

Taking the C out of steam

In the global quest to reduce and even eliminate CO₂ emissions, there are already clear solutions for the built environment and mobility. However, the energy needs of industry are much more complicated to cater for without emitting CO₂. This report identifies and compares future technologies to generate carbon-neutral steam, which is one of the most common types of energy prevalent in industry.

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Samenvatting

Stoom stond als energiedrager aan de wieg van de industriële revolutie en nog altijd is stoom een belangrijke energiedrager voor de industrie. Het vertegenwoordigt een derde van het energiegebruik in de industrie en een kwart van de CO₂-uitstoot van de industrie. Eén op één vervanging van de huidige stoomketels door een CO₂-vrije oplossing is aantrekkelijk voor het reduceren van de CO₂-uitstoot van de industrie omdat op die manier de processen waarin de stoom gebruikt wordt ongewijzigd kunnen blijven. Dit rapport onderzoekt dergelijke oplossingen voor stoom van lage tot middelhoge (200 °C) temperatuur. Een transitie van het gebruik van dit type stoom naar koolstof-vrije alternatieven, heeft invloed op meer dan 11% van het energiegebruik in de industrie en kan de industriële CO₂-emissie met zeker 10% terugdringen. Dit zou daarom een prioriteit van zowel de industrie als beleidsmakers moeten zijn.

Het feit dat de impact van deze oplossingen zo groot is, betekent echter ook dat een nauwe samenwerking tussen industrie en energiebeleid en -regelgeving noodzakelijk is. Dit rapport was een samenwerking tussen ECN en Lux Research. ECN beheert het Nederlandse model voor het energiesysteem. Dit model wordt door de overheid gebruikt om energiebeleid te ontwerpen en evalueren. Lux Research voorziet de industrie van informatie over nieuwe technologie. Bedrijven gebruiken die informatie om hun investeringsbeleid in nieuwe technologie en middelen te evalueren en verbeteren. Dit rapport onderzoekt hoe de gegevens van Lux Research de modellen van ECN kunnen voeden zodat de kennis over nieuwe energie-technologie die de industrie gebruikt voor zijn investeringsbeslissingen, ook kan worden gebruikt voor het ontwikkelen van beleid. Op die manier ontstaat een platform dat overheid en bedrijfsleven kunnen gebruiken om beleid en investeringen op elkaar af te stemmen.

Om de technologie die in dit rapport wordt beschreven te selecteren hebben we de volgende procedure gehanteerd.

- Identificeer alle mogelijke technologie die een stoomketel zou kunnen vervangen; ongeacht het TRL niveau
- Selecteer de meest veelbelovende opties in overleg met de industrie en de overheid
- Verzamel alle beschikbare gegevens over de gekozen opties
- Selecteer één of twee representatieve ontwikkelingen voor elke optie
- Extrapoler de gegevens van de gekozen opties naar de prestaties en kosten van die technologie als hij helemaal uitontwikkeld en op grote schaal toegepast zou zijn.
- Bereken massa- en energiebalansen van de gekozen opties en de economisch prestaties

Door deze procedure te volgen is input voor het systeemmodel verkregen. Deze data is vervolgens in het systeemmodel gebruikt om scenario's door te rekenen. De scenario's verschillen in bijvoorbeeld toegepast beleid, waardoor de energieprijzen verschillen per scenario. Evaluatie van deze scenario's laat zien hoe beleid de investeringsbeslissingen van de industrie kan beïnvloeden; in dit geval met betrekking tot het reduceren van CO₂-emissies voor de productie van stoom. De scenario analyses staan in een rapport dat door ECN wordt uitgegeven.

Executive Summary

Steam is the energy carrier that triggered the industrial revolution and today it still constitutes one third of industrial energy use and a quarter of CO₂ emissions. Drop-in solutions for medium temperature steam are attractive to reduce CO₂ emissions, because the manufacturing processes that use them can then remain unaltered. A transition of low and medium temperature steam (up to approximately 200 °C) in industry to carbon-free alternatives will affect more than 11% of all energy use in industry and results in at least 10% reduction of CO₂ emissions by industrial production. It should therefore be a priority to replace low and medium temperature steam by carbon-free alternatives.

At the same time, the fact that this has such a large impact on energy use, means that there needs to be a close collaboration between energy policy and regulation and investments by industry. This report was a collaboration between the Energy Research Centre of the Netherlands (ECN) and Lux Research. ECN develops and maintains the energy system model for the Netherlands, which is used by the government to evaluate and design energy policy. Lux Research provides information on new (energy) technology to improve company's innovation investment decisions. This report investigates how Lux's data can feed ECN's models so that knowledge about new energy technology can also improve policy-making and ensure that both industry and governments are looking at the same possibilities.

