EMPOWERING THE CHEMICAL INDUSTRY

OPPORTUNITIES FOR ELECTRIFICATION

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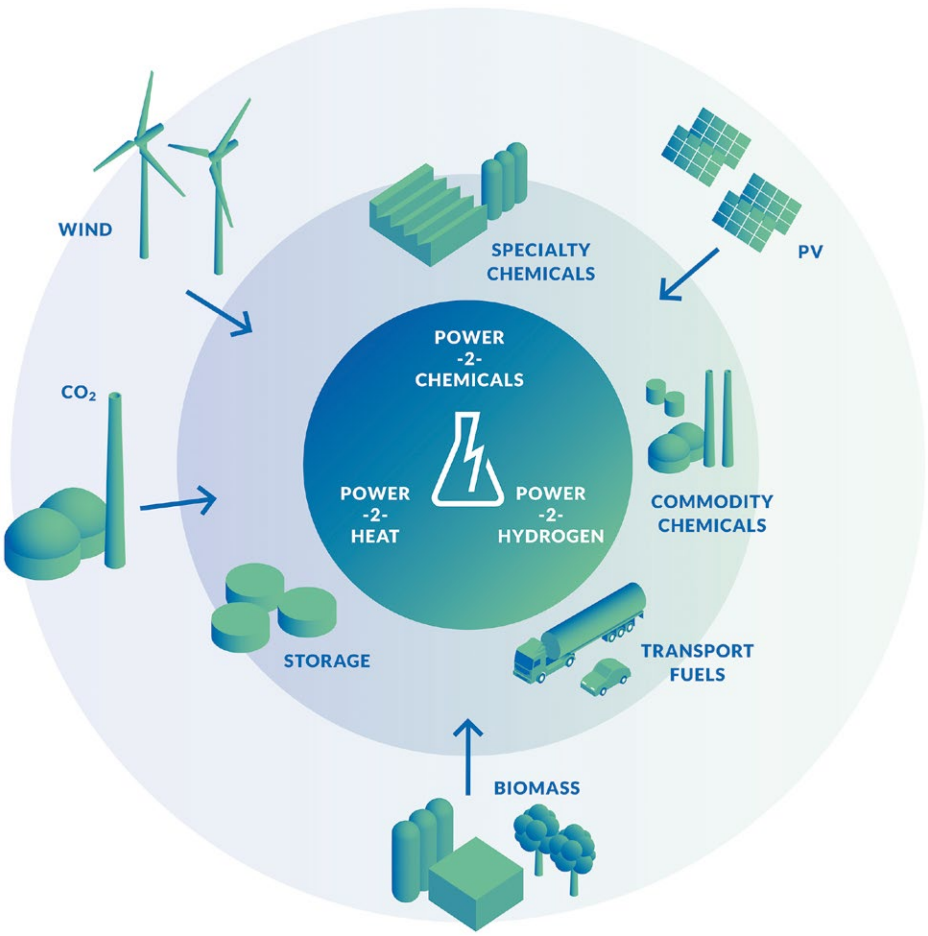
MANAGEMENT SUMMARY

The EU chemical industry faces multiple challenges with respect to its competitive position. Though EU chemical sales almost doubled during the last two decades, its global market share has been almost cut in half. Meanwhile, the industry is expected to become more sustainable and reduce its CO_2 emissions. A drastic improvement in energy and feedstock efficiency and far-reaching decarbonisation are required to sustain the chemical industries' license to operate in a future fossil-lean and carbon constrained world. Electrification offers promising opportunities to significantly reduce the CO_2 footprint of the chemical industry and improve its competitiveness.

During an industry consultation, representatives of the EU chemical industry and the energy sector underlined the potential of electrification. Also the energy sector will benefit: electrification of the chemical industry could offer a source of flexibility. Electrification can help integrate large shares of intermittent renewables and optimise investments in the electricity grid.

This whitepaper distinguishes between the following types of electrification:

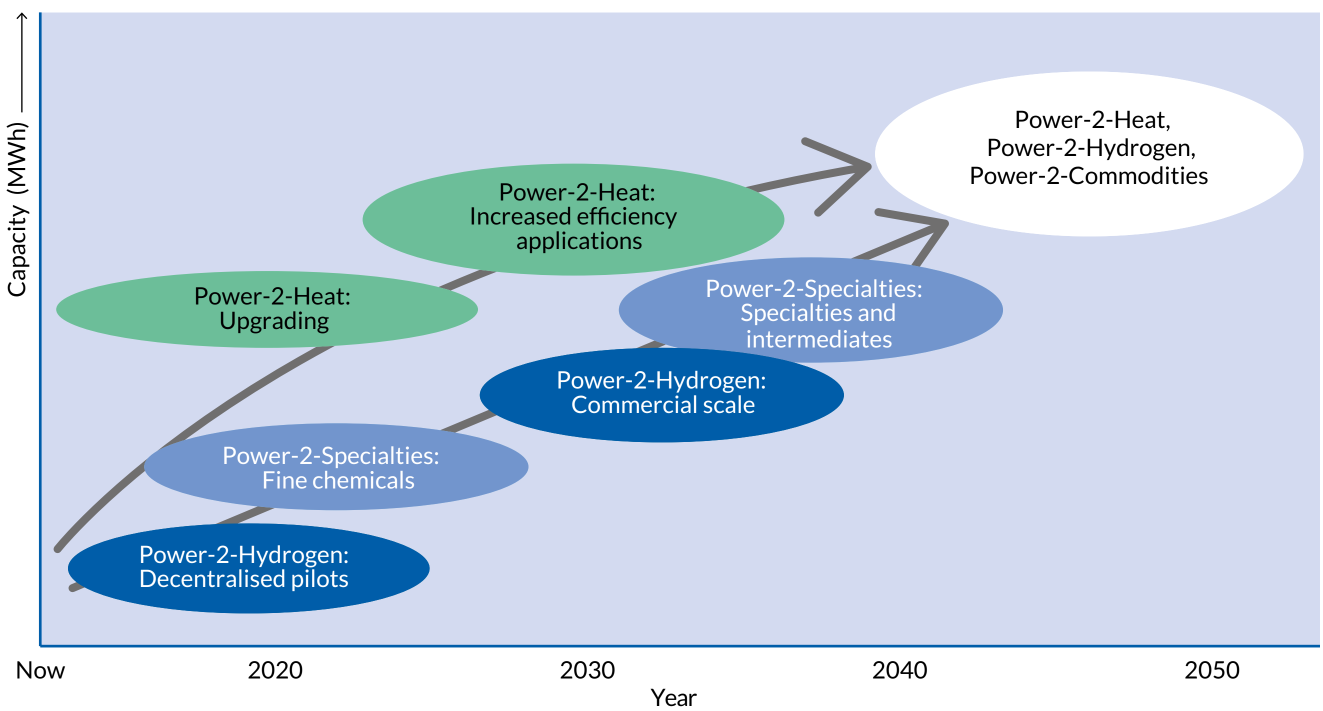
- **Power-2-Heat**: the efficient generation and upgrading of heat and steam with electricity for use in chemical processes;
- **Power-2-Hydrogen**: the use of electricity to produce hydrogen through the electrolysis of water, which is subsequently used for a number of applications;
- **Power-2-Specialties**: the direct electrochemical synthesis of high value fine and specialty chemical intermediates and products using conventional and biomass-derived feedstocks;
- **Power-2-Commodities**: the direct electrochemical synthesis (both centralised and decentralised) of large volume commodity chemicals using conventional and sustainable feedstocks, such as CO_2.



