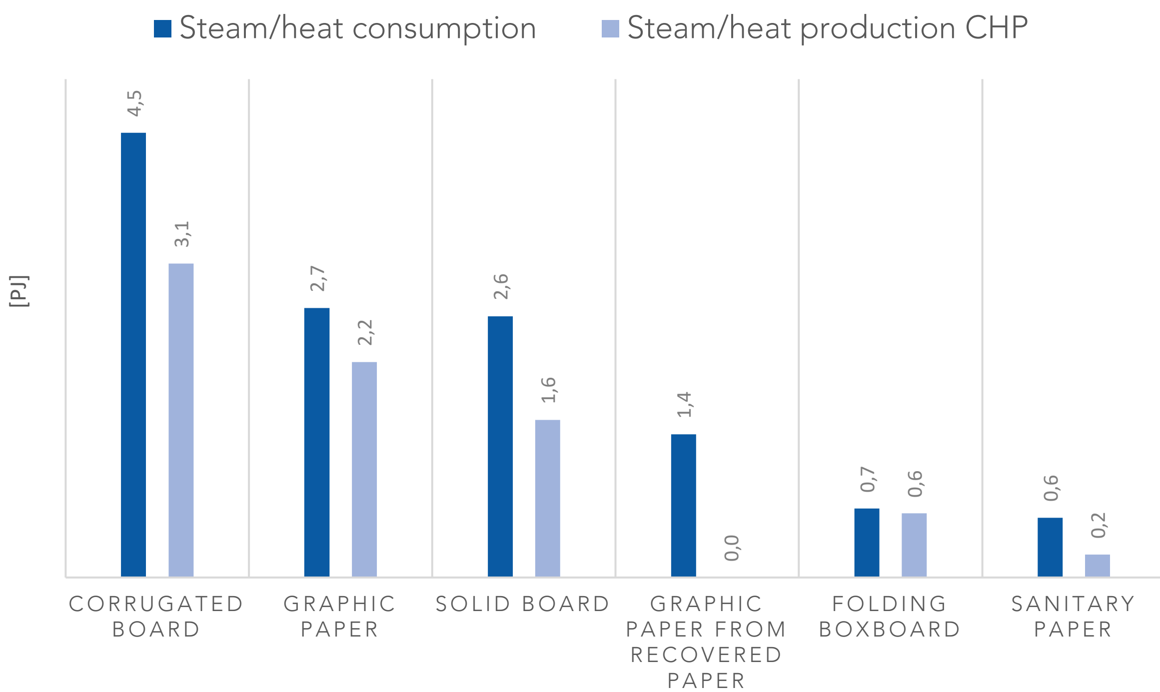


FIGURE 6 STEAM/HEAT CONSUMPTION AND STEAM/HEAT PRODUCTION OF CHP PER PRODUCT TYPE IN 2015 (SOURCE: ADAPTED VNP DATA)

Greenhouse gas emissions

The greenhouse gas emissions of the paper mills that participate in the EU Emissions Trading System (EU ETS) are publicly available (see Table 5). The dataset of the Dutch Emissions Authority (NEa) has been linked to the dataset which has been compiled for this study.

In 2015, the total ETS emissions of the paper and board plants amounted to 1,054 kton CO_2-eq. Only VHP Ugchelen B.V. and Papierfabriek Schut B.V. did not participate in the ETS.

TABLE 5: OVERVIEW OF ETS EMISSIONS PER PRODUCTION SITE (SOURCE: DUTCH EMISSIONS AUTHORITY (NEA))

Production site	Town/locality	ETS emissions 2015 [kton CO_2-eq.]
DS Smith Paper De Hoop Mill	EERBEEK	216,5
Smurfit Kappa Roermond Papier B.V.	ROERMOND	162,7
Sappi Maastricht BV	MAASTRICHT	151,3
Crown Van Gelder B.V.	VELSEN	142,7
Mayr-Melnhof Eerbeek B.V.	EERBEEK	67,6
Eska Graphic Board Hoogezand	HOOGEZAND	59,6
Solidus Solutions Board B.V. loc. Bad Nieuweschans	BAD NIEUWESCHANS	37,4
Eska Graphic Board Sappemeer	SAPPEMEER	32,8

Solidus Solutions Board B.V. locatie Oude Pekela	OUDE PEKELA	24,3
Van Houtum Holding B.V.	SWALMEN	23,4
Solidus Solutions Board B.V. locatie Coevorden	COEVORDEN	21,9
Papierfabriek Doetinchem B.V.	DOETINCHEM	20,2
SCA Hygiene Products Cuijk B.V.	KATWIJK A/D MAAS (NB)	19,5
Parenco B.V.	RENKUM	18,8
Solidus Solutions Board B.V. locatie Hoogkerk	HOOGHERK	17,2
Huhtamaki Nederland BV	FRANEKER	12,9
Smart Packaging Solutions B.V.	LOENEN	12,6
W.A. Sanders Coldenhove Holding B.V.	EERBEEK	10,1
Marsna Paper B.V.	MEERSSEN	2,7
VHP Ugchelen B.V.	UGCHELEN	-
Papierfabriek Schut B.V.	HEELSUM	-
Totaal		1054,2

Figure shows the share of each product type in the EU ETS greenhouse gas emissions of the paper mills in 2015. The contributions of production of corrugated board (42%) and graphic paper (31%) are the largest.

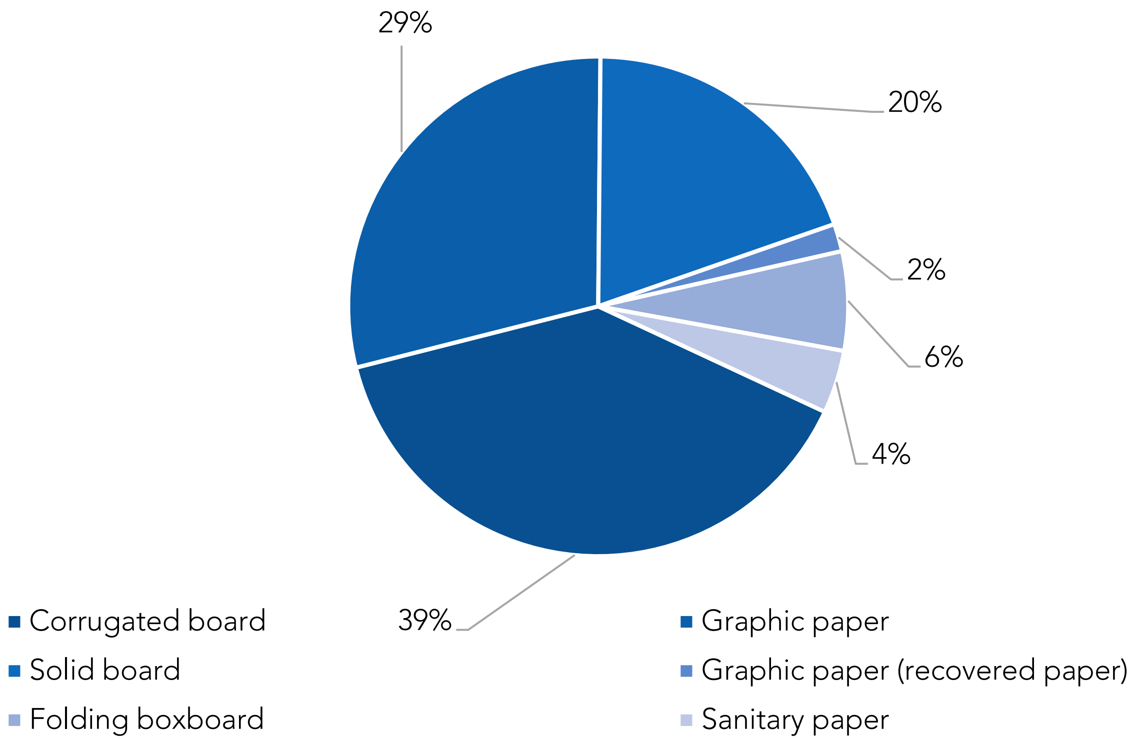


FIGURE 7 SHARE OF ETS GREENHOUSE GAS EMISSIONS PER PRODUCT TYPE IN 2015 (SOURCE: ADAPTED VNP DATA AND NEA DATA)

Investments, market prices and O&M costs

In 2015, the paper and board industry had 3.896 employees and a total revenue of 1.7 billion EUR (Koninklijke VNP, 2017). A large share of the total cost of paper and board production comes from the cost for raw materials. This section also discusses investments and operation and maintenance (O&M) costs.

Investments

The paper and board industry is a sector that is characterized, for the most part, by bulk production. The investments per paper machine can exceed half a billion euro (see Table 6). The frame of the paper machine can generally last a very long time, but its individual components (wire section, presses, drying hood, cylinders, etc.) need to be replaced more regularly. An overhaul is assumed to take place every 15 years.

Investments are necessary for the stock preparation as well as the paper machine. Table 6 shows that the paper machine equipment, consisting of the heavy machinery needed to form, press and dry the paper and high speed drives, is far more capital intensive than the equipment required for the stock preparation. The table also shows that larger paper machines are less expensive than smaller ones, when compared per installed unit of capacity.

TABLE 6 INVESTMENT COSTS FOR PAPER MACHINES AND STOCK PREPARATION (SOURCE: ESTIMATE BY VNP)

	Capacity (ton/yr)	Investment (mln euro)	Investment per unit of annual capacity (euro/ton)
New paper machine	80,000	250	3,125
New paper machine	400,000	500	1,250
New paper machine	500,000	600	1,200
Stock preparation	400,000	3.0	8
Stock preparation	500,000	4.0	8

Market prices for materials

Much of the production cost in paper and board production is related to the cost of raw materials (Technopolis group, 2016). Note that the prices for virgin fibres can be higher, per ton, than the market price of the graphic paper for which it is the feedstock. The reason for this is that a significant amount of the input material for these types of paper consists of fillers, which cost far less, thereby compensating for the price of the pulp.

TABLE 7: MARKET PRICES FOR MATERIALS IN 2017 (SOURCE: RISI)

Material	Market price (€/ton)
Old paper (mixed)	129
Pulp; Cellulose, Northern bleached softwood kraft (NBSK)	788
Pulp; Cellulose, Bleached eucalyptus kraft pulp (BEKP)	836
Graphic paper	628
Newsprint	431
Uncoated mechanical	550
Coated mechanical	619
Uncoated woodfree	811
Coated woodfree	729
Corrugated board	629
Containerboard Virgin fibre	699
Containerboard Recycled Paper	559
Sanitary paper (Frankrijk)	920
Solid board	375
Folding boxboard	891
Cartonboard coated duplex	1,065

Cartonboard White-lined chipboard	717
Specialty paper	900

Operation and maintenance costs

Operation and maintenance (O&M) costs[3] are an important part of the operational costs in paper and board production. Estimates for the operation and maintenance costs (see Table 8) were provided by the Knowledge Centre for Paper and Cardboard (KCPK), using a report of the Technopolis Group (Technopolis group, 2016). The O&M costs are relatively high for sanitary paper and relatively low for corrugated board.

TABLE 8 ASSUMPTIONS ON OPERATING AND MAINTENANCE COSTS (SOURCE: KCPK/CEPI)

€ in 2014 per ton product	Operating and maintenance costs (O&M)
Corrugated board	64
Graphic paper	84
Sanitary paper	132
Solid board	94
Folding boxboard	94
Graphic paper made from recovered paper	83

[3] The costs for energy and raw materials are not included in the O&M costs.

ALTERNATIVE TECHNOLOGIES FOR STEAM PRODUCTION

This chapter gives an overview of the selected technology options. It considers the technology characteristics and the cost of generating steam. The results are discussed in the context of the targets for greenhouse gas emissions reductions in the industry.

Lux Research provided information on new (energy) technology to improve company's innovation investment decisions. Lux has much data on individual technology developments. To model future performance of a technology, Lux looked at all this data, picked representative high performing developers and assessed the potential performance of their technology. The methodology and procedure that Lux used is described in more detail in the Annex 1.