To select and subsequently describe future technologies to include in the system model, we 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

This resulted in data to use in the system model. The system model was then used to evaluate various scenarios.

The need for carbon-neutral steam

Steam is the energy carrier that triggered the industrial revolution and today it still constitutes one third of industrial energy use and a quarter of CO₂ emissions. Drop-in solutions for medium temperature steam are attractive to reduce CO₂ emissions, because the manufacturing processes that use them can then remain unaltered. This report investigates the possible technology options from micro- and macro-economic perspective.

Steam is still the lifeblood of industry

The industrial revolution started with the availability of affordable and powerful steam engines. Ever since, steam has been one of the main forms of energy that industry uses. Even though much of the mechanical work has now been replaced by electric motors, steam still is the main energy carrier for heating in industry.

The most comprehensive recent study of energy use in industry was performed by the IEA (IEA, 2007). This study estimates that steam still constitutes 38% of industrial energy use (excluding steam generated in coal fired and combined cycle power plants). In 2007 this was equivalent to 33 EJ of primary energy input globally and it resulted in approximately 2.42 GT of CO₂ emissions globally, which was 24% of the CO₂ emissions attributable to industry. The market for new steam boilers was worth USD 12 billion in 2016 and is still growing at a CAGR of 5.3%.

Most manufacturing industries make use of steam. 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 (UNFCCC, 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 of 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. This report analyses the technology options for a drop-in replacement for low to medium temperature steam. Some of these options may also be applicable to raising high temperature steam, but that is a much more complicated problem that requires a different type of analysis. Since low to medium temperature steam covers already and estimated 75% of steam use (and thus CO₂ emissions) in the manufacturing industry, replacing that type of steam is very effective and should be a priority.

Policy and industry investments must align for a successful transition

Low and medium temperature steam represent 75% of 38% of industrial energy use. Industrial energy use represents about 40% of all energy use. A transition of low and medium temperature steam in industry to carbon-free alternatives will thus affect more than 11% of all energy use. If, for example, all boilers would be replaced by direct electric boilers (converting electricity in steam with close to 100% efficiency), then that alone would increase the world electricity demand with approximately one third of the current production.

In other words, we are looking at a major transition that will noticeably impact other parts of the energy system. That also means that industry cannot rely on a simple business case (such as an NPV calculation under current market conditions) to choose a suitable alternative technology. The choice of technology itself will alter the market conditions and change the business case. If the choice results in a massive increase in electricity demand, the price of electricity will likely change because of the transition and this needs to be part of the analysis.

We have had many discussion with steam users in The Netherlands (most notably the Dutch Paper Industry association, [VNP](#)) and the Dutch Ministry of Economic Affairs and Climate ([Min EZK](#)) while writing this report. This report was requested by the Ministry of Economic Affairs and Climate and was supported by the VNP. The request was a direct result from the recognition by both that long-term industry investment and government policy on the energy transition need to align to make a successful transition.

The industry needs to know how other, simultaneous, transitions affect their options. For example, the government might have a policy to promote electric vehicle usage. Such an accelerated deployment of electric vehicles will affect availability of electricity for the industry for its transition in a negative way. On the other hand, it will also affect availability of biogas positively. If the government would have a policy to promote CNG vehicles using bio-CNG, then the picture would again be different.

The government needs to have a full picture of the energy transition. With all actors in motion, it is not sufficient to consider policy measures in isolation, assuming the rest of the system will remain the same. The energy transition is so profound and all-encompassing that policies need to be evaluated as a package.

Governments and industry need the same predictions of novel technology options

Governments use detailed models of the national energy system. These models allow the evaluation of proposed policy. A typical analysis consists of a constraint cost optimization of the energy supply with the policy measures as constraints. A simplified example might be a calculation of the most cost-effective energy mix for The Netherlands with a decreasing CO₂ emission as constraint. The Dutch model is called Opera and is maintained by the Energy Research Center of The Netherlands (now part of [TNO](#)). The US has the National Energy Modeling System (NEMS), maintained by the Energy Information Agency ([EIA](#)). Germany uses multiple models; one of the key models is the Panta Rhei macro-economic model by [GWS](#). These models require input about costs and efficiency of energy technology. This input is available for commercially available technology, but not for novel technology. As a result, these models struggle to account for potentially disruptive technology developments. Policy based on these models is therefore not robust against

technology disruption, and, more importantly, such policy also fails to leverage the potential new technology can offer.

Those technology options are not mature yet. Currently, industry does not have a drop-in replacement for steam boilers it can deploy. Therefore, companies must invest in developing these options. This is a long-term investment with associated technology risk, market risk and policy risk. To decide on these investments, industry needs models that can predict the future performance of various technologies and needs to assess which technology will be the best option, once fully developed, *within the proposed regulatory framework*.

Both purposes require data on the future performance of technology that is currently still immature.