To retain a solid competitive position of the EU chemical industry and to fully utilise the potential of electrification, innovation and implementation should be accelerated. To achieve this, a number of barriers should be overcome. Industry representatives named as a main barrier the fact that many applications of electrification currently seem economically unfeasible. To solve this, low cost technologies should become available at industrial scales. Since downtime should be prevented, the availability of proven technology is also vital. Moreover, using fossil fuels is currently very inexpensive, which prevents companies from choosing more costly sustainable alternatives.

To overcome these and other barriers, stakeholders will have to cooperate and balance their interests in order to get the flywheel up to speed. An ecosystem should evolve in which stakeholders work together on topics like technology development, innovative business models and assessment of economic feasibility. All stakeholders will benefit when innovation in the field of electrification accelerates, because electrification fits with their individual interests.

A roadmap has been developed in which the various technologies are expected to be realised at different timescales, based on maturity levels and wide-ranging business cases. The first applications will be those with more positive economics, such as waste heat upgrading and electrochemical production of fine chemicals. With more technical developments, higher volume products and more advanced applications of Power-2-Heat, such as technologies which not only utilise waste heat but reduce the heat demand altogether, will become feasible. At the same time, Power-2-Hydrogen will expand from the pilot scales that are being developed today to commercially relevant scales. Though it will take time, maybe even decades, the long-term perspective of a highly electrified chemical industry where renewable feedstocks and energy are the basic ingredients of chemicals, including specialties, commodities, and fuels, is very appealing to many stakeholders.



Development roadmap for the different types of electrification.