To select and subsequently describe future technologies to include in the system model, Lux used the following procedure:

- Identify all possible technology options that could replace a steam boiler
- Select the most promising options together with industry and government
- Collect data on each of the selected technologies
- Select one or two representative developments to extrapolate to future performance
- Extrapolate the key metrics of the technology to a fully developed state
- Calculate mass and energy balances for each technology

Identifying technology options based on a defined function

To find suitable technology options, Lux break the technology to be replaced down to its core function. In this case, the core function for the pulp and paper industry. Steam is primarily used in the pulp and paper industry to dry sheets of pulped cellulose. Steam flows through rotating drums. The paper is pulled over these drums. The steam keeps the drum surface temperature constant at the saturation temperature of the steam and transfers heat to the paper while condensing steam. The condensate is returned to the boiler, where the hot water is evaporated again. In this way, heat generated in the boiler by burning fuel is transferred to the wet sheets of proto-paper at the right temperature and rate.

This understanding of the core function of steam still leaves room for three different definitions of the function of this technology to be replaced:

1. The function is to supply saturated steam of a given temperature to the process
2. The function is to keep the drum surface temperature constant and transfer heat to the paper through the drum
3. The function is to dry the paper

These definitions would all be valid for the paper industry. From option 1 to 3 the definitions become increasingly "invasive" for the paper making process itself. The likelihood that the paper making equipment will need to be adapted increases from definition 1 to 3. At the same time, the number of technologies to choose from will probably also increase from definition 1 to 3.

Eighteen potential technologies identified

The key question is: "What future or current technology can generate saturated steam of up to 200°C without emitting (fossil) CO_2?" The possible answers highlights twelve technology options to potentially do that and another six options that provide alternatives for drying. The latter group of technologies doesn't fall within the scope of this study, but are listed here for completeness. The full list of the first twelve is shown in table 9. The other six, out of scope ideas, are shown in table 10.

TABLE 9 A LIST OF TWELVE TECHNOLOGIES THAT WE CONSIDERED AS POTENTIAL DROP-IN REPLACEMENTS FOR THE CURRENT LOW AND MEDIUM TEMPERATURE STEAM BOILERS

Technology	Description	Maturity
Concentrated solar power (CSP)	Sunlight is concentrated using a parabolic mirror. In the focal point of the mirror, very high temperatures can be reached. This is used to generate steam.	Scaling. Commercial installations exist, primarily for electricity generation using steam turbines
Glauber's Salt	Heat is stored by drying a salt. When the salt is rehydrated, the heat is released again at the desired level. This way residual heat or solar heat from other locations can be shipped efficiently to the industry.	Development. There are pilot installations targeting heating applications for buildings
Heat pumps	Heat from the environment or a reservoir is raised to a higher temperature level using electricity.	Scaling for low temperature, still development for temperature above 80°C
Plasmonics	When noble metal nano-particles are immersed in water, visible light can be used to evaporate the water. This is the plasmonic effect. Exposing water with particles to light at the right pressure might be able to raise the steam.	Laboratory. This is a fascinating phenomenon that has attracted a lot of research, but has no practical applications yet.
Biogas	Biogas is the simplest drop-in replacement, since most steam boilers in The Netherlands are currently natural gas fired. Obviously this still emits CO_2, but no fossil carbon anymore.	Scaling. Biogas installations exist and are used.
Biomass gasification	Many steam boilers in the pulp and paper industry already burn biomass. Here Lux propose to gasify biomass and use the gas to run a CHP unit	Introduction. A couple of commercial gasification based CHP units exist. This technology is on the brink of market introduction.
Hydrogen combustion	The industry could buy hydrogen and burn that instead of gas. Currently most hydrogen is produced from methane, so in the short term it is likely more expensive and not reducing CO2 emissions. It just shifts the problem to the hydrogen supplier. If there is a possible in place to create sustainable hydrogen, this is a viable alternative	Scaling. The technology to combust hydrogen is available and used in many applications already
Electrolysis	Rather than buying hydrogen, companies could generate hydrogen on-site using electrolysis and then burn the hydrogen to generate the desired temperature	Introduction. The first large-scale electrolyzers are now being deployed.
Direct electric	Steam can also be raised using direct electric heating. This is not much different from an electric kettle, just operating on a much larger scale and at higher temperatures and pressures	Scaling. Electric steam boilers exist and are commercially available

Geothermal	Heat from the crust of the earth can be used to generate steam	Scaling. Geothermal installations exist and are in use.
Zeolite	Much like Glauber's salt, zeolites can also be used the store heat and release it. This could be combined with using the zeolite as a drying agent that absorbs water.	Development. Some pilots exist, but much development must still be done
Waste heat	Neighboring industry might have surplus steam of heat available	Scaling. Sharing of waste heat is well known. The main issues in deploying are not technological but logistic.

TABLE 10 THE LIST OF SIX ADDITIONAL TECHNOLOGIES THAT ARE OUT OF SCOPE FOR THIS STUDY

Technology	Description	Maturity
Infrared	Infrared radiation can transfer electric energy directly as heat to the drying paper. This would replace the steam drums	Scaling. Commercial installations exist.
Microwave	Microwave is similar to infrared, but can theoretically target water specifically, making it more energy efficient and faster. The equipment would be much more complicated however because the microwave radiation needs to be contained.	Development. There are some early demonstrations, not specific to paper.
Forward osmosis	Water is drawn from the paper using a draw solution with a higher affinity for water than the paper. This would involve running the paper over a membrane with the draw solution on the other side	Introduction. Commercial units for forward osmosis exist for water purification. Paper drying would be a new application.
Membrane distillation	The advantage of membrane distillation is that it allows a very tight heat integration in the drying process. Heat of evaporation can be reused to dry another stage. There are however no design that could be integrated in paper drying yet.	Laboratory. Membrane distillation itself is just barely introduced in the market. This would require further development.
Vacuum	If the paper drying process could operate in a low pressure environment, the temperature could be drastically reduced and it would be possible to use conventional high efficiency heat pumps.	Development. The principles are known. It is a matter of engineering to develop large scale equipment working under low pressure.
Vibrating membranes	Manure processing units are using membranes that vibrate at a high frequency to remove water. This could be implemented in the paper process as a replacement or extension of the wet pressing section.	Development. The technology is available for manure, but needs to be tested and re-engineered for paper.

Focus on five promising options

The technologies identified were discussed with government and industry in order to select the technologies to be analyzed in more detail in this study. Table 11 lists the considerations and the conclusion of the analysis for each of the twelve technologies.

Biogas, Ultra Deep Geothermal Energy and Waste heat are valid options option for the paper industry but were not included for specific reasons. Biogas is considered a very viable option and should is included in any discussion. However, there is a recent study[4] on using biogas in the Paper industry, so the added value of including it here is limited. For Ultra Deep Geothermal Energy the EBN and TNO are working on a play-based portfolio for the development of UDG Energy in the

[4] . Business Case Analyse Energievoorziening Door Mestvergisting Agrifirm Exlan (2018)

Netherlands[5] It makes sense to refer to the ongoing research on UDG in the EBN program. Waste heat, highly location specific, for the Paper industry in general due to the locations of the mill is was excluded.

TABLE 11 THE LIST OF CONSIDERATIONS AND DECISIONS ON EACH OF THE IDENTIFIED OPTIONS

Technology	Consideration	Decision
Concentrated solar power (CSP)	This technology is probably very difficult and costly to use in The Netherlands because it depends on direct sunlight. Even though day-night rhythm is not an issue (heat is stored in molten salt), a cloudy day may interfere with production. It may be an attractive option in other regions, but not for the Dutch or more generically Northern European industry.	Do not include
Glauber's Salt	This technology is not yet very mature and requires a complicated market development to deploy. Some sort of spot market for stored heat must develop with the associated logistics. At this moment this option is deemed to complicated and premature.	Do not include
Heat pumps	Heat pumps are considered one of the obvious solutions, even though they may not yet reach the desired temperatures. Heat pumps are much more efficient than direct electric heating and are therefore very attractive.	Include
Plasmonics	Fascinating and everyone certainly was tempted to include this. However, this is now still just a fascinating phenomenon and nothing more. Lux would not even be able to include this because there is not yet enough data available.	Do not include
Biogas	Biogas is considered a very viable option and should certainly be included in any discussion. However, there are already many studies on using biogas, so the added value of including it here is limited.	Do not include
Biomass gasification	Using biomass for heating is very natural for the pulp and paper industry. They own the relevant biomass waste-streams. Biomass combustion is already used and this would be a significant efficiency improvement.	Include
Hydrogen combustion	Hydrogen is the obvious industrial fuel for a low-carbon future. It is therefore interesting to explore this option	Include
Electrolysis	It is interesting to compare this option to direct electric heating. The efficiency is expected to be less, but investment in retrofitting may be less	Include
Direct electric	Direct electric heating is the most obvious current method to produce steam using electricity and should be part of the comparison	Include
Geothermal	Applicability of geothermal energy depends on location. This is therefore a specific solution applicable only to industry that happens to be located in a suitable place. For the purpose of this study, that is too serendipitous	Do not include
Zeolite	This options is deemed to be complicated and somewhat exotic. It is also specific to any application, so it doesn't fully fit the description of a drop-in replacement for any steam boiler.	Do not include
Waste heat	Like geothermal, this is highly location specific. For this reason its excluded from the study.	Do not include

The subsequent sections discuss the analysis for each technology.

Heat pumps

[5] https://www.ebn.nl/wp-content/uploads/2018/06/TNO-EBN-rapport-Play-based-portfoliobenadering-geothermie-30-mei-2018-2.pdf

System description

A heat pump needs a reliable, constant supply of low level heat to work with. Since waste heat is excluded, the only universal reservoir available on the cold end of the heat pump is ground water. Ground water has a temperature of approximately 10°C. A heat pump can usually support a maximum temperature increase of 60°C -- 80°C. that means that a cascade of at least three heat pumps is required to bridge the gap between the cold end and the desired steam conditions.

A first heat pump could bring heat from the cold reservoir to 70°C. This would then act as the cold end of the next heat pump, that would pump heat from 65°C (allowing for 5°C to facilitate heat transfer) to 125°C. A third heat pump would use this heat source and increase temperature from 120°C to a final 180°C. Even this cascade doesn't reach the desired 200°C, but this system can be used as a good approximation.

The system is then a system that takes electricity and heat of 10°C and generates heat at elevated temperature.

In the current study waste heat was excluded, but it is worth mentioning here that there is an option to use waste heat of about 60 °C in combination with a heat pump to generate steam of 120 °C. This technology was demonstrated by ECN with partners in a facility of Smurfit Kappa on a 160 kW scale (A.K. Wemmers, 2017). This is not a full drop-in solution because it doesn't provide a way to start the process. However in this report it is added as a viable option because it is a good way of running the process in steady state, perhaps supplemented by a simple electric boiler for start-up. The test showed that this solution can reach a COP of 3.5 (maximum). This means that the system would be able to support the entire energy supply of the plant if between 70% and 75% of the heat input can be recovered in the form of waste heat of 60 °C.

ECN reported that the expected CAPEX at full scale for this heat pump can be as low as 200 €/kW (output), for a skid mounted system (i.e. without installation and infrastructure). Lux could not verify that number and think it is surprisingly low compared to other developers. A more reasonable expectation would be 450 €/kW in their opinion. For the analyzis the ECN's input was used.