We connect Lux's data to macro- and micro-economic models

This report investigates two things:

- **A methodology to connect Lux Research's data to economic models**
Lux Research has a vast amount of data on specific new technology developments. This data is not directly suitable to be used in the economic models described above: the macro-economic models used for policy development and the micro-economic models used for industry's innovation strategy. To make it suitable, the data must be aggregated, collapsing multiple developments into one forecast of the performance of the technology. The data must also be extrapolated from the current state of the technology to an assessment of the potential performance of the technology once fully developed. In this project we collaborated with the Energy Research Center of The Netherlands to make that translation. The result is a first crude version of a methodology to do this.
- **An overview of carbon-free drop-in replacements for low to medium temperature steam boilers**
To develop the methodology we needed a challenging, yet well-defined case. We also needed an industry to be involved to provide feed-back on the utility of the extrapolated and aggregated data for industry. This led to a cooperation with the Dutch Paper Industry Association (VNP) and the choice of industrial low to medium temperature steam boilers as the focus for this project.

The next chapter discusses the methodology we developed. The final chapter of this report discusses the results of the analysis.

Out of eighteen identified technology options, we analyzed five in detail: hydrogen combustion, hydrogen from electrolysis followed by combustion, gasification of biomass residues, heat pumps and direct electric heating.

The analysis shows that these options are close together, so the regulatory environment will eventually have a relevant and significant impact on what will be the "best" technology. The study by ECN used the input on technologies to calculate scenarios based on current energy policy in The Netherlands. That analysis shows that heat pumps are the winning technology under the current regulatory regime. Alternative policy measures such as investing in a country-wide hydrogen pipeline infrastructure could change that picture however.

Predicting future performance of new technology

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

We analyze global innovation to estimate future performance

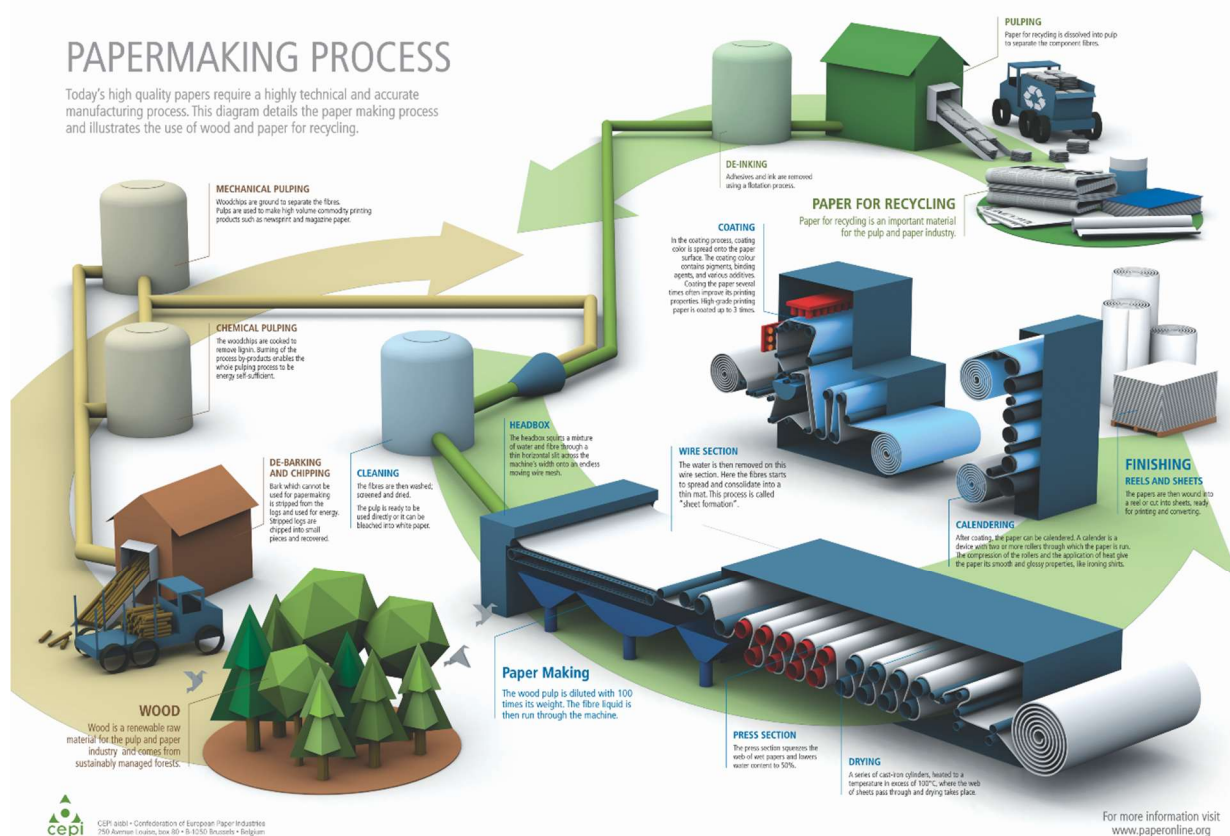
The methodology we developed consists of the following steps.