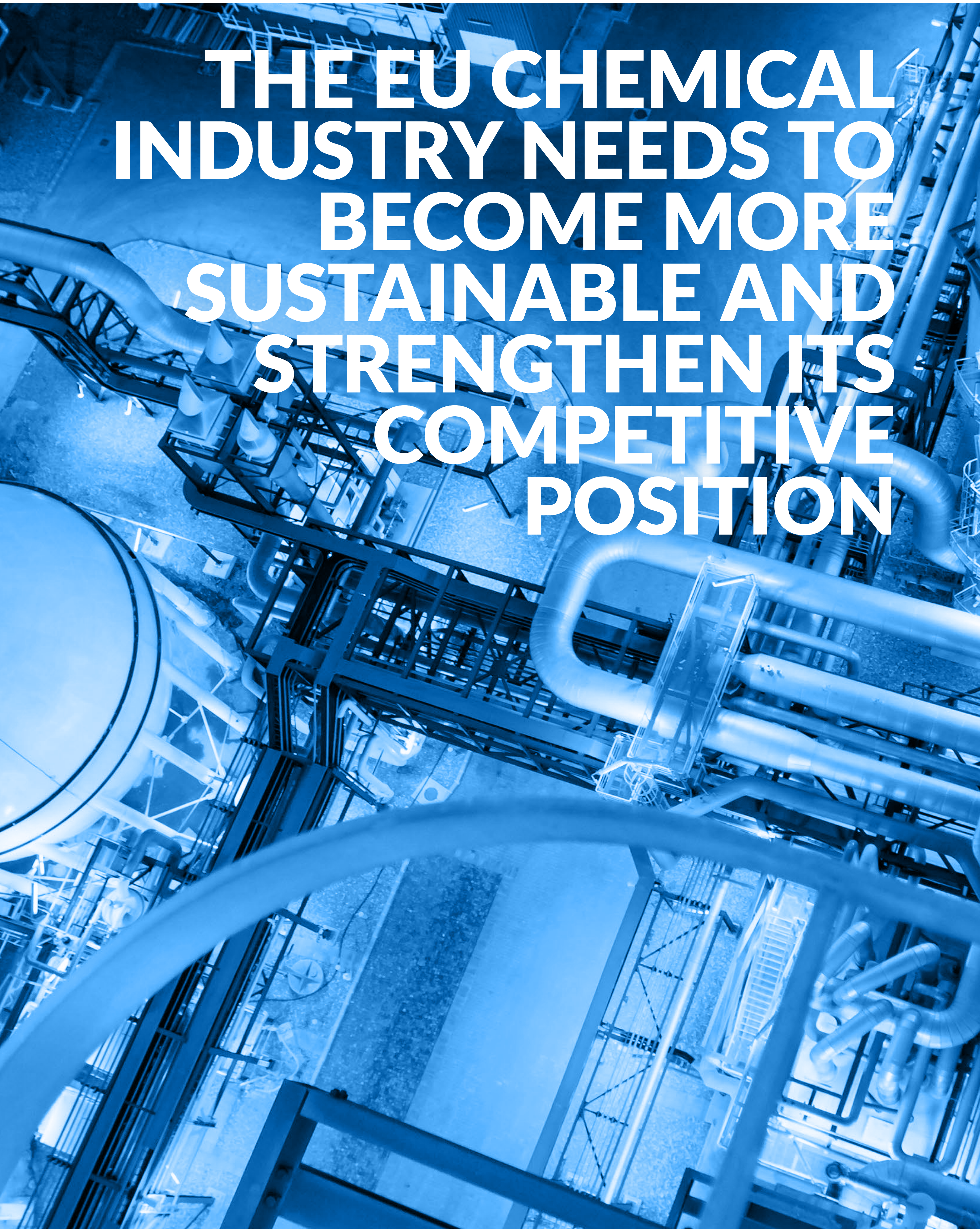
TABLE OF CONTENTS

This whitepaper discusses:
— Why electrification is relevant for the chemical industry and the electricity sector.
— Which different types of electrification are possible and what the drivers are for the chemical industry.
— What the potential value of electrification is and how economic feasibility could be realised.
— What technical developments enable the implementation of electrification in the chemical industry.
— How innovation can be accelerated by the stakeholders.

INDUSTRY CONSULTATION

In an industry consultation, 18 representatives of the EU chemical industry and the energy sector (see page 31) were interviewed. They were asked to present their vision on electrification, the opportunities they see for their company, the business drivers behind these opportunities and the barriers to overcome in order to pave the way for large scale implementation of electrification technologies. This consultation provided valuable insights for this whitepaper.

THE EU CHEMICAL INDUSTRY NEEDS TO BECOME MORE SUSTAINABLE AND STRENGTHEN ITS COMPETITIVE POSITION



The European chemical industry faces a number of challenges. The two most prominent issues for EU chemical companies at the moment are (1) how to strengthen their competitive position in a global market and (2) how to become more sustainable – in an economically feasible manner.

THE COMPETITIVE POSITION OF THE CHEMICAL INDUSTRY IS UNDER PRESSURE

EU chemical sales amounted to €551 billion in 2014[1]. Though EU chemical sales nearly doubled over the last two decades, the global market share of the EU chemical industry almost halved in that same period. The Trade Competitiveness Index (TCI) is declining, meaning that imports are growing faster than exports. The EU's position in petrochemicals and commodities, especially, is weakening. This illustrates that the EU's competitiveness in the global chemical industry is under pressure. Higher value products like specialties and fine chemicals are still realising a growing contribution to the TCI of the EU chemical industry[2], but it is unlikely that this will easily compensate for the decline in commodities.

To strengthen the competitive position, cost reductions are continuously on the top of the agenda of chemical companies. The EU chemical industry has a major disadvantage on its cost position – not only because of the relatively high price of labour, but also because of the presence of low cost oil and gas reserves in the Middle East and US that favour the chemical industry in those regions. Becoming less dependent on fossil fuels, both as an energy source and as a feedstock, is therefore desirable. But cost reductions alone will not be enough. Bringing innovative and high value products to the market at a quick pace is becoming ever more crucial. This will increase margins and put Europe in a position where it can take profit from the growing market demand elsewhere, e.g. in Asia. Therefore, it is essential for the EU chemical industry to build upon its main strength: its leading position on knowledge and innovation[3]. Meanwhile, cost effective production of commodities will remain vital for the EU chemical industry.

SUSTAINABILITY IS BECOMING A MUST

At the same time, societal awareness to become more sustainable is growing. Consumers are asking for more sustainable products, and regulations are being devised to ensure the implementation of measures fostering more sustainable production. This puts further pressure on the industry. In 2011, EU leaders endorsed the long-term objective of reducing Europe's greenhouse gas emissions by 80-95% by 2050, as compared to 1990 levels, to mitigate climate change to acceptable levels. This has since been followed up at COP21 in December 2015, with the collective aim to limit global warming to well below 2 °C[4], and supporting initiatives, such as Action 2020 from the World Business Council for Sustainable Development[5]. As a result, there is a need to rapidly decarbonise the EU's energy and feedstock supply. With this prospect, sustainability has become part of the mission statement and strategy of many chemical companies. CO_2 reduction, more efficient use of energy and feedstocks and reducing waste are key to turning the need for sustainability into practice.

EU INITIATIVES TO CREATE A MORE SUSTAINABLE CHEMICAL INDUSTRY

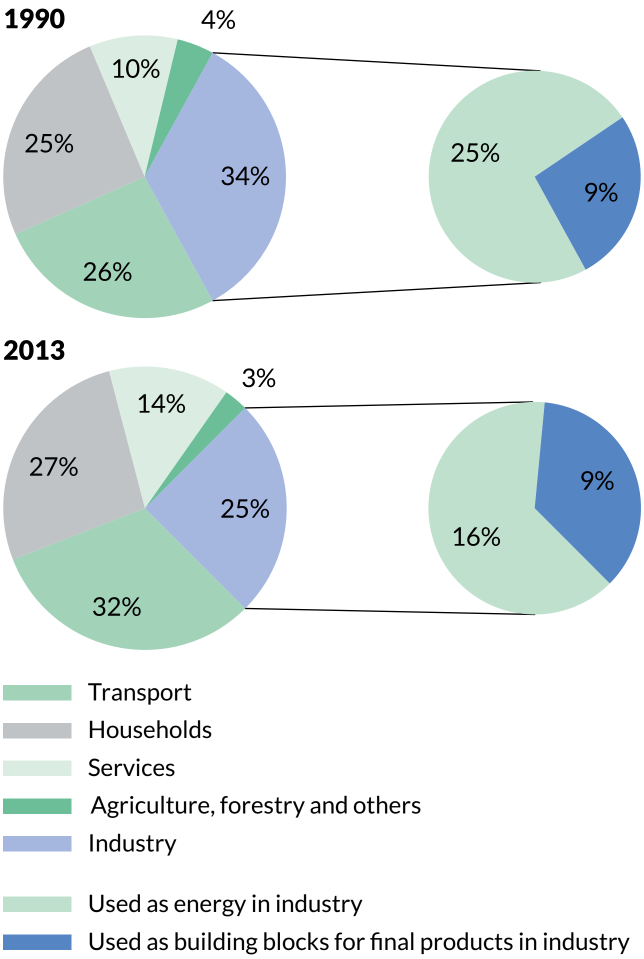
The societal need for increased sustainability has intensified discussions between policy makers and industry, particularly in Europe. The ongoing debate centres on how to reconcile sustainability and competitiveness. Discussions have led to the following initiatives for the chemical industry:

- The CEFIC Sustainability Vision in 2012.
- The Technology roadmap 'Energy and GHG Reductions in the Chemical Industry via Catalytic Processes'.
- The SPiCE3 platform (Sectoral Platform in Chemicals for Energy Efficiency Excellence).
- The European Public-Private Partnership (PPP) SPIRE, dedicated to innovation in resource and energy efficiency enabled by the process industries.