Technology developers

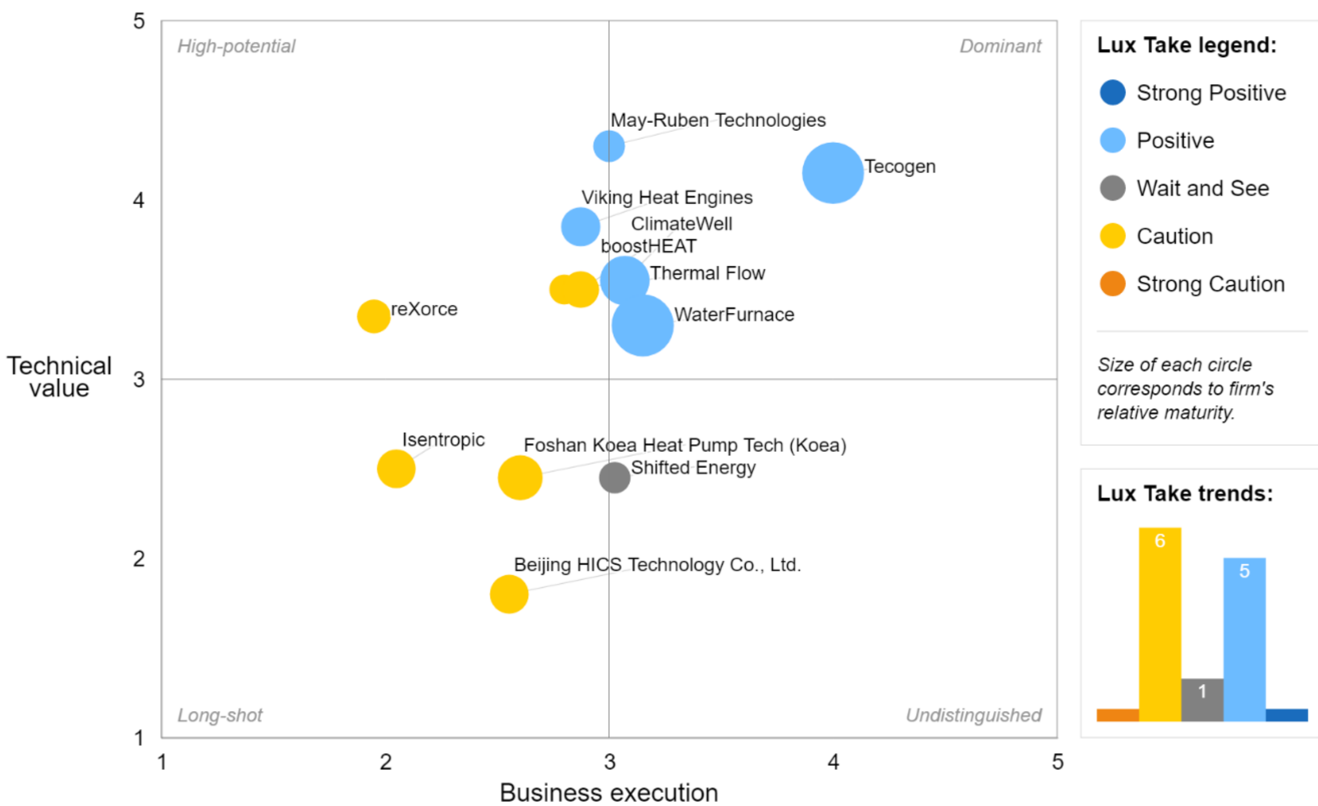
There are currently no technology developers aiming to supply a cascaded heat pump system. There are developers working on high temperature heat pumps, but they all focus on either waste heat, geothermal heat or solar heat at the cold end of the heat pump. There are, in other words, no developers trying to bridge a gap in temperature levels this wide. The Lux Innovation Grid (LIG) in Figure 8 shows the relevant academic and small company developers.

The main relevant large company developers are (in that order, see also Figure 9):

1. Thermax
2. LG Electronics
3. Shuangliang eco-energy systems
4. Hitachi

The patent analysis reveals a "Li H" as the owner of most patents on industrial applications of heat pumps. Our research shows that this is a private person from China. It is not uncommon in China that private persons own many patents. These people usually also own a business that uses these patents, but they choose to assign the patents to themselves rather than to the business. In this case, Lux could not find commercial activities around this portfolio of patents. It may be that there still is activity in China, that is not traceable without being on-site.

Figure 8 LUX INNOVATION GRID OF TECHNOLOGY DEVELOPERS OF HEAT PUMP SYSTEMS



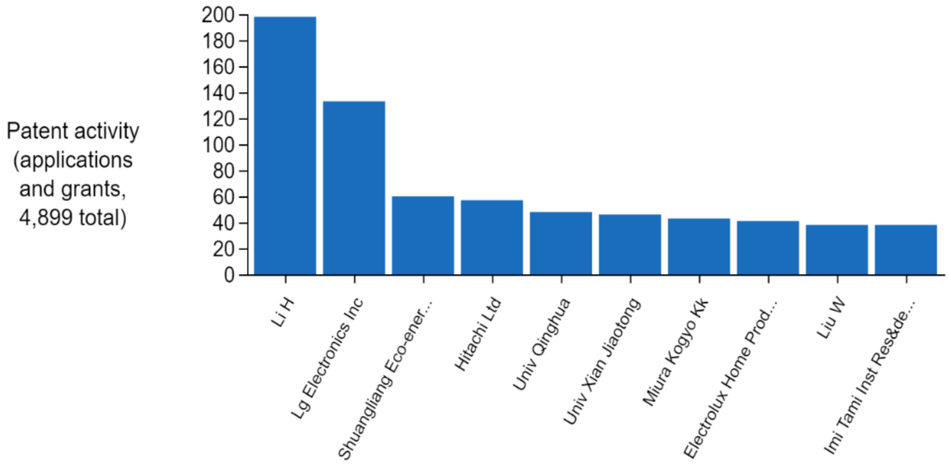


Figure 9 THE TOP TEN OWNERS OF RELEVANT PATENTS ARE ALL FROM ASIA, WITH THE EXCEPTION OF ELECTROLUX

Technology key metrics

Since there are no relevant systems being developed that meet the requirements Lux specified in the system description, and engineered a conceptual design of a system that would. Lux did so by combining two standard "residential" heat pumps and one high temperature heat pump. For the residential heat pumps they used the specifications of the Hitachi systems. These are among the most-used heat pumps by a number of suppliers and they are thus well-developed and well-tested systems.

For the high temperature heat pump, Lux used the heat pump supplied by Viking heat engines. This product is available and very flexible. It also is the heat pump system that can reach the highest temperature. Even so, it is realistic to expect the entire system to reach steam temperatures not higher than 160°C. This should not be an issue for the pulp and paper industry, but it does mean that the technology will not be able to fully meet our requirement of supplying steam up to 200°C. Heat pump technology to independently supply low and medium temperature steam is currently not available and not being developed. Heat pumps should only be applied in combination with a higher temperature reservoir such as geothermal energy, solar energy or waste heat.

To make the design Lux had to scale residential heat pumps to higher capacity. Heat pumps follow the scaling rules of process technology. So the assumption is made that a 10x larger heat pump will cost only 5x as much. Heat pumps typically achieve 80% of the maximum achievable efficiency. This is what is assumed for the two lower temperature heat pumps. For the Viking heat engines system, measured data on the COP was available.

Lower temperature heat pumps are already being mass-produced, so the experience curve does not apply to them. A mild experience curve to the Viking heat engines system was applied, resulting in a 30% price decrease.

Lux estimated that it takes 5 to 8 years to make this technology a commercially available option. The heat temperature heat pumps are already available commercially. The development work needed is in the system design.

The resulting system metrics are shown in table 12

For the waste heat recovery system, Lux used the data published by ECN, resulting in the data shown in table 13. A factor 2.5 is used on the skid mounted system costs here to account for installation. This is higher than the usual engineering rule of thumb of 1.7 because Lux expect that there need to be additional heat exchangers installed to extract the waste heat. This technology was already tested on a 160 kW scale. The work needed to obtain a commercial installation is upscaling and system design. This puts this technology on a similar time-scale as the other heat pump solutions

TABLE 12 KEY METRICS AS DETERMINED FROM OUR MODEL FOR A HEAT PUMP SYSTEM SUPPLYING STEAM OF UP TO 160°C, STARTING FROM GROUND WATER OF 10°C

Metric	Value
CAPEX equipment only	1.3 EUR per W thermal output
CAPEX including installation	2.4 EUR per W thermal output
Effective COP	2.38
Refurbishment interval of the installation	10 years
Term in which this technology becomes available commercially	After 2025

TABLE 13 KEY METRICS AS DETERMINED FROM DATA SUPPLIED BY ECN FOR A HEAT PUMP RECOVERING WASTE HEAT OF 60 °C TO PRODUCE STEAM OF 120°C

Metric	Value
CAPEX equipment only	0.2 EUR per W thermal output
CAPEX including installation	0.5 EUR per W thermal output
Effective COP	3.5
Refurbishment interval of the installation	10 years
Term in which this technology becomes available commercially	After 2025

Biomass gasification

System description

Every pulp and paper factory has a side stream of reject materials and other biomass materials that do not make it in the final product. Assumed here is that there is sufficient material to supply heat to the entire factory. One way of utilizing this side stream is to combust it for steam generation. This is already a common practice. Typically, fluidized bed boilers are used for this.

In this study Lux looked at a CHP system based on gasification of the side stream. This has proven to be difficult because it is hard to generate gas of the right quality with a biomass gasifier. Usually the gas from the gasifier is too polluted (for example with tar) to be of use to a gas engine or gas turbine. Still, there are a number of promising developments that could become robust commercial systems in the next five years.

The system analyzed here is a gasifier, fed with residues from paper production, coupled to a gas engine (not turbine). The system supplies heat (steam) and electricity. It is assumed that the existing steam boiler can be retrofitted to work with the engine flue gases and to burn some of the producer gas of the gasifier. The gasifier operates with air (not oxygen) and produces producer gas (not syn-gas).

Technology developers

Gasification is an incredibly crowded space with many active developers. Figure 10 shows only a sample of these developers. Most developers active on gasification are working to develop a gasification system, not just an isolated gasifier. The system may be either a gasifier coupled to an engine or to a chemical process such as methanol synthesis or hydrogen production. Broadly speaking there are two classes of systems: large scale systems (> 10 MW) usually employ fluidized bed gasifier and sometimes entrained flow systems. These systems can process large amounts of biomass but struggle with gas quality. The industry has been trying to solve issues of tar pollution for the past 40 years. There are some working solutions, but they all increase system costs significantly.

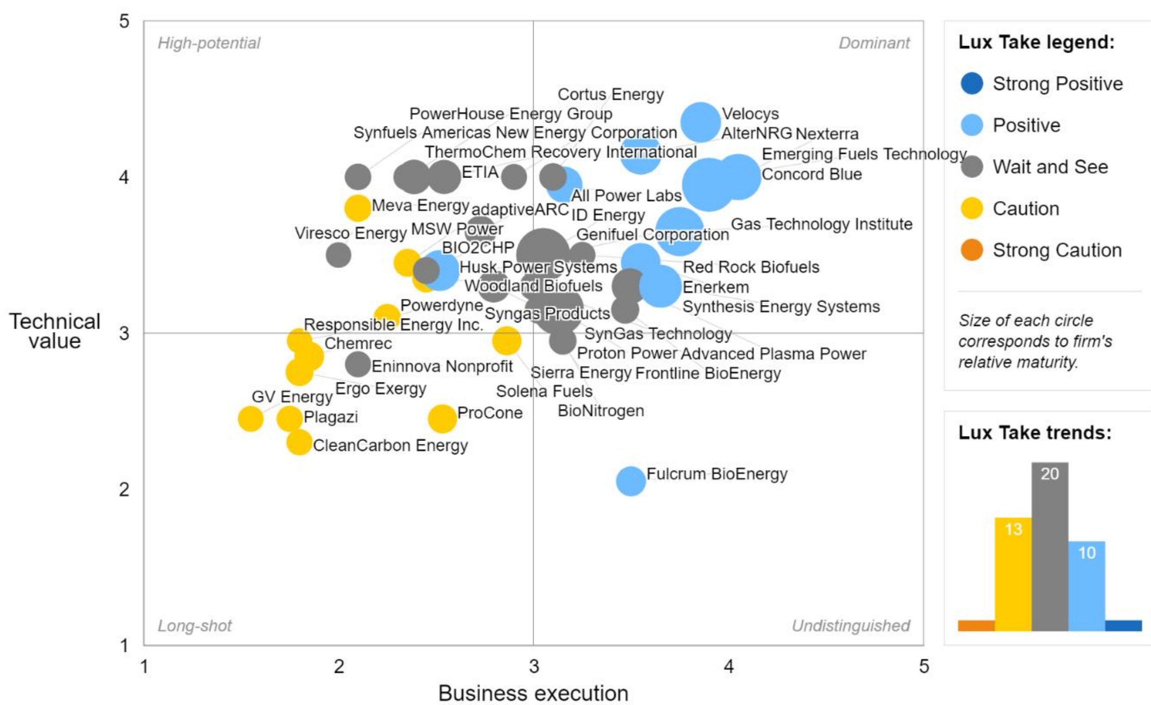
Small scale systems (< 1 MW) use fixed bed gasifiers. These systems are usually robust and downdraft gasifiers, in particular, have achieved good gas qualities. The issue here is that gasifier performance tends to rapidly decline as systems are scaled to above 1 MW. There is a holy grail of a gasifier on a scale of 5 to 10 MW with robust and simple (operator-less) operation and low tar production that would be a perfect fit for supplying low and medium temperature steam to industry. One example of a developer that offers such a system is Zeropoint. They are an interesting developer, because they have a number of CHP systems already running. Even though the runs they claim are still modest (longest run was about 60 hours continuous operation), the technology looks promising and this is one of the few fixed bed gasifiers that works reliably at 5 MW scale. Zeropoint thinks they can scale to even 10 MW (thermal input).