- **Identify all possible technology options that could replace a steam boiler**
We 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 we 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 we made a list of companies and research groups that are working to develop this technology out of our database. We also made a patent analysis to identify key actors and key trends in the development of this technology. Finally we 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 be 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. We selected one (or two) representative developer. We 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**
We 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, we made a mass and energy balance of each of the technologies.

Identifying technology options based on a defined function

To find suitable technology options, we 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 (shown in Figure 1). 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.

Fig. 1: This infographic from the European paper industry association (CEPI) provides a comprehensive, simplified, description of the papermaking process. Steam plays a role in pulping, drying and coating.



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.

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.

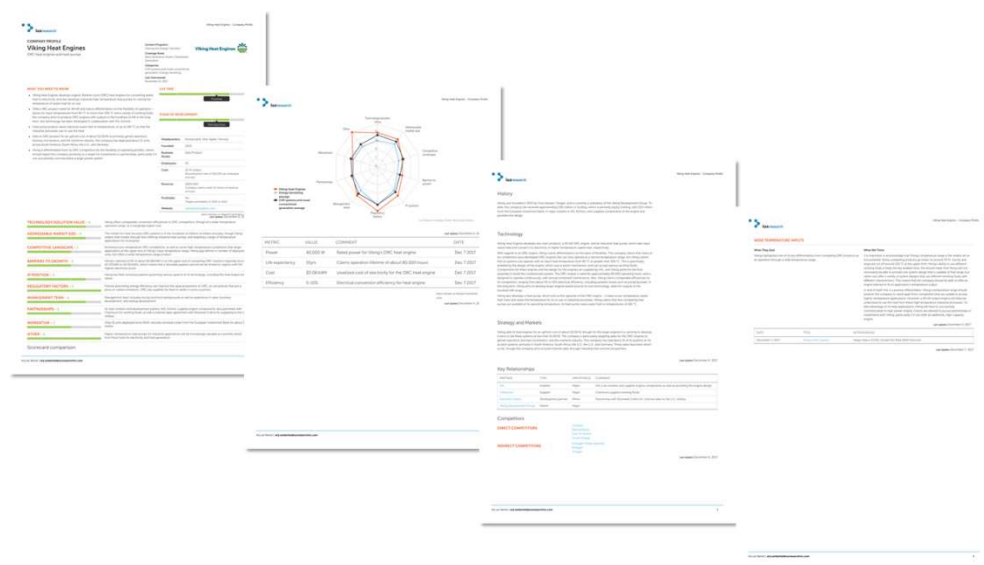
Lux’s proprietary data and tools help to understand all aspects of the technology options

Once the technology options have been selected, we 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 (profiles, see Figure 2) 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

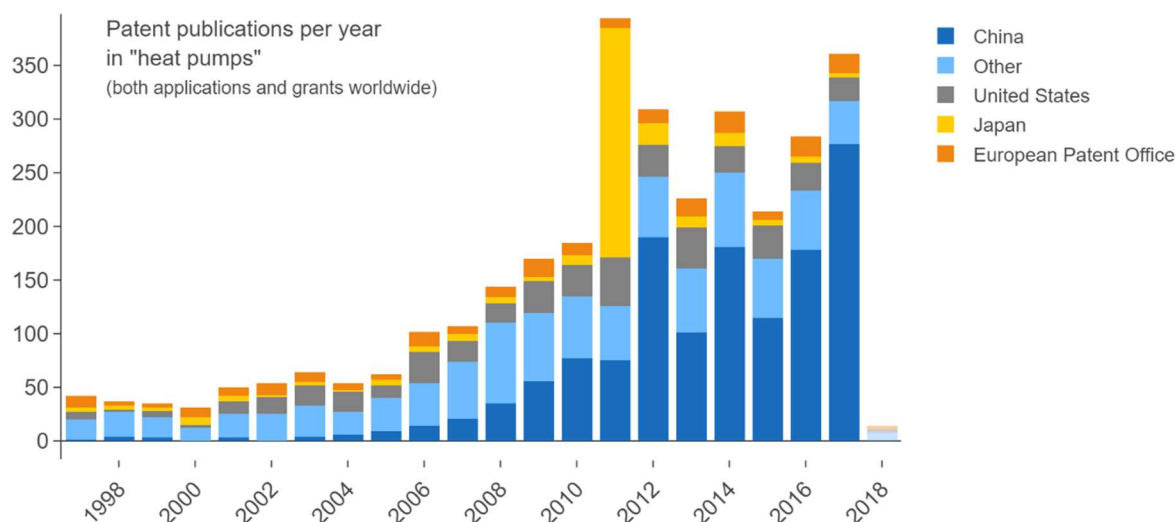
Fig. 2: A profile is a structured document containing all relevant technological and commercial information about a development



- **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.