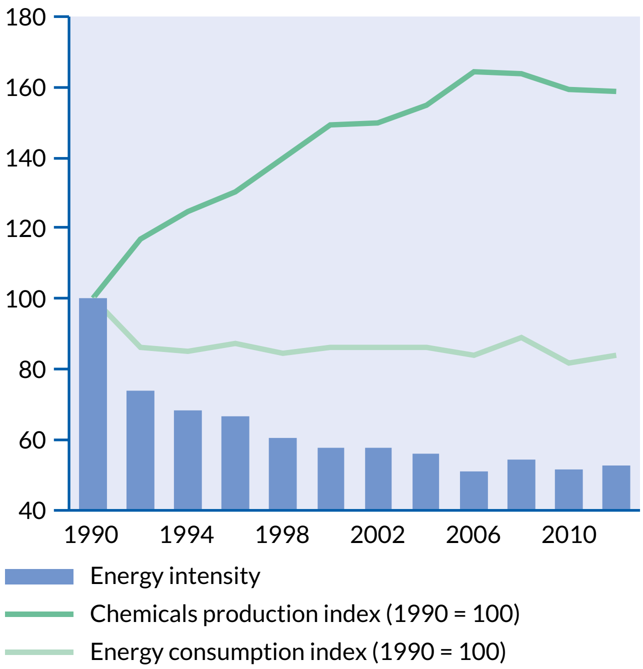
Sustainability has become part of the mission statement and strategy of many chemical companies

RECENT PROGRESS IN INCREASING SUSTAINABILITY

Between 1990 and 2013, the amount of energy consumed by all end-use sectors in the EU increased by 2.2 % annually. This has offset the positive environmental impacts of improvements in the energy production mix and of other technological developments that were achieved in the same period. The share of final energy consumption of the industry in the total final energy consumption in Europe has gradually decreased from 34% in 1990 to about 25% in recent years. The reduced share of industrial energy use is an illustration of the gradual transition towards service-based economies and a shift towards less energy-intensive manufacturing modes; it also reflects the negative impact of the financial and economic crisis in Europe (Eurostat).



Industry share in total European energy consumption has declined from 34% in 1990 to 25% in 2013.



The energy intensity of the EU chemical industry has been reduced by half since 1990 while the total chemicals production has increased by 59%.

While the before mentioned numbers concern the EU industry as a whole, the part accounted for by the EU chemical industry shows an even more significant reduction in energy usage. While the total production of chemicals has increased by 59% since 1990, the chemical industry in Europe now uses just half of the energy to produce a unit of chemicals, as compared to 22 years ago. To a large extent, this reduction can be attributed to the use of combined heat and power units, the shift to higher value-added and lower energy intensive products, and continuous process improvements. The largest change has been in the use of natural gas, that was reduced by 30% between 1990 and 2012[6]. In the same timeframe, electricity demand has also been reduced by 12%, while oil use has increased by 5%.

Though much has been achieved so far, substantial efforts are still needed to reach the short and long term EU GHG objectives (e.g. 20% reduction by 2020). Deployment of best practice technologies, carbon capture and storage (CCS) and application of low carbon technologies in the short to mid-term, combined with an increasing implementation of wind and photovoltaic electricity systems, has the potential to dramatically add to the reduction in GHG emissions. By replacing fossil fuels with electricity as an energy source in chemicals production, the industry can take advantage of these developments to help realise its sustainability targets.

THE NEED FOR FLEXIBILITY IN THE ELECTRICITY SYSTEM

Sustainability targets also impact the energy sector. Electricity supply is transforming at a steady pace to create a system without any fossil CO_2 emissions somewhere around 2050. The landscape of power generation will change drastically. Deployment of renewables will become the new standard at the same time that fossil energy sources are phased out.

The landscape of power generation will change drastically

The shift from fossil to renewable sources will be accompanied by a shift from centralised generation of electricity in high capacity power plants to decentralised generation with more low capacity locations. Also, individuals and companies are increasingly becoming producers of electricity and heat, in addition to being end-users of energy. The supply of energy increasingly appears at the demand-side of the system, which is leading to changes in supply and demand profiles.

Wind and solar energy are mainly harvested as electricity, by means of wind turbines and photovoltaic (PV) solar cells. The supply of these renewables fluctuates continuously and is non-controllable. With increasing shares of renewables in the total electricity production, the magnitude of fluctuations is increasing. In addition, growing shares will ultimately also lead to situations in which the supply of electricity exceeds the demand (at various geographical levels).

Both effects result in a growing need for flexibility in the electricity system. This is the ability of market parties (like producers, traders, system operators and end-users) to respond to changes in the demand and supply of electricity as fast as necessary in order to keep the electricity system in balance at all times. At low penetrations of renewables, the flexibility of conventional power plants can be utilised to compensate for the fluctuations. As the need for flexibility increases, other options will also be required. These include demand side response measures, storage, further expansion and upgrading of electricity grids and curtailment of renewables generation.

ELECTRIFICATION AS A PROMISING SOLUTION

The key challenge in achieving a carbon-neutral energy and production system is to decarbonise the sectors that are currently heavily dependent on fossil fuel resources, such as oil and natural gas. The most promising option for future decarbonisation of final energy and feedstock use in the chemical industry is to convert the relatively abundant potential of wind and solar energy – produced in the form of electricity – into heat, chemicals and fuels. Electrification has the potential to realise major progress on sustainability and reduction in fossil energy and feedstock use. At the same time, it offers possibilities to strengthen the competitive position of the EU chemical industry. Having knowledge, expertise and capital resources to convert raw materials into products and fuels, the chemical sector is well positioned in the transition to renewable electricity as an energy resource. The energy sector will benefit as well, since electrification of the chemical industry offers a source of flexibility that is needed for the energy transition. The electricity grid in North Western Europe is of very high quality, and offers an opportunity to both the chemical industry and the energy sector to become a front-runner in electrification.