Gasification for CHP is a space where innovation is mainly done by universities, RTOs and start-ups. There are hardly any large companies active. Siemens acquired the gasification technology of Schwarze Pumpe at one moment, but has since divested again. Large companies and organizations active in gasification are:

1. Shell
2. Wuhan Kaidi
3. General Electric
4. Fraunhofer (multiple institutes independently)
5. Rentech

Of these developers, only general electric and rentech have relevant product offerings. The other companies have many patents and publications, but do not explicitly offer a gasification product.

FIGURE 10 LUX INNOVATION GRID OF TECHNOLOGY DEVELOPERS OF GASIFIER SYSTEMS



Technology key metrics

Gasification is an interesting option for smaller steam systems of up to 20 MW thermal output. A system such as developed by Zeropoint could reliably supply steam using three gasifiers for such a system. Larger systems would have to use fluidized beds and gas turbines. This combination has been proven to work. One example are the experiments conducted in Varnamo in the 1990's (Krister Stahl, 1999). Even though large scale pilot experiments were conducted over 20 years ago, this technology has not become widely used because of the complications of either compressing tar-containing syn-gas or operating the entire gasifier at high pressure (which turns it into a very elaborate and expensive biomass burner). Limited progress is still made on resolving these issues, but momentum is low.

Overall gasification-based CHP is a maturing technology for scales up to 20 MW thermal output and should be ready to deploy on a large scale within the next five years. Development risk for these type of systems is low.

TABLE 14 KEY METRICS AS DETERMINED FOR A GASIFICATION BASED CHP SYSTEM

Metric	Value
CAPEX equipment only	2.66 EUR per W steam output
CAPEX including installation	4.80 EUR per W steam output
Overall energy efficiency	67% (energy used from biomass input)
Refurbishment interval of the installation	15 years
Electric output	0,875 W per W steam output
Term in which this technology becomes available commercially	Already available today

Hydrogen combustion

System description

This is the simplest system considered. It involves just replacing the burners in the boiler by burners using hydrogen. In practice this will probably be more complicated than it sounds. Hydrogen flames behave very differently from natural gas flames. The radiative heat transfer is much less for example. This should have a mild impact on the boiler capacity, reducing it by perhaps 10%. Most heat transfer in steam boilers is convective and that should be somewhat better with hydrogen flames.

Hydrogen is burned using air. This results in a flue gas rich in water vapor. Because it is diluted with nitrogen, only a small fraction of the water can be condensed. Therefore the lower heating value of hydrogen is used for the assessment of this system.

Technology developers

There are no technology developers that explicitly target retrofitting boilers to burn hydrogen (yet). That means the main suppliers for this technology should be the major supplier of boiler systems or combustion specialists such as Duiker combustion systems.

Technology key metrics

This technology does not require major investments, but it does mean switching to more expensive fuel. The investments are in the hydrogen infrastructure and the burners. Additionally, there must probably be energy efficiency measures in the factory, because the steam boiler will likely have up to 10% less capacity Alternatively, additional heat exchanger surface can be added to the boiler.

This solution is a quick fix, but will likely incur much higher operational costs. The key metrics as calculated from our model are listed in table 15

TABLE 15 KEY METRICS AS DETERMINED FOR HYDROGEN COMBUSTION

Metric	Value
CAPEX equipment only	0.1 EUR per W steam output
CAPEX including installation	0.25 EUR per W steam output
Overall energy efficiency	85% (on HHV)
Refurbishment interval of the installation	20 years
Term in which the technology becomes commercially available	Already available today

Electrolysis

System description

This system is similar to hydrogen combustion, but now the hydrogen is not bought. It is generated on-site using electricity from the grid. This could also be electricity generated on-site using wind turbines or solar panels of course. In this analysis grid electricity is used. This is a worst case. If there is a possibility to obtain lower cost electricity using wind on-site generation, the business case will only be better.

The system is thus: an electrolyzer producing hydrogen and oxygen that then feeds the boiler. The boiler has been retrofitted with hydrogen burners. In this application, the burner can use oxygen or at least enriched air which results in less degradation of boiler capacity and a higher efficiency, because more water vapor can be condensed.

Technology developers

There is a limited number of technology developers active in developing electrolysis equipment. This space is dominated by larger companies. The relevant developers are shown in the LIG in Figure 11.

FIGURE 11 LUX INNOVATION GRID OF TECHNOLOGY DEVELOPERS OF HYDROGEN GENERATION AND STORAGE

The main large corporations that are actively developing this technology are:

1. De Nora
2. Siemens
3. Solvay
4. Honda
5. Permelec (now part of De Nora)

It is worth noting that electrolysis is mainly a European endeavor in contrast to for example heat pumps.

Technology key metrics

Lux used the data of the Proton onsite system as they have a well-developed system for which sufficient data is available. Lux used the experience curve for estimating CAPEX from the current pilot system, resulting in a 45% decrease in CAPEX (applying the experience to the assembly of cells, not stacks). The current system of Proton Onsite achieves about 65% efficiency. Larger system can achieve higher efficiencies. The main cause of inefficiency in electrolyzers is the impedance of the system. To overcome that, a higher voltage than required for the electrochemical conversion must be supplied to the system. Larger systems allow for design that optimize the impedance further, resulting in higher efficiency. Based on a number of simulations of smaller and larger systems, Lux established that the final system efficiency could be as high as 80%.

The attractiveness of this systems stems from two important differences with buying hydrogen and burning that:

1. The onsite hydrogen infrastructure is much simpler. Hydrogen does not have to be stored under pressure.
2. The efficiency of the hydrogen burner can be higher because there is oxygen available

The advantage of simple hydrogen infrastructure also extents to the logistics. The reason that hydrogen supplied at the gate is not much cheaper than onsite generation through electrolysis is due to the transportation of hydrogen at high pressure. **Hydrogen from steam methane reforming is currently much cheaper than hydrogen from electrolysis, but transportation without pipelines cancels most of the cost advantage. In a scenario where all hydrogen needs to be sustainable eventually, it is very likely that onsite generation will beat buying hydrogen on the commodity market. Unless all current gas transportation infrastructure is converted to carry hydrogen.**

Electrolysis equipment at the scale of 20 MW is already available on the market today, so this technology could be implemented right now. The problem however is the availability of electricity. Lux estimate it will take at least ten years to guarantee sufficient electricity supply to enable the large scale application of this technology.

Table 16 lists the key metrics of this technology as calculated from our model

TABLE 16 KEY METRICS AS DETERMINED FOR HYDROGEN COMBUSTION

Metric	Value
CAPEX equipment only	1.36 EUR per W steam output
CAPEX including installation	2.50 EUR per W steam output
Overall energy efficiency	73%
Refurbishment interval of the installation	10 years
Term in which the technology becomes available commercially	After 2030

Direct electric heating

System description

This system is just a very large electric resistor. There are two types of systems. One is a large electric heating element. The other is using the water itself as resistor, dissipating the electric energy directly in the water. The latter system is attractive for discontinuous systems (like hot tap water boiler) because is has a very fast response time. For continuous systems, this solution is too complicated (it involves many narrow channels) and doesn’t offer advantages, since response times are no consideration (only during start-up of the installation).

The system is then very simple. A large electric heater, where water and electricity are entering and steam is leaving.

Technology developers

There are already many companies supplying these types of systems. Most of them supply small systems for situations where it is not worthwhile to create a dedicated gas infrastructure for example.

Many of these suppliers are located in China. Because the technology is fairly simple, patenting and research activity is very limited. This is more of less a commodity product that can be bought off the shelf. Implementation could start tomorrow, but the issue is again (as with electrolysis) that there is not a good electricity supply yet. This puts the commercial implementation of this technology on the same time-scale as electrolysis.

Technology key metrics

The key metrics of this technology are listed in table 17

TABLE 17 KEY METRICS FOR DIRECT ELECTRIC BOILERS

Metric	Value
CAPEX equipment only	0.15 EUR per W steam output
CAPEX including installation	0.45 EUR per W steam output (high because of electricity connection)
Overall energy efficiency	90%
Refurbishment interval of the installation	10 years
Term in which the technology becomes available commercially	After 2030

Overview of selected technologies

Lux Research has selected some of the most promising technology options for a drop-in replacement for natural-gas fired steam boilers that produce steam of up to 200 ºC. Table gives a brief description of these technologies.

TABLE 18 TECHNOLOGY OPTIONS SELECTED BY LUX RESEARCH. SOURCE: (VAN BERKEL & HERNANDEZ, 2018).

Technology	Description	Maturity
Direct electric heating	Steam can be raised using direct electric heating. This is not much different from an electric kettle, just operating on a much larger scale and at higher temperatures and pressures.	Scaling. Electric steam boilers exist and are commercially available.

Electrolysis	Rather than buying hydrogen, companies could generate hydrogen on-site using electrolysis and then burn the hydrogen to generate the desired temperature.	Introduction. The first large-scale electrolysers are now being deployed.
Biomass gasification based CHP system	Biomass is gasified and the gas is used to run a CHP unit.	Introduction. A couple of commercial gasification based CHP units exist. This technology is on the brink of market introduction.
Heat pump recovering waste heat	Heat from the environment or a reservoir is raised to a higher temperature level using electricity.	Scaling for low temperature, still development for temperature above 80 °C.
Hydrogen combustion	The industry could buy hydrogen and burn that instead of natural gas.	Scaling. The technology to combust hydrogen is available and used in many applications already.

Other options (such as geothermal energy, waste heat from nearby industry and biogas) can play an important role in decarbonisation of the steam supply as well. Lux Research has explained the considerations for the technology selection (van Berkel & Hernandez, 2018). Geothermal energy has not been selected as it is only applicable to industry that is located in a suitable place. The possibility to use waste heat from nearby industry depends on the availability of suppliers of waste heat. Biogas is considered to be a viable option, but the added value of selecting biogas was considered to be limited, as there are already many studies on using biogas.

For the selected technologies, Lux Research has collected data and made estimations regarding their likely future performance. Table 19 summarizes the characteristics of the technology options.

TABLE 19 CHARACTERISTICS OF TECHNOLOGY OPTIONS. SOURCE: (VAN BERKEL & HERNANDEZ, 2018)

	Direct electric heating	Electrolysis	Biomass gasification based CHP system	Heat pump recovering waste heat	Hydrogen combustion
CAPEX equipment only	0.15 EUR per W steam output	1.36 EUR per W steam output	2.66 EUR per W steam output	0.2 EUR per W thermal output	0.1 EUR per W steam output
CAPEX including installation	0.45 EUR per W steam output (high because of	2.50 EUR per W steam output	4.80 EUR per W steam output	0.5 EUR per W thermal output	0.25 EUR per W steam output

	electricity connection)				
Effective COP	-	-	-	3.5	-
Refurbishment interval of the installation	10 years	10 years	15 years	10 years	20 years
Electric output	-	-	0.875 W per W steam output	-	-
Overall energy efficiency	90%	73%	67% (energy used from biomass input)	-	85% (on HHV)

The characteristics are based on an installation size of 15 MW and a 2,000 units production volume. Calculations based on these characteristics can give rough insights into the possible effects and costs of applying the technologies. In reality, the characteristics will depend on the specific application, such as the required steam temperature and other aspects of the production process.

Figure shows how much fuel or electricity is needed to produce 1 GJ of steam with each of the selected technology options. The figure only shows the net energy consumption at the production site. Energy that is consumed elsewhere (for example to produce electricity or hydrogen) is not included. The biomass-based CHP system produces electricity, and therefore has a net output of electricity. Using electrolysis (to produce hydrogen which is then burned) requires more electricity than direct use of electricity for heating.