Fig. 3: Our 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).



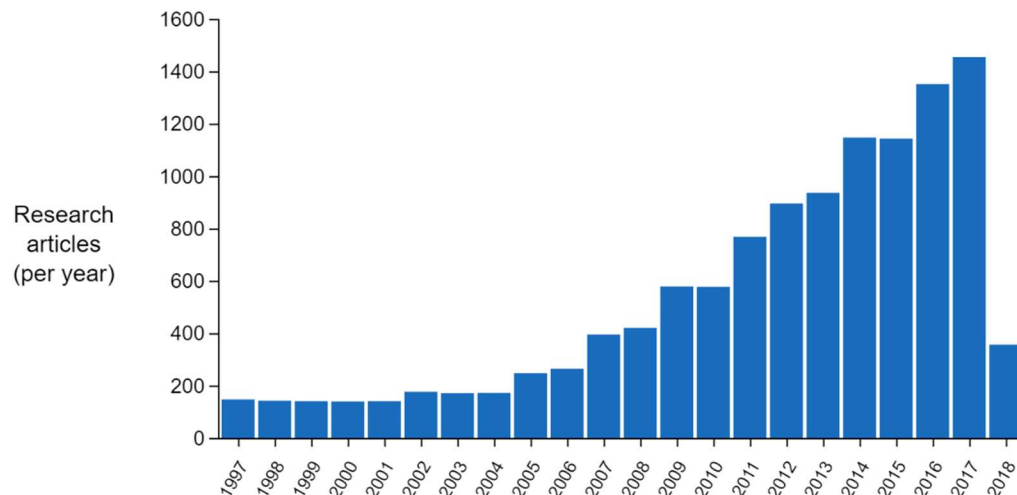
- **VC investment analysis**

We 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, we analyze published peer-reviewed scientific papers to identify and assess trends in activity around a topic.

Fig. 4: 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.

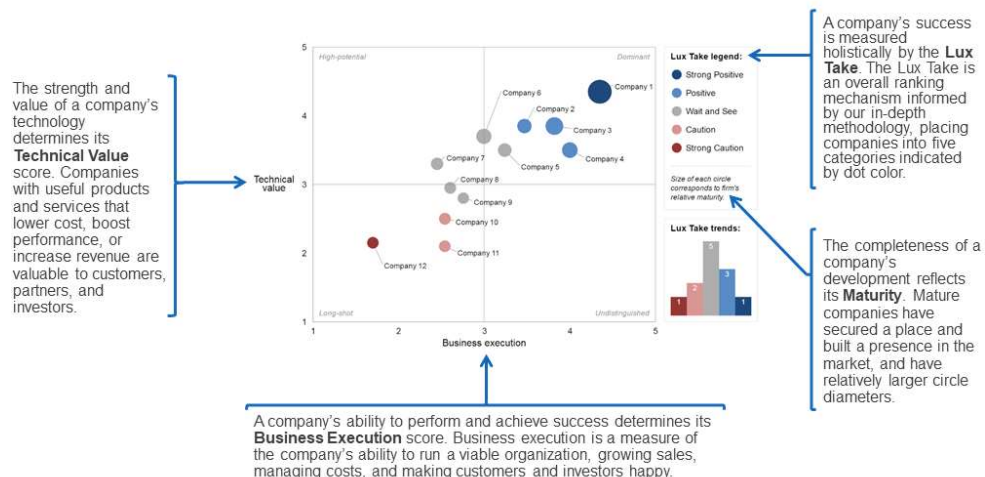


Lux's innovation grid helps to identify the most promising developments

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 (see Figure 5). 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. We use this method to identify which development we should use to predict future performance.

Fig. 5: The Lux innovation grid ranks developments along axes of technology value and ability to execute

Methodology: The LIG framework analyzes companies on technical value, business execution, maturity



We 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. We 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 we 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. We 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 we 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, we use an estimate that we know to be conservative. **This means that the study is biased in favor of more mature technologies, as they need less extrapolation to larger scales and will therefore be affected less by the conservatism of these estimates.**

All extrapolations of the technology were 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 discussed on page 6. 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). We 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, we will use equipment factored estimation to account for installation costs. In this study we 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.

Electrolysis and gasification are promising options

Out of eighteen identified technology options, we analyzed five in detail. The analysis shows that all of them are viable options to develop. Based on the merits of the technology, electrolysis and gasification are promising options; heat pumps are potentially the most attractive option but will require a high degree of process integration. However, a full analysis including the effects of policy must be made to make the final selection. This chapter provides the input needed for the policy analysis.