The chemical sector is well positioned in the transition to renewable electricity

The changing landscape of power generation.

ELECTRIFICATION OFFERS OPPORTUNITIES FOR COST REDUCTION, SUSTAINABILITY AND PRODUCT INNOVATION

Electricity is increasingly being used by the chemical industry to replace thermal and chemical energy. Traditionally, electrification is associated with replacing the steam and gas driven compressors, pumps and valves – of which many are still in use nowadays. However, electrification can be applied in several other ways. Electrical energy can be used to produce and upgrade steam and to heat processes directly. Another application is the direct use of electricity for the production of hydrogen or for various other chemical transformations. All of these routes have the potential to contribute substantially to the decarbonisation of the chemical industry and to positively impact business cases and sustainability.

In this whitepaper, we focus on the following four types of electrification:

1. **Power-2-Heat**: the use of electricity to either directly produce heat or upgrade sources of waste heat to useable temperature levels.
2. **Power-2-Hydrogen**: the use of electricity to produce hydrogen through the electrolysis of water, which is subsequently used for any of a number of applications.
3. **Power-2-Specialties**: the direct electrochemical synthesis of high value fine and specialty chemical intermediates and products using conventional and biomass-derived feedstocks.
4. **Power-2-Commodities**: the direct electrochemical synthesis (both centralised and decentralised) of large volume commodity chemicals using conventional and sustainable feedstocks, such as CO_2.

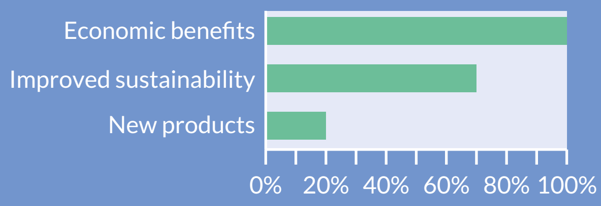
The basic concepts for these different types of electrification are shown schematically in the figure on page 12.

WHAT ARE THE MAIN DRIVERS FOR ELECTRIFICATION?

An industry consultation was carried out to obtain insights into the drivers and barriers for electrification and into the impact electrification may have on the industry.

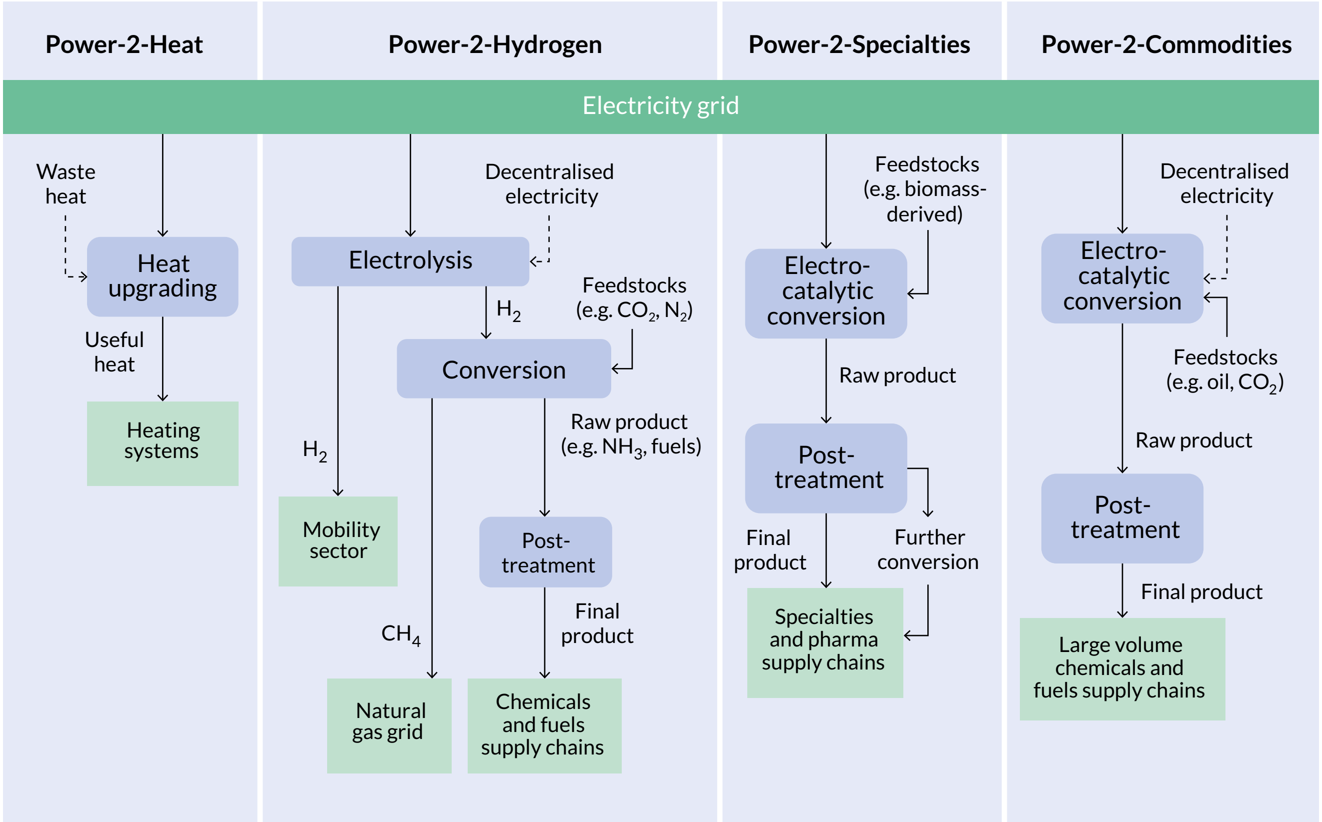
During the industry consultation, *chemical companies* were asked for their drivers for electrification. The main drivers that were named are the following:

- **Economic benefits**, because of cost reductions by using cheap energy and by making processes more efficient and selective, thus leading to higher margins. This driver was named by each interviewee.
- **Improved sustainability** through the reduction of feedstocks, by-products, waste, energy use, solvents and CO_2 (named by 70% of interviewees).
- Development of **new products** by applying innovative electrochemical technologies (named by 20% of interviewees, especially those who are interested in Power-2-Specialties).