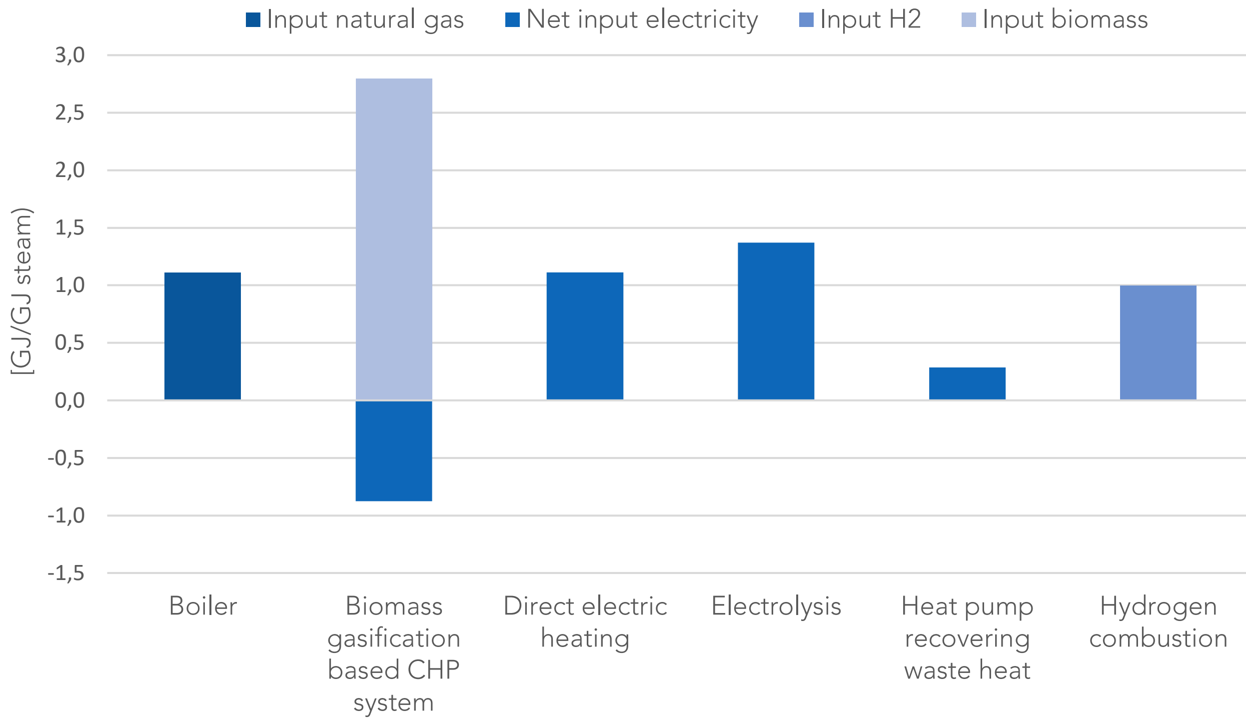


FIGURE 12 CONSUMPTION OF FUEL/ELECTRICITY TO PRODUCE 1 GJ OF STEAM FOR THE SELECTED TECHNOLOGIES BASED ON THE TECHNOLOGY CHARACTERISTICS IN (VAN BERKEL & HERNANDEZ, 2018) AND BOILER EFFICIENCY OF 90%.

Development of energy and CO_2 prices

The future developments of the natural gas, electricity and CO_2 prices are highly uncertain. The energy and CO_2 prices used in this report are based on the reference scenario of the National Energy Outlook 2017 (NEV 2017) (Schoots, Hekkenberg, & Hammingh, 2017).

The NEV 2017 provides insight into developments in the Dutch energy system in an international context. The reference scenario incorporates external factors, such as the economy, demographics and fuel and CO_2-prices. The reference scenario has two policy alternatives. Here, the policy alternative 'Proposed policy measures' (VV) is used.

Two scenario variants are used for a sensitivity analysis (see (Achtergronddocument onzekerheden NEV 2017, 2017)):

- 'VV-H' is a scenario variant with higher energy and CO2-prices.
- 'VV-L' is a scenario variant with lower energy and CO2 prices.

Figure 13 shows the development of the natural gas price in the reference scenario (VV) and the two scenario variants. In the reference scenario, the natural gas price is expected to increase but there is a substantial bandwidth. The long term price developments for natural gas are based on projections of the International Energy Agency (IEA). The bandwidths for the natural gas price are based on the long term WLO outlook (PBL/CPB, 2015).

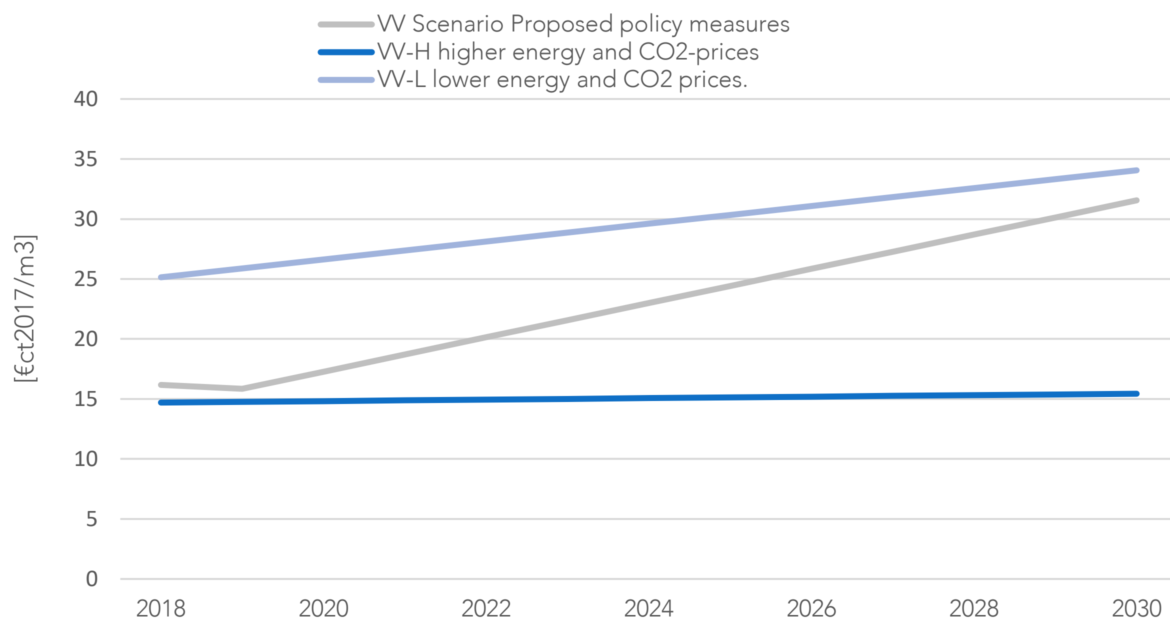


FIGURE 13 DEVELOPMENT OF THE NATURAL GAS PRICE PER SCENARIO VARIANT. SOURCE: (ACHTERGRONDDOCUMENT ONZEKERHEDEN NEV 2017, 2017)

The CO_2-price is expected to remain low in the near future (see Figure 14), but increasing scarcity of emission allowances is projected to drive up the CO_2-price in the longer term. The uncertainty bandwidth for the CO_2-price in 2030 ranges from 12 to 79 euro/ton.

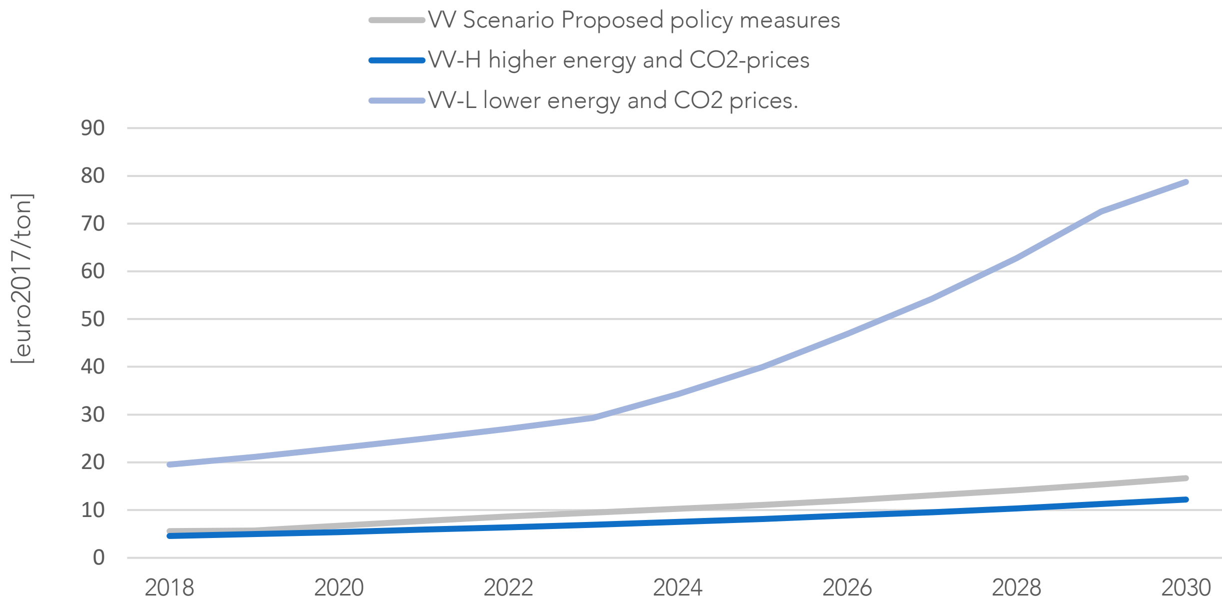


FIGURE 14 DEVELOPMENT OF THE CO_2 PRICE PER SCENARIO VARIANT. SOURCE: (ACHTERGRONDDOCUMENT ONZEKERHEDEN NEV 2017, 2017)

Fuel and CO_2 prices are important determining factors for the electricity price. The growth of renewable electricity generation has an important impact as well. Developments in other countries are of increasing importance for the Dutch trade balance of electricity and the electricity prices, because of increasing interconnection capacities and integration of the European energy markets. Figure shows the development of the electricity prices in the reference scenario (VV) and the two scenario variants.

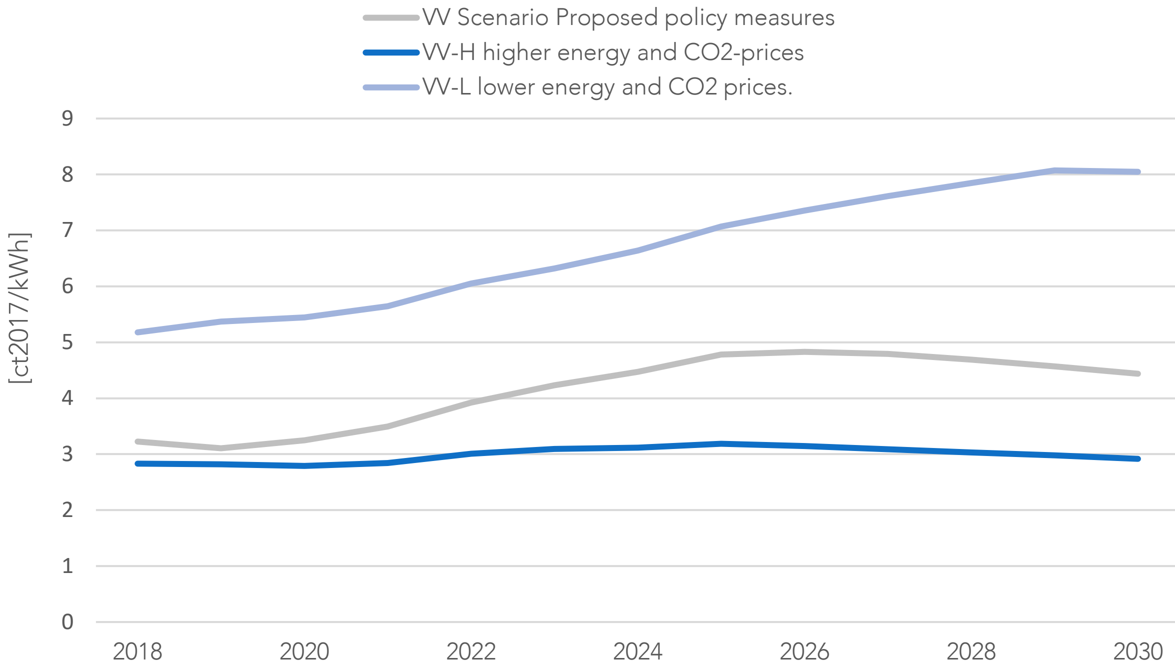


FIGURE 15 DEVELOPMENT OF THE ELECTRICITY PRICE PER SCENARIO VARIANT. SOURCE: (ACHTERGRONDDOCUMENT ONZEKERHEDEN NEV 2017, 2017)

Results per technology

Based on the technology characteristics and the price scenarios, capital costs, fuel costs, electricity costs and CO2-costs have been calculated for each technology.