We identified eighteen potential technologies

We posed the question to our analysts: “What technology do you see to generate saturated steam of up to 200°C without emitting (fossil) CO₂?” They replied with 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 we list them here for completeness. The full list of the first twelve is shown in Figure 6. The other six, out of scope ideas, are shown in Figure 7.

Fig. 6: 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 we 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 CO ₂ emissions. It	Scaling. The technology to combust hydrogen is available and used in many applications already

	just shifts the problem to the hydrogen supplier. If there is a possible in place to create sustainable hydrogen, this is a viable alternative	
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 to 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.

Fig. 7: 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.

With government and industry we focused on five promising options

The technologies we identified were discussed with government and industry in order to select the technologies to be analyzed in more detail in this study. Figure 8 lists the considerations and the conclusion of the analysis for each of the twelve technologies

Fig. 8: 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. We 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 we exclude this from the study.	Do not include

The subsequent sections discuss the analysis for each technology.

Heat pumps

System description

A heat pump needs a reliable, constant supply of low level heat to work with. Since we excluded waste heat, 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 we will use this system 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 we decided to exclude waste heat, 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. We will however add it in this report 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. Since we did not study the paper manufacturing process here, we don't know if this is a realistic expectation to have. In this analysis we will assume that it is possible.

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). We could not verify that number and think it is surprisingly low compared to other developers. A more reasonable expectation would be 450 €/kW in our opinion. We'll include this system and the cascaded approach in this study. Since we have not been able to verify the numbers independently, we will use ECN's input here.

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 9 shows the relevant academic and small company developers.

The main relevant large company developers are (in that order, see also Figure 10):

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, we 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.

Fig. 9: Lux innovation grid of technology developers of heat pump systems

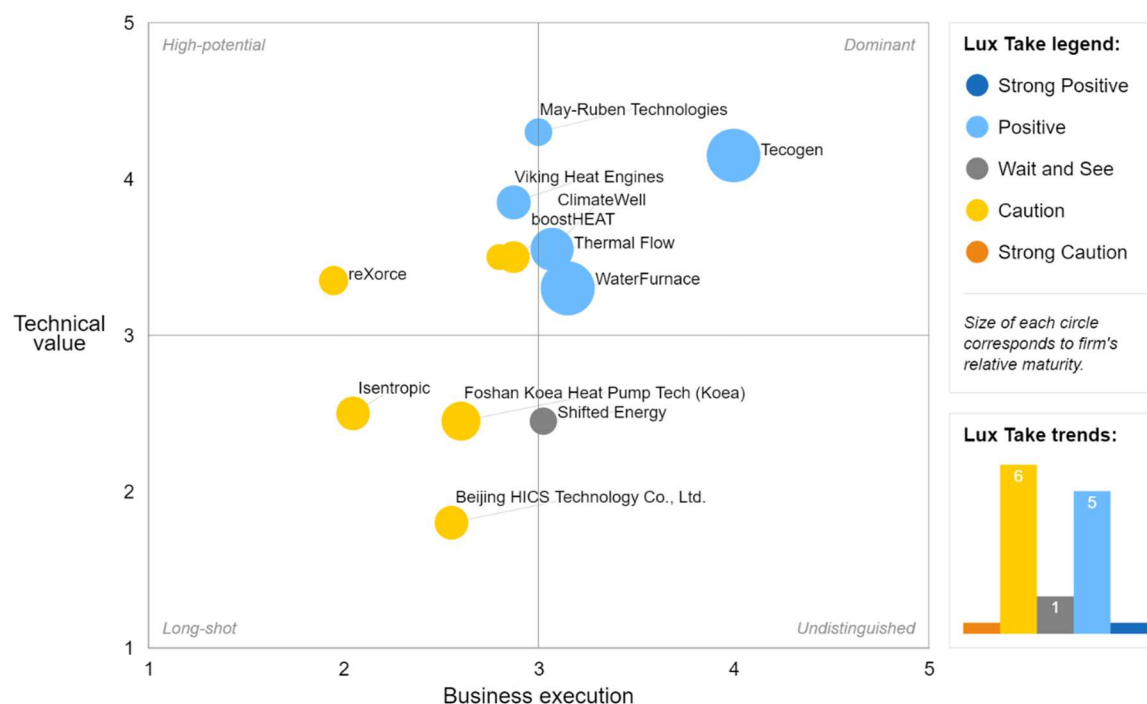
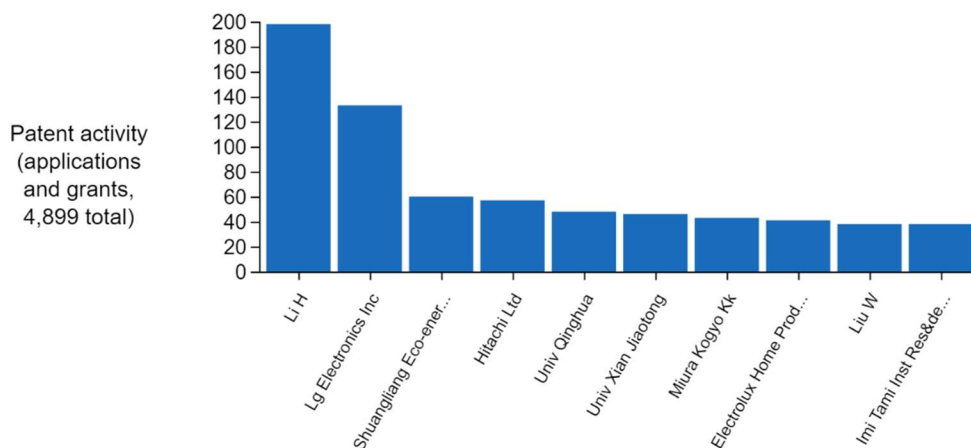