Other interviewees (mainly from the *energy sector*) also named the following drivers for electrification:

- Easier realisation of **flexibility** with electricity (e.g. local production near electricity sources);
- Optimisation of **investments in the electricity grid** e.g. by matching local supply and demand;
- Increased **stability** in the electricity grid;
- **Reduced dependence** on (foreign) natural gas;
- Anticipation of stricter **regulations** regarding CO_2 emissions.



Schematic representation of the four different types of electrification.

POWER-2-HEAT

With Power-2-Heat, electricity is used to either generate heat directly or to upgrade steam and waste heat for efficient (re-)use in chemical processes. Traditionally, heat is generated by burning natural gas, but new technologies are making replacement by heat generation with electricity more attractive. With both efficiency gains and the re-use of waste heat as process heat, the overall energy requirements of a process can be reduced.

Power-2-Heat is expected to be the first type of electrification that the chemical industry will implement on a large scale

The main drivers for realising Power-2-Heat are cost efficiency and sustainability. Low electricity prices compared to natural gas prices make electricity a cost efficient alternative to natural gas, especially when combined with options to flexibly apply Power-2-Heat at moments when electricity prices are low. Electrically driven heat pumps can produce heat in a very cost effective way by upgrading waste heat to useable temperature levels. This recycling of waste heat fits into the circular economy concept, leading to energy savings and CO_2 emissions reduction, and substitutes a fossil energy carrier by electricity. Power-2-Heat technologies have a fast response time and are able to cope with fluctuations in electricity availability and prices. Investments in technology and making the infrastructure suitable for delivering large quantities of electricity should be compensated by low electricity prices and a higher energy efficiency.

MECHANICAL VAPOUR RECOMPRESSION BY SHELL

Propylene is an important feedstock in the production of a number of chemical products, including polypropylene. It is produced by distillation separation of propylene and propane in a splitter column. Traditionally, the reboiler is heated by low pressure steam or hot condensate. Since 1995, Shell Pernis uses a propylene-propane distillation column that applies *mechanical vapour recompression* (MVR). In the MVR, an electrical compressor increases the pressure of the top vapours. As the column operates independently of a cooling fluid, the column pressure can be reduced. This results in a better split between the propylene and propane and a purity of 99.5% is reached.

The MVR process has resulted in reduced energy use, reduced use of cooling water and an increase in distillation yield. Energy savings add up to 1.2 PJ yearly, equivalent to 37.8 mln m^3 of natural gas. A very short payback time of two years was realised.

Source: Industrial heat pumps in the Netherlands, IEA Heat Pump Programme Annex 35, May 2014. Photograph by courtesy of Shell.

Electrically driven heat pumps in industry will become an important means for re-using waste heat as process heat. Significant savings potential can be reached within the coming years when current technology is further developed to achieve higher temperature levels and temperature lifts to make heat pumps more broadly applicable. Business cases are now being evaluated for heat pumps and other technologies. For example Dow Benelux completed an economic feasibility study of the use of mechanical damp recompression, where steam is upgraded by using electricity[7]. The business case appears to be attractive and Dow is now considering piloting the technology and testing the technical reliability of the concept. As more such cases become known and are proven in industry, Power-2-Heat is expected to be the first type of electrification that the chemical industry will implement on a large scale.

POWER-2-HYDROGEN

Another means of electrification is Power-2-Hydrogen, in which electricity is used to produce hydrogen through the electrolysis of water. When renewable electricity is used to power the electrolyser, the hydrogen is a carbon-free energy carrier and chemical intermediate. The main applications of this technology are:

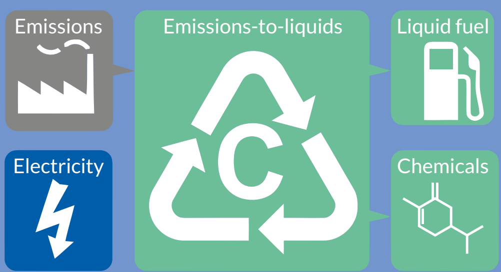
Hydrogen as a feedstock for chemical processes

Other than traditional uses of hydrogen, such as within oil refineries and the steel industry, sustainably produced hydrogen can be combined with CO_2 and N_2, both sustainable feedstocks, to produce an array of important green products, such as methanol, ethylene, and ammonia. In specific cases, local conditions or geographical considerations make this a commercially attractive option (see text box on the next page). However, production of hydrogen by electrolysis is generally still more costly than production from natural gas.

When produced with renewable electricity, hydrogen can be a carbon-free energy carrier