Direct electric heating

The technology 'direct electric heating' uses a large electric resistor to produce steam. Water and electricity are entering the system and steam is leaving. The overall emission reduction that can be realised depends on the CO_2-intensity of electricity generation.

Electrolysis

The technology 'electrolysis' is similar to hydrogen combustion, but in this case the hydrogen is generated on-site using electricity from the grid. An electrolyser produces hydrogen and oxygen that then feeds a boiler which has been retrofitted with hydrogen burners. The burner can use oxygen or enriched air, which results in less degradation of the boiler capacity and a higher efficiency.

Biomass gasification based CHP system

Pulp and paper plants have side streams of reject materials and other biomass materials that do not end up in the final paper and board products. For the technology option 'Biomass gasification based CHP system', it has been assumed that the residues are fed into a gasifier coupled to a gas engine. The system supplies heat (steam) and electricity. The gas that is generated needs to be of sufficient quality to be used in gas engines. The application of the technology is limited by the availability of reject materials and other biomass materials.

Heat pump recovering waste heat

The technology 'heat pump recovering waste heat' uses waste heat of about 60°C in combination with a heat pump to generate steam of 120°C. Heat pumps are more efficient than direct electric heating.

Hydrogen combustion

For the technology option 'hydrogen combustion', it has been assumed that burners of natural gas boilers are replaced by burners using hydrogen. Hydrogen is burned using air. This technology does not require major investments, but it means that a more expensive fuel has to be bought.

Figure shows the capital costs per technology per unit of steam. The biomass gasification based CHP system and the electrolysis require the largest investments per unit of capacity. The capital costs have been calculated using a discount rate of 10% in an annualized net present value calculation. It was assumed that the annual number of full-load hours is 8,000 for each of the technologies. In reality, the number of full-load hours may vary from year to year and depend on the situation.

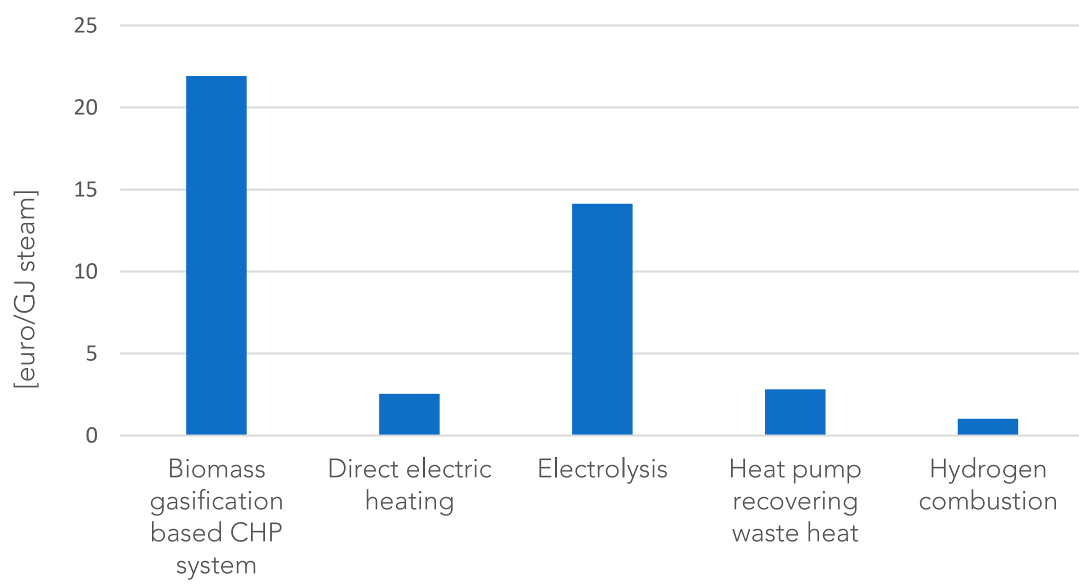


Figure 16 Capital costs per technology per unit of steam (based on (VAN BERKEL & HERNANDEZ, 2018) and additional assumptions)

Figure shows the energy and CO2 costs per technology per unit of steam. It has been assumed that the installations become operational in 2025 and therefore energy and CO2 prices for the years 2025 onwards have been used.

Of the three electricity-consuming technologies, the energy costs for the heat pump system are the lowest. The heat pump has an effective C.O.P. of 3.5 and therefore uses less electricity than the direct electric heating system (with overall efficiency of 90%) and the electrolysis system (with overall efficiency of 73%).

The net energy costs of the biomass gasification based CHP system are negative. It has been assumed that the avoided costs for disposing of reject materials is 80 euro/ton (with a range of 60-100 euro/ton).6 For this CHP system, there are also benefits from the sales of electricity. The required investment for this technology is relatively high. The attractiveness depends on the quantity and the price of available reject materials and other biomass materials.

For the production of hydrogen, several routes and technologies exist. Currently, steam methane reforming (SMR) of natural gas is the most widely applied technology. Other options include electrolysis of water and the production hydrogen from biomass (Gigler & Weeda, 2018) The costs of hydrogen depend strongly on the situation and availability of infrastructure. For hydrogen delivery (based on steam methane reforming with CCS) costs of 2.2 euro/kg hydrogen are assumed.7

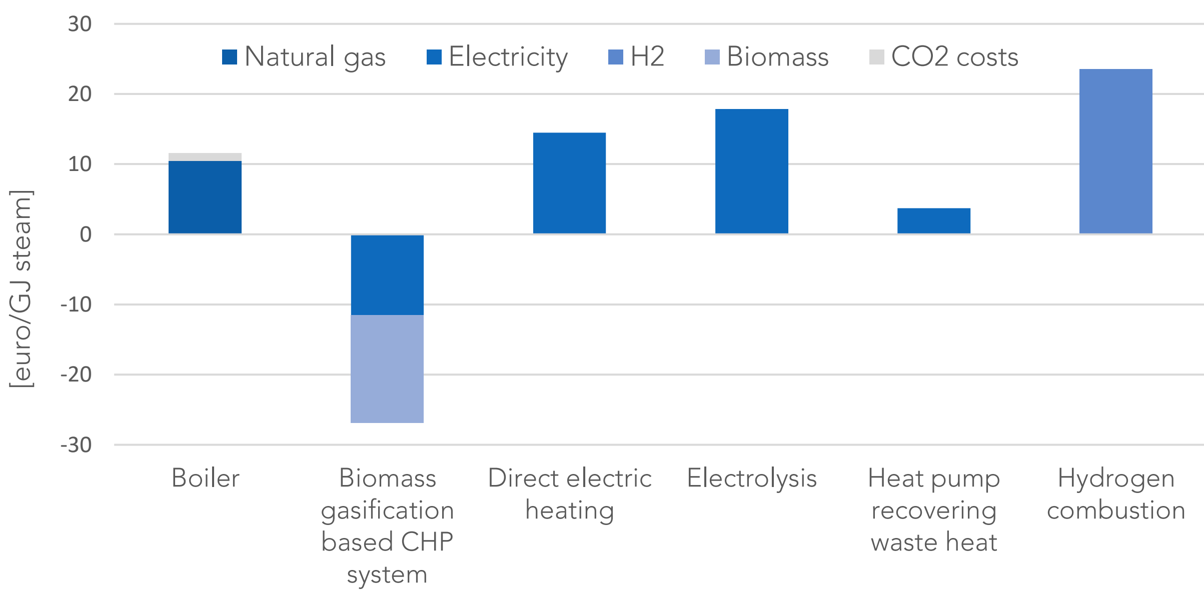


Figure 17 Net energy and CO2 costs per technology per unit of steam (scenario VV) (based on **(VAN BERKEL & HERNANDEZ, 2018)** and additional assumptions)

[6] The lower heating value of the reject materials is assumed to be 14.6 MJ/kg.
[7] The lower heating value of hydrogen is 120 MJ/kg. The production costs of hydrogen are assumed to be 1 €/kg H_2. With large-scale production of hydrogen through SMR, the natural gas makes up 70-80% of production costs (~0.75 €/kg H_2). (Gigler & Weeda, 2018)

Figure 13 shows the results of a sensitivity analyses for lower and higher energy and CO2 prices. The VV-scenario is the scenario with implemented and proposed policies of the National Energy Outlook 2017. VV-H is a scenario with higher prices and VV-L is a scenario with lower prices.

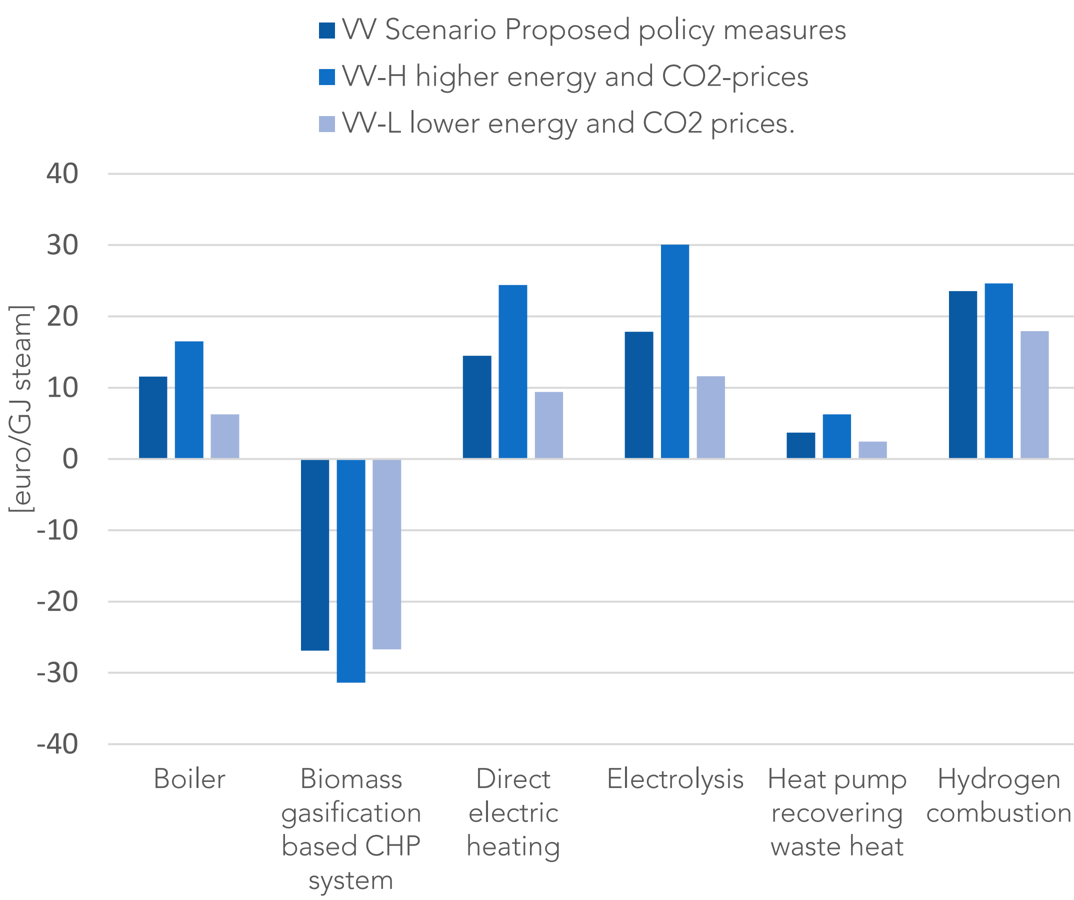


Figure 13 Energy commodity costs and CO2-costs for heat generation per technology in the VV, VV-L and VV-H scenario's.

Figure 13 does not provide a full overview of the costs of application of the technologies. There are several cost components that have not been quantified, such as the energy taxes, energy tariffs, operating and maintenance costs, subsidies. Many technology characteristics depend on the specific situation in which the technology is applied. The figure therefore only gives rough insights into the energy cost differences between the technologies.

DISCUSSION

The goal that has been set for the Dutch Climate Agreement is to reach a reduction of the national emission of greenhouse gases by 49% in 2030 (compared to 1990). The current European ambition is to reach a reduction of 80 to 95% in 2050. Such reduction targets can only be reached through major changes in the energy system of the Netherlands.