Fig. 10: The top ten owners of relevant patents are all from Asia, with the exception of Electrolux



Technology key metrics

Since there are no relevant systems being developed that meet the requirements we specified in the system description, we engineered a conceptual design of a system that would. We did so by combining two standard “residential” heat pumps and one high temperature heat pump. For the residential heat pumps we 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, we 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 we had to scale residential heat pumps to higher capacity. Heat pumps follow the scaling rules of process technology. So we assumed 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 we 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 we did not apply the experience curve to them. We did apply a mild experience curve to the Viking heat engines system, resulting in a 30% price decrease.

We estimate 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 Figure 11

For the waste heat recovery system, we used the data published by ECN, resulting in the data shown in Figure 12. We used a factor 2.5 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 we 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

Fig. 11: 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

Fig. 12: 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. We assume here 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 we look 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 we 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 12 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

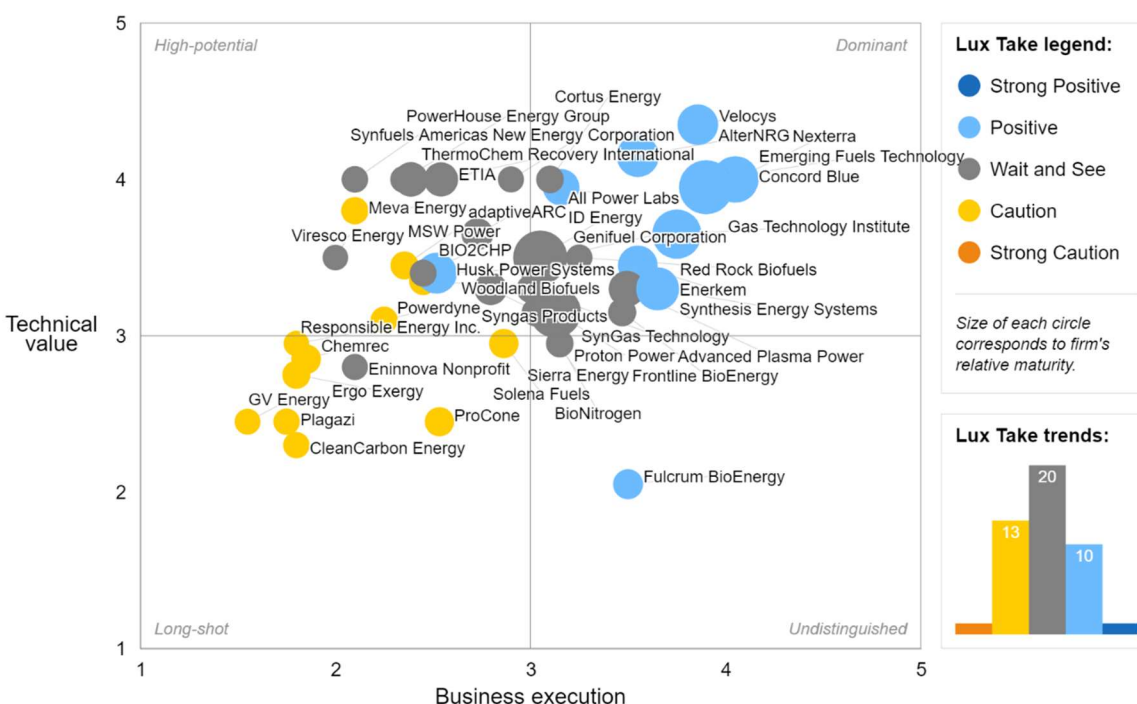
operation), the technology looks promising and this is one of the few fixed bed gasifiers that works reliably at 5 MW scale. Zeropoint thinks they can scale to even 10 MW (thermal input).