CARBON RECYCLING INTERNATIONAL IN ICELAND

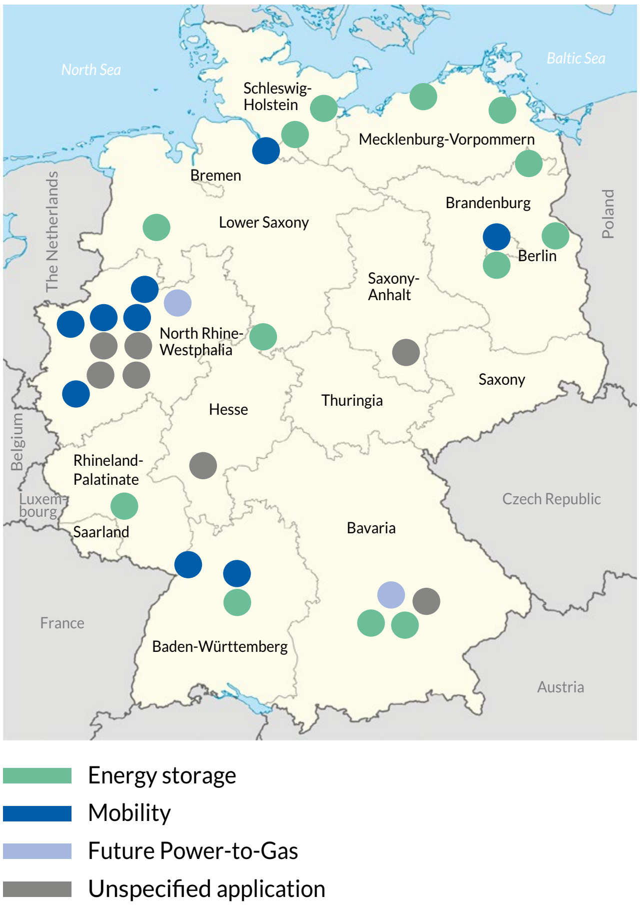
Applying Power-2-Hydrogen for local use on-site is already being applied by the industry at small scales for specific cases. Carbon Recycling International in Iceland is a good example. It is using local conditions to make a commercially feasible renewable product, namely methanol. Their commercial plant, operating since 2011 and connected to the Svartsengi geothermal power plant, produces 5 million litres of completely renewable methanol per year and recycles 5.5 thousand tonnes of CO_2 emissions per year.



Source: www.carbonrecycling.is

Hydrogen for storage of energy at large scales

This concept, usually termed 'power-to-gas', is mainly interesting as a storage option for electricity grids with a significant share of highly volatile renewable electricity supply, like wind and solar. The produced hydrogen can be stored directly or first reacted with CO_2, e.g. captured from a coal-fired power plant or a biomass gasifier, to produce methane. Both gases can be injected into the natural gas grid. Germany is piloting this form of energy storage in at least 13 demonstration and pre-commercialisation projects[8]. More recently also the storage of seasonal electricity in the form of renewable ammonia is being investigated[9]. Next to the fact that it can be used as a carbon neutral fuel for e.g. electricity production, it provides opportunities to decarbonize fertilizer and food production. The economic feasibility of energy storage is still a challenge, however, since the technology is cost intensive[10].



Map of the various hydrogen production projects in Germany, including those for energy storage (including power-to-gas) and mobility applications. *Data source: www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Smarter-business/Smart-energy/power-to-gas.*

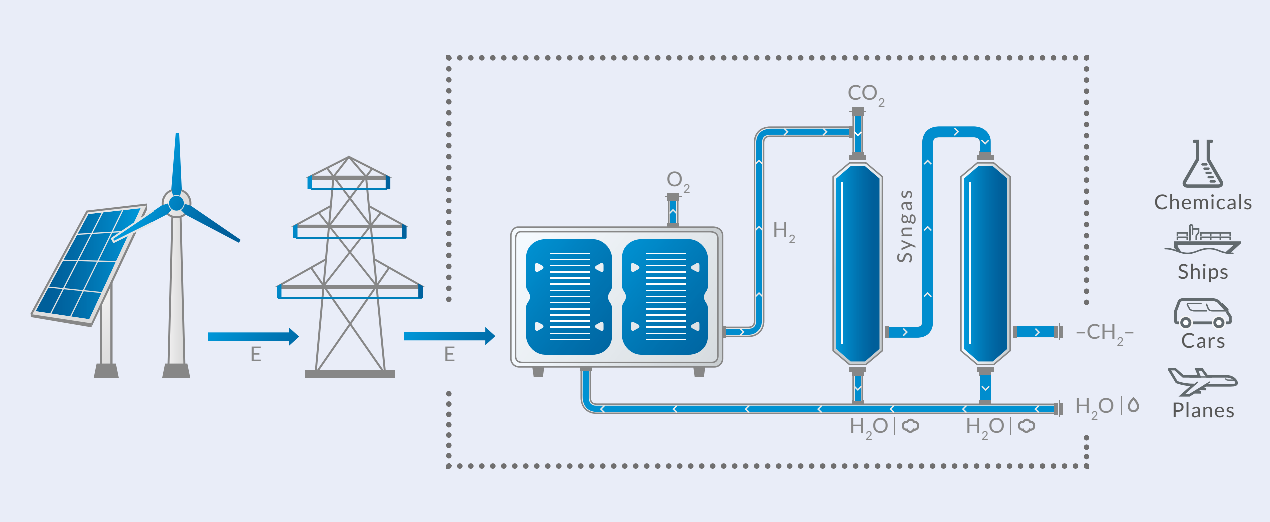
Hydrogen for mobility

Consumers and businesses ask more and more for sustainable means of mobility. Companies that are closest to the end users in the value chain are looking towards production of hydrogen as a fuel. Fuel cell electric vehicles (FCEV, in particular cars) are technically ready and are on the verge of market introduction. Because end-users increasingly favour green over fossil, and because the reference of conventional cars with liquid fuels allows for a higher selling price of hydrogen than for most industrial and energy sector applications, the transport sector could become an important market for renewable hydrogen.

Recent techno-economic analyses suggest that electrolysers could play a role in energy applications, and that in some cases they can directly compete with producing hydrogen from other sources. However, further development of electrolyser technology is required to achieve the projected cost and performance targets. Even in favourable policy environments, electrolytic hydrogen often is not yet competitive with hydrogen from conventional sources. Additional revenue streams are required to compete with conventional hydrogen from fossil sources. Supplying hydrogen to remote customers, taking advantage of further support mechanisms, such as green certificates or subsidies for hydrogen generated from renewable electricity, or providing additional services to grid operators could bring in these additional revenue streams.

POWER-TO-LIQUIDS BY SUNFIRE

Sunfire has developed and demonstrated technology to produce hydrocarbons from water and electricity based on high-temperature steam electrolysis. The hydrogen is reacted with CO_2 to form a syngas through the reverse water-gas shift reaction. Subsequently, this syngas can be converted into fuels and chemicals by using traditional refinery processes. Currently, about 50% of the input of electrical energy contributes to the calorific value of the fuel produced. The Sunfire process has applications in for example refineries, as a fuel substitute, or for storage and transport of renewable electrical energy generated at remote locations, such as deserts.