To support the negotiations on the Climate Agreement, PBL has written a report on the most recent insights regarding the cost effectiveness (expressed in euro per ton avoided CO2) of different CO2-emission reducing measures and the potential for emission reduction in 2030 (Kosten energie en klimaattransitie 2030 - update 2018, 2018). PBL concludes that energy efficiency improvements, electrification of the heat demand, CCS and the use of biomass are important options for emission reduction in the industry up to 2030.

This section discusses the potential role of available options to reduce the greenhouse gas emissions from the production of steam in the industry.

The role of electrification

This report has looked into three technologies than can contribute to electrification of the steam supply of the industry: heat pump systems, direct electric heating and electrolysis.

Electrification using electrical heat pumps can give rise to significant energy efficiency improvements compared to natural gas boilers. In the paper industry, waste heat is available from the dryer sections at approximately 60 °C. Because the required steam temperatures in the paper industry are lower than in most other energy-intensive industrial sectors, heat pumps are a good match. Research and development efforts are ongoing to reduce the capital expenditures and to increase the output temperatures.

Electrification using resistors or electrolysis does not lead to substantial energy efficiency improvements, but can still result in emission reduction when combined with CO2-free electricity generation.

In the near future, electrification may not always lead to emission reduction, because the emissions from electricity generation are still substantial. However, the National Energy Outlook 2017 shows a clear downward trend in fossil electricity generation. It is projected that over half of all electricity will be generated by renewables in 2025 and it is expected that this share will rise to two-thirds in 2030 (Schoots, Hekkenberg, & Hammingh, 2017).

This trend is caused by a decrease of fossil generating capacity in the Netherlands and an increase of renewable electricity generation, in the Netherlands as well as in countries such as Germany. The transport capacity between the Netherlands and surrounding countries increases, which allows for more exchange of (renewable) electricity. This means that less conventional generation is needed for periods with low renewable generation.

The first phase of electrification may take place using hybrid systems. These systems allow to choose between direct electric heating and fossil heating (depending on the price of electricity). Such systems can use the solar and wind energy that would otherwise be lost through curtailment. The profitability and emission reduction potential of these systems depend on developments in the electricity market.

The PBL study "Verkenning van klimaatdoelen" presents analyses made with two integral energy models for the Netherlands (Ros & Daniëls, 2017). The models calculate a cost optimal configuration of the energy system, using an emission reduction of 80 or 95% in 2050 as a boundary. In all variants, there is a clear shift from the use of fuels to the use of electricity. PBL concludes that electrification is a robust component of the energy transition.

The role of hydrogen

Compared to electricity, hydrogen has some advantages and some disadvantages. It is easier to store hydrogen and to transport it with high energy density. Production of hydrogen from electricity can help to make use of surpluses of solar and wind energy.

A disadvantage is that the energy consumption increases because the chain efficiencies are typically lower. Production of hydrogen from electricity has an efficiency of approximately 70%. (Ros & Daniëls, 2017) The use of hydrogen usually requires considerable measures on the side of the energy consumers and changes to infrastructure.

In cost-optimal solutions for long-term deep decarbonisation in the "Verkenning van klimaatdoelen" study, hydrogen production take place predominantly from electricity (electrolysis of water) or from natural gas with carbon capture and storage (CCS) (Ros & Daniëls, 2017). By conversion of natural gas to hydrogen and applying CCS, CO2 emissions can be avoided.

The technology to use and produce hydrogen is already available (e.g. electrolysis, hydrogen burners), but these technologies are often not yet competitive with the current (fossil) alternatives (Gigler & Weeda, 2018).

The role of biomass

Biomass has many applications in the energy production and in the energy demand sectors. It can be used for the production of heat, hydrogen, electricity, biofuels and for specific industrial processes.

The use of biomass waste streams (e.g. using the biomass gasification technology discussed in this report) is an interesting option. The availability of such waste streams is however limited. Through the use of other types of biomass, such as imported wood pellets, a larger share of the heat demand can be fulfilled.

From a long-term perspective, the large scale use of biomass in the industry can be logical, especially because biomass in combination with CCS can result in negative emissions (Koelemeijer, R.; Daniëls, B.; Koutstaal, P.; Geilenkirchen, G.; Ros, J.; Boot, P.; van den Born, G.J.; van Schijndel, M., 2018). However, CCS can only be applied when the scale is sufficiently large, such as at large industrial point sources or industrial agglomerations.

The use of biomass in the industry instead of fossil fuels offers the possibility to reduce CO2-emissions. It is however very important to guarantee the sustainability of the biomass and to limit the greenhouse gas emissions in the supply chain. A growing demand for biomass in other countries can make it difficult to obtain enough sustainable biomass. It can also drive up biomass prices. This is the reason that the use of biomass is not necessarily a robust element of a cost-effective reduction package according to PBL's study into cost-optimal long-term solutions (Ros & Daniëls, 2017).

The role of geothermal energy

The industry has only limited experience with geothermal energy. A large amount of heat is available in the deep underground. The extent to which this heat can be used in the industry depends on the location and possible side effects. Geothermal energy often plays a role in cost-optimal solutions for deep decarbonisation of the industry (Ros & Daniëls, 2017).

The role of waste heat

Industrial locations can use waste heat from other industry when the waste heat supplier is nearby enough and heat distribution infrastructure is available. In clusters of industrial activity it is often possible to match supply and demand of waste heat. The industry can also deliver waste heat to other sectors.

GENERAL CONCLUSION

This report discusses promising drop-in replacements for natural-gas fired steam boilers in the industry. It does not provide a complete overview of technological options for decarbonisation of the steam supply.

The success of such technologies is dependent on future developments in the energy system and energy policies, which are often uncertain. Changes may be required to energy generation, distribution and infrastructure. There will not be one technological solution that can be applied in all cases.

The climate challenge for the energy-intensive industry is large. Policy makers need information to create effective policies to stimulate the energy transition. The industry requires information to draw up roadmaps and gain a better understanding of the advantages and disadvantages of decarbonisation options. In order to meet the climate challenge, a better overview of the current production methods and possible sustainable improvement options for the Dutch industry is vital. To bring more clarity to these issues, cooperation with the industry is essential.

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ANNEX 1 LUX METHODOLOGY

Lux has much data on individual technology developments. To model future performance of a technology, Lux looked at all this data, picked representative high performing developers and assessed the potential performance of their technology.

Lux analyse global innovation to estimate future performance

The methodology Lux developed consists of the following steps.

- Identify all possible technology options that could replace a steam boiler

Lux began by asking our analysts to list all options they could see that could potentially provide water vapor at 200°C. In this stage any technology is listed, even if it is still in a very early stage of development. On each of these technologies only basic information is listed. Enough to understand the potential advantages and disadvantages, but no detailed quantitative information yet.

- Select the most promising options together with industry and government

The gross list of technology options was discussed with representatives from industry and government (in this case ECN) to select the options that they would realistically consider investing in or supporting with policy. In this project Lux agreed beforehand to reduce the gross list of options to between three and six options.

- Collect data on each of the selected technologies

On the selected technologies Lux made a list of companies and research groups that are working to develop this technology out of our database. Lux also made a patent analysis to identify key actors and key trends in the development of this technology. Finally Lux looked at investment in this technology. All of this data was brought together to form a full description of the technology.

- Select one or two representative developments to extrapolate to future performance

Technology cannot be averaged between all developers. Different developers take different approaches with good reason. The resulting performance of the technology, once fully developed, will not be the average between all developers. It will the best performance between all approaches. Moreover, the best developer is not always simply the developer with the best approach to the technology. Other factors such as commercial strategy and partnerships are also important to determine the success of a technology. Lux selected one (or two) representative developer. Lux used their specific technology to estimate what the future performance of this technology would likely be.

- Extrapolate the key metrics of the technology to a fully developed state

Lux estimated, based on best engineering practice, the potential improvements the technology can still achieve compared to its current state. This results in a description of what would be a realistic expectation of the potential of this technology.

- Calculate mass and energy balances for each technology

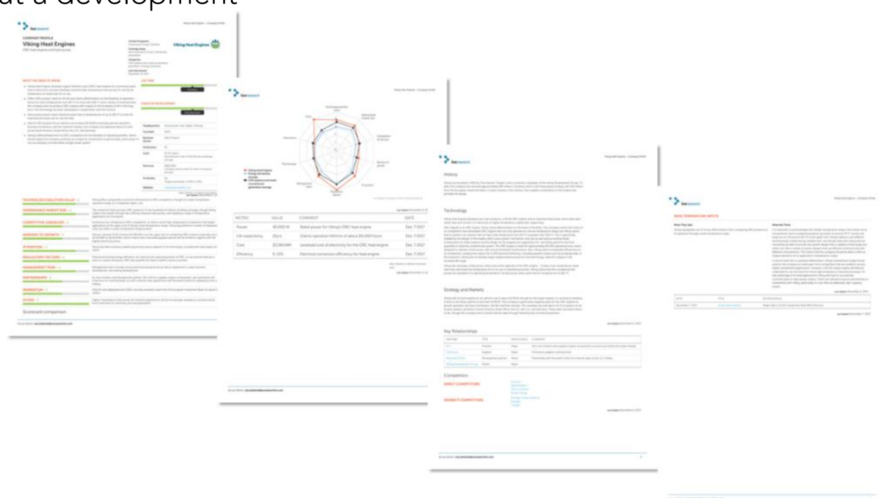
The energy system models regard the steam boiler as a black box with a number of inputs and outputs. The data required to make these technologies available to these models is a list of inputs with the associated outputs and some economic data. To translate the characteristics of the technology into this data on inputs and outputs, Lux made a mass and energy balance of each of the technologies.

Both the VNP and CEPI conduct several projects to fundamentally innovate the paper making process. A concise overview of all activities was recently published by CEPI (CEPI, 2017). The industry invests in new products, recycling, fuel switches and completely new paper making processes (e.g. without using water). Within Europe, the Dutch paper industry is one of the front-runners. The VNP recently published a technology roadmap for breakthrough technologies in paper making, together with Findest (VNP and Findest, 2018). That roadmap explores all technologies that would fit definitions 2 and 3.
This report focuses on the first definition. In other words: on replacing the function of supplying saturated steam of a certain temperature to the process. This is the least invasive interpretation for the rest of the process. Also, it is most applicable to all other industrial processes employing low and medium temperature steam. Some processes in industry require overheated steam. Any equipment that can provide saturated steam of a certain temperature can also provide overheated steam at all temperatures below.

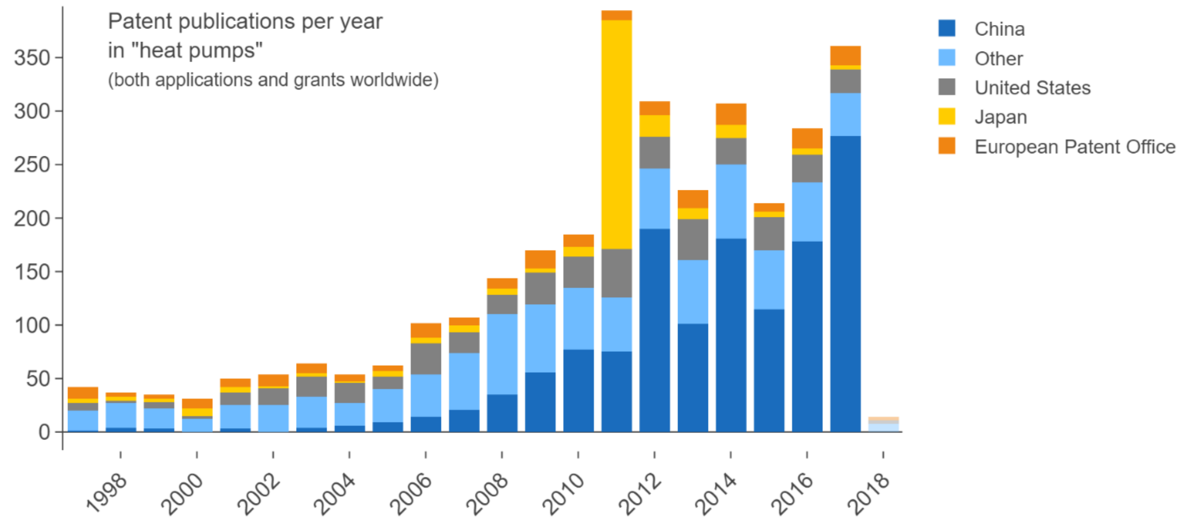
Lux's proprietary data and tools help to understand all aspects of the technology options
Once the technology options have been selected, Lux used Lux's proprietary data and tools to obtain a complete picture of the current state of the art of this technology. Below is a brief description of these data and tools.