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.

Fig. 13: 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.

The key metrics resulting from our calculations are shown in Figure 13

Fig. 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 we consider. 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 we use the lower heating value of hydrogen 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 Figure 14

Fig. 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

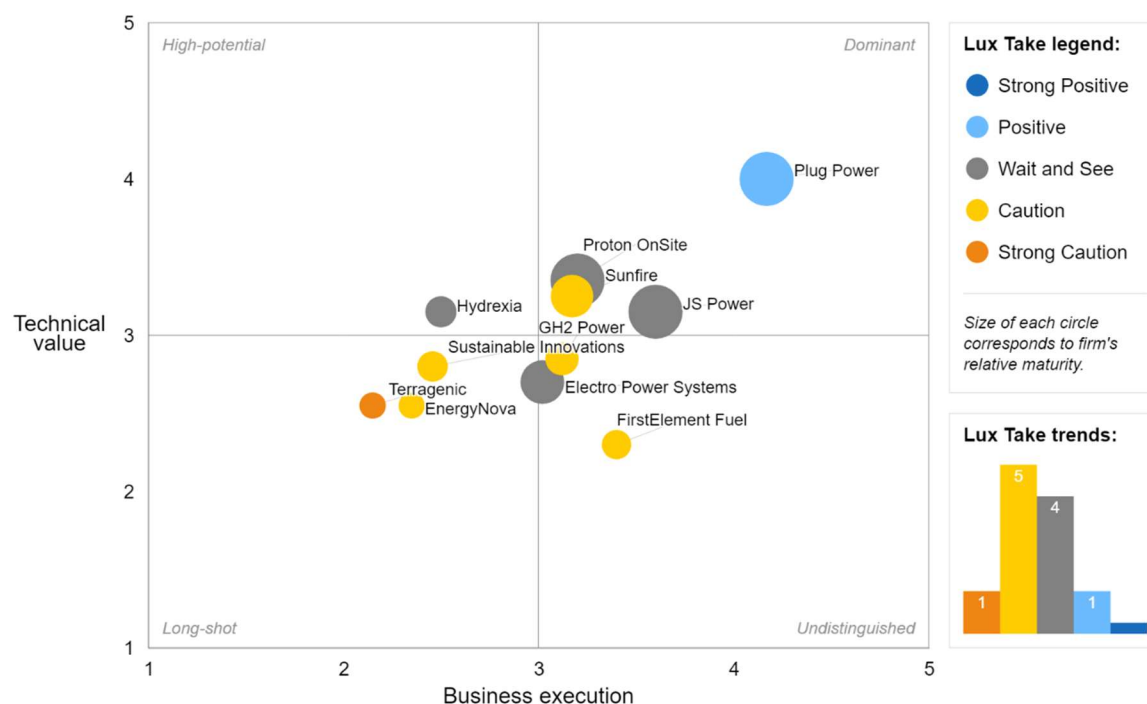
This system is similar to hydrogen combustion, but now the hydrogen is not bought. It is generated on-site using electricity from the grid. This could also be electricity generated on-site using wind turbines or solar panels of course. In this analysis we take grid electricity. This is a worst case. 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 15.

Fig. 16: 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

We used the data of the Proton onsite system as they have a well-developed system for which sufficient data is available. We 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, we 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 extends 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. We estimate it will take at least ten years to guarantee sufficient electricity supply to enable the large scale application of this technology.

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

Fig. 17: 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 it 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 Figure 17

Fig. 18: 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

Conclusion

Looking at the merits of the various technologies we analyzed here, there is no clear winner. The various options are close to each other in terms of implementation costs and state of development. The differences will be dictated by operational differences. We can distinguish between three main policy scenarios here:

1. Policy results in a conversion of the current natural gas infrastructure to hydrogen. This will likely mean that hydrogen combustion will be the solution of choice. Heat pumps struggle to find their way into the industry now and will continue to do so in that situation. The key issues holding heat pumps back are the development that is still requirement combined with the need to invest in much heavier electricity connections.
2. Policy results in a renewed appreciation for CHP, needed as back-up and base-load capacity in the grid. In this case, biomass fired CHP will be the clear winner because there will be sufficient premium to sell electricity.
3. If there is no alternative but to go all-electric, then the direct electric and electrolysis options can be short term attractive options, but in the longer term they will lose from heat pumps, once these systems are sufficiently mature.

A system analysis must now show where the tipping points for the various scenarios are.

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Appendix: the sensitivity of the scaling rules

We 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, we use one system. The other systems will be giving the same sensitivity results as this is a purely mathematical exercise. As an example, we 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 we 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 we 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 we 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).