Profiles of technology developments
Lux performs approximately 5000 interviews each year with technology developers everywhere in the world. These interviews result in structured descriptions of the development that have been fact-checked by the developer. Currently the Lux database contains information about 5125 developments relevant to the energy industry. The entire database contains information on nearly 30000 developments

A profile is a structured document containing all relevant technological and commercial information about a development



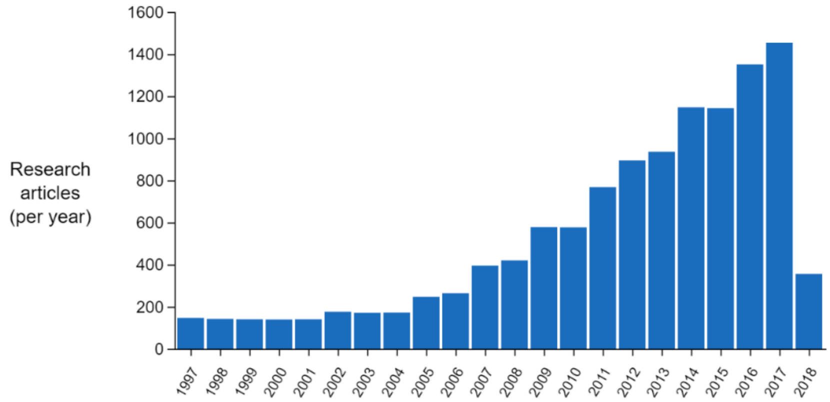
Proprietary patent analysis
Lux Research has access to PCT patent databases and applies its own search algorithms to it. This allows us to see trends in research and activity around a technology as well as identify the most active companies and academia. The analysis shows, among other things, which companies and regions are most active in a particular area; heat pump developments for example are dominated by Asia: China and Japan and "other" is mostly other Asian countries (upon inspection of the patents).



VC investment analysis
Lux also analyze the activity of venture capital in a technology. This is a good way to assess if this topic is addressed by start-ups or other non-corporate developers. It should be mentioned that VC data is scattered and the US tends to be much more open about these investments than other parts of the world. As a result, the analysis is incomplete and skewed. Still, an experienced analyst can use this to assess the relative importance of both the technology itself and start-ups as an innovation vehicle in the space.

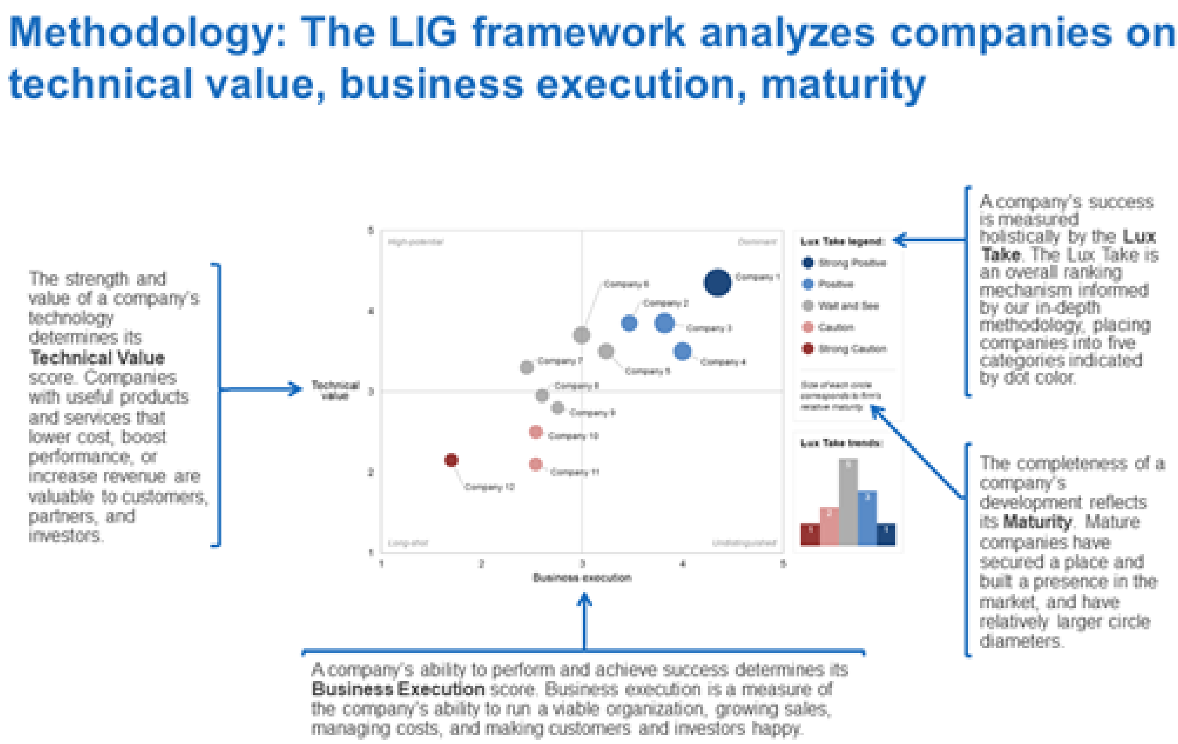
Analysis of scientific papers to identify trends
Finally, Lux analyze published peer-reviewed scientific papers to identify and assess trends in activity around a topic.

Analysis of scientific research on heat pumps reveals that there has been a strong and continuous increase in interest in the topic over the past 15 years.



Lux's innovation grid helps to identify the most promising developments
Excellent technology is not sufficient for a successful deployment. Other factors affecting the success of a technology include timing, economic factors, a supportive ecosystem, a clever business model and sufficient momentum in the development. Lux Research uses a scientifically proven method (Evan Kodra, 2015) to score developments on all these factors. The scores are summarized and structured in our innovation grid. The graph shows aggregate scores on the added value of the technology and the execution of its deployment. Developments that score high on both dimensions are dominant and are likely to set the pace of new technology deployment in their field. Developments that only score high on the added value of the technology are labeled high potentials. The basis of these developments is sound, but they could use help on execution. Developments that score high on execution but low on technology are undistinguished. They can be successful by executing well, but are vulnerable for competitors with better technology. Lux use this method to identify which development Lux should use to predict future performance.

The Lux innovation grid ranks developments along axes of technology value and ability to execute



Lux assess future performance using literature and engineering guidelines
As technology matures, there are developments that affect how the current performance translates into the performance of the mature technology. On the side of technology, the efficiency may improve further. This effect is highly specific for the technology and the assessment of this effect is therefore done by our analysts based on their knowledge of the technology.

The costs of the technology will usually also decrease. Lux distinguish two effects. First there is scaling of the technology. In process technology, if a process scales with a factor, the associated costs scale with a factor $n^{0.7}$. the background of this scaling rule however is the ratio of volume and surface area of installations. A critical review of this scaling was given by Tribe and Alpine (Alpine, 1986). Their review showed that this rule is the effect of averaging many different scaling factors applicable to different components of process technology (such as pipes, heat exchangers, rotating equipment). The exponents vary between approximately 0.25 and 1.25 depending on the type of component. They also found the exponent of 0.6 that is commonly used to be mostly correct. Here Lux use 0.7, which is also used frequently in industry. This will give a conservative estimate.

Second, there is the effect of mass production. This is usually expressed in the experience curve. Lux use the rule of thumb here that the cost price decreases by 15% for every doubling of production volume. This rule was first introduced by the Boston Consulting Group (The Boston Consulting Group, 1970). There has been much research around it since. One of the groups that did most research in this in the energy space is the Cambridge University Energy Policy Research Group (EPRG). See their website on https://www.eprg.group.cam.ac.uk. Based on extensive evaluation of these curves they reach the conclusion that the one-factor learning curve model tends to provide a conservative (too high) estimate of the technology price. Instead they propose a two-factor model, where they distinguish between learning-by-doing (i.e. increasing volume of production) and learning-by-research (i.e. increasing knowledge around the product). The latter can be measured in patents. In this study Lux take the original BCG learning curve into account. It would be good to model learning by research too, but that requires more research into patenting and literature around each of these technologies. For now, Lux use an estimate that Lux know to be conservative. This means that the study is biased in favor of more mature technologies, as they need less extrapolation to larger scaler and will therefore be affected less by the conservatism of these estimates.

All extrapolations of the technology Luxre made to the scale of a 15 MW system, with a total production volume to accommodate the current global world market of 2000 installations added per year. The number of 2000 installations is relatively arbitrary, but based on the IEA data. Current global energy use in the relevant type of steam boilers is approximately 20 EJ. If boilers last about 20 years, then the global replacement market (using only 15 MW boilers) is about 3000 boilers per year. Since not everyone will use the same solution and not all boilers are 15 MW, this provides a rough order of magnitude (thousands of units, not hundreds or tens of thousands). Lux used 2000 as the number to work with here.

These extrapolations will provide the cost of equipment, excluding the installation costs. Unless better data is available, Lux will use equipment factored estimation to account for installation costs. In this study Lux use a factor of 1.7 to estimate the installed costs. The total cost of equipment is multiplied by this factor to obtain an estimation of the installed costs. This factor is an industry standard for the installed costs on a brown field installation, including any infrastructure, piping, electrical installation and foundation and buildings for the new equipment, but excluding any costs for preparing the terrain.

Finally, a word on maintenance costs. These costs are in essence impossible to estimate for a hypothetical installation as they depend both on the design details of the installation (different car brands vary wildly in maintenance costs for the same function), the organization using the installation and the kind of use they are exposed to. A rule of thumb is to use about 2% of the fully installed costs of the installation as the annual maintenance costs. In this study, the uncertainty created by the extrapolation is much larger than 2% and it is therefore better to not include maintenance costs at all and just consider them lumped into the extrapolated CAPEX. If desired they can be included as a placeholder so that the model can easily be adjusted when more accurate data is available.

ANNEX 2 THE SENSITIVITY OF THE SCALING RULES

Lux look at the sensitivity of the extrapolation of the technology for the scaling rules to see how our assumptions affect the results.

The CHP system as an example:
To look at the sensitivity of the CAPEX estimates for the assumptions in the extrapolation, Lux use one system. The other systems will be giving the same sensitivity results as this is a purely mathematical exercise. As an example, Lux use the CHP system because it is the system for which most data is available so that the result can be compared to actual data.

Varying the scale of the system results in 7% difference.

The CHP system of 15 MW has an estimated CAPEX (equipment only) of € 2.66 per W installed capacity. If Lux had use a system scale of 30 MW instead (and hence a volume of not 2000, but 1000 units), the price would have been 93% of this price, which is € 2.49 per W.

Scaling in the other direction: 7.5 MW results in a price increase per W of 6%, resulting in € 2.83 per W. Overall varying the scale of the system by a factor 2 in either direction results in only slight variations of the specific CAPEX of the technology. This is the result of the two counter-acting forces of increasing scale and decreasing production volume.

Varying the model parameters can completely change the dynamics
The system was scaled from a production volume of 5 units at a size of 5 MW. The original specific CAPEX was thus € 5.65 per W.

Now if Lux change the scaling exponent from 0,7 to 0,6, the resulting specific CAPEX for the baseline 15 MW unit becomes € 2.38 per W, a 10% change. Moreover, if the experience curve effect is changed from 15% to 20% (using a scaling exponent of 0,7 again), the price changes to € 2,27 per W, again a 15% deviation from the original extrapolation.

More importantly, if Lux use a learning curve effect of 20%, the specific CAPEX of a 30 MW is higher than that of 15 MW. In this case it would be better to buy two smaller units and use them in parallel than to build a bigger unit. This is simply because the effect of scaling production outweighs the effect of scaling the unit with these assumptions. The difference is small however (1% increase in specific CAPEX).

Concluding
The variations of the extrapolation around the chosen size of 15 MW with a 2000 units production volume are very mild. There is a 7% if other reasonable scales would have been chosen. The effect of the assumed parameters is larger. It can be said that the extrapolations contain an inherent variation of plus or minus 15% as a result of reasonable variations of the model parameters. This is not the same as the accuracy of the extrapolation. The accuracy can only be estimated once a full scale unit has been build (model validation).