Source: www.sunfire.de/en

POWER-2-SPECIALTIES

The objective of Power-2-Specialties is to realise the production of chemical intermediates and higher value products via direct synthesis using electricity. When compared to traditional processes, applying electrochemistry has the major advantages of higher purity and selectivity. Other benefits are the realisation of ambient process conditions and a reduction in feedstock need, waste and by-products.

Electrochemical synthesis opens up ways to produce new chemicals

Electrochemical synthesis opens up ways to produce new chemicals that are difficult or too expensive to produce in a traditional manner. It thus offers opportunities to the EU chemical industry to utilise its leading position in knowledge and innovation and develop new product-market combinations (PMCs), thereby increasing competitiveness through newly possible business models and diversification. The combination with bio-based chemicals, another growth area in the EU chemical industry, is one such example of this. Selective oxidations can be performed efficiently in electrochemical systems to increase the value of renewably produced chemicals, such as the oxidation of bio-based HMF to FDCA. The main economic benefit of Power-2-Specialties therefore lies in value creation around high value products.

During the industry consultation, industry representatives stated that Power-2-Specialties is already being applied in their companies to replace highly inefficient traditional production routes of high value products, mostly for cost reduction reasons. While sustainability is not a driver in this case, mostly due to the relatively small volumes that are involved, the concept does have the potential for improvements in this area, because of the reduced feedstock needs and less waste and by-products. However, this concerns only a limited amount of cases and it is expected that widespread adoption of electrochemical technologies will take at least 5-10 years.

Electrochemistry has the major advantages of higher purity and selectivity

ELECTROCHEMICAL PRODUCTION OF INDUSTRIAL CHEMICALS FROM CO_2 BY LIQUID LIGHT

Liquid Light is a company offering technology to use electricity for not only achieving a cost advantage, but also to contribute to sustainability. Based on the discovery of an efficient and stable electrocatalyst for the conversion of CO_2 to valuable products, such as ethylene glycol, isopropanol and acetic acid, conventional oil and gas feedstocks are avoided and replaced by recycled CO_2 and electricity. While their technology is still to be proven at commercial scale, investors and the industry are confident in its potential, as shown by numerous awards and recognitions.

Source: llchemical.com

POWER-2-COMMODITIES

The electrochemical production of commodity chemicals concerns both the centralised and decentralised production of large volume chemicals. Due to well-developed production processes and highly competitive market conditions, the profit margins are much lower than with fine and specialty chemicals, making the drivers for electrification of these processes different than with Power-2-Specialties. Increased sustainability, whether due to a company's social responsibility commitment or in anticipation of future regulations, is a major reason for the current investigations into Power-2-Commodities processes.

In some cases, cost reductions and positive business cases can also be achieved by electrochemically producing commodities. It is expected that decentralised production of bulk chemicals, such as hydrogen peroxide or fertilisers, at smaller scales than the conventional processes will be the first examples to be realised in practice. Decentralised production of bulk chemicals will utilise local conditions that reduce costs, such as connections with cheap or surplus electricity or proximity to end-users, resulting in less transport and handling charges, a factor that is especially important for remote areas and for hazardous chemicals.

DECENTRALISED PRODUCTION OF CHLORINE

Chlorine production is probably the most well-known electrochemical process which annually produces 9937 ktonne of chlorine, 9678 ktonne of caustic soda and 298 ktonne of hydrogen within the EU. For safety reasons, most of the chlorine is moved by short distance pipelines, with transportation by road or rail being less than 5% of the total production. Large-scale transportation of chlorine by train in the Netherlands ended completely in 2006.

Skid-mounted chlor-alkali plants avoid transport and handling of liquid chlorine in order to offer a secured supply. Ease of installation and highly automated production are further key advantages under certain circumstances. These circumstances include high labour costs at the plant location, remote production sites, harsh climate conditions, lack of infrastructure, and shortage of skilled labour. Companies such as Conve & Avs Inc. and UhdeNora are developing and optimising these systems, with rated production capacities up to 100,000 tonnes per year.

Source: www.conveavs.net/projects

Decentralised electrochemical production of commodities will begin to be realised in the mid-term for specific cases and more widely in a longer term of about 20 years. This will eventually be followed by implementation of centralised Power-2-Commodities, as the energy transition to renewables continues and electricity replaces oil and natural gas. Exceptions to this are the production of chlorine, which is already being produced by applying electrolysis, e.g. by AkzoNobel[11], Wacker[12] and Bayer[13], the extraction of aluminium and the production of silicon nitride.

Still, several processes are in development and being researched widely. One of the promising technologies is the electrochemical reduction of CO_2 to products such as methane, carbon monoxide, formic acid, and ethylene. As substantial amounts of CO_2 become available in the future, due to implementation of carbon capture systems, the producers of the CO_2 (power plants, cement factories, steel mills, etc.) will look for more ways to utilise or sell the CO_2 to avoid costs of sequestration. Connecting this with renewable electricity supplies will allow for substantial reductions in CO_2 emissions, as CO_2 will become a sustainable feedstock that replaces oil and gas. More flexibility in the energy system will also be introduced, with fuel produced from CO_2 functioning as an energy storage medium. Such synergies and extra roles that electrification can play in the EU industrial sectors will help to drive the development and implementation of Power-2-Commodities.

SUMMARY OF DRIVERS

A summary of the main drivers for the EU chemical industry to develop and implement technologies based on electricity is given in the table below. These are specified per each type of electrification by relevance and based on the feedback from the industry consultation.

Industrial driver	Power-2-Heat	Power-2-Hydrogen	Power-2-Specialties	Power-2-Commodities
Cost reduction	Important	Relevant	Relevant	Important
Sustainability	Important	Important	Not relevant	Important
New products	Not relevant	Not relevant	Important	Not relevant

ELECTRIFICATION OF THE CHEMICAL INDUSTRY OFFERS VALUE TO BOTH THE CHEMICAL INDUSTRY AND THE ENERGY SECTOR

Both the chemical industry and the energy sector value the economic potential that electrification offers to them. For the chemical industry, the economic potential mainly consists of cost reduction and the development of new products. The energy sector is interested in creating grid flexibility to optimise investments in the grid. In many cases it is quite a challenge to quantify the economic potential. Below some first quantifications are presented to give a first impression of the economic potential of electrification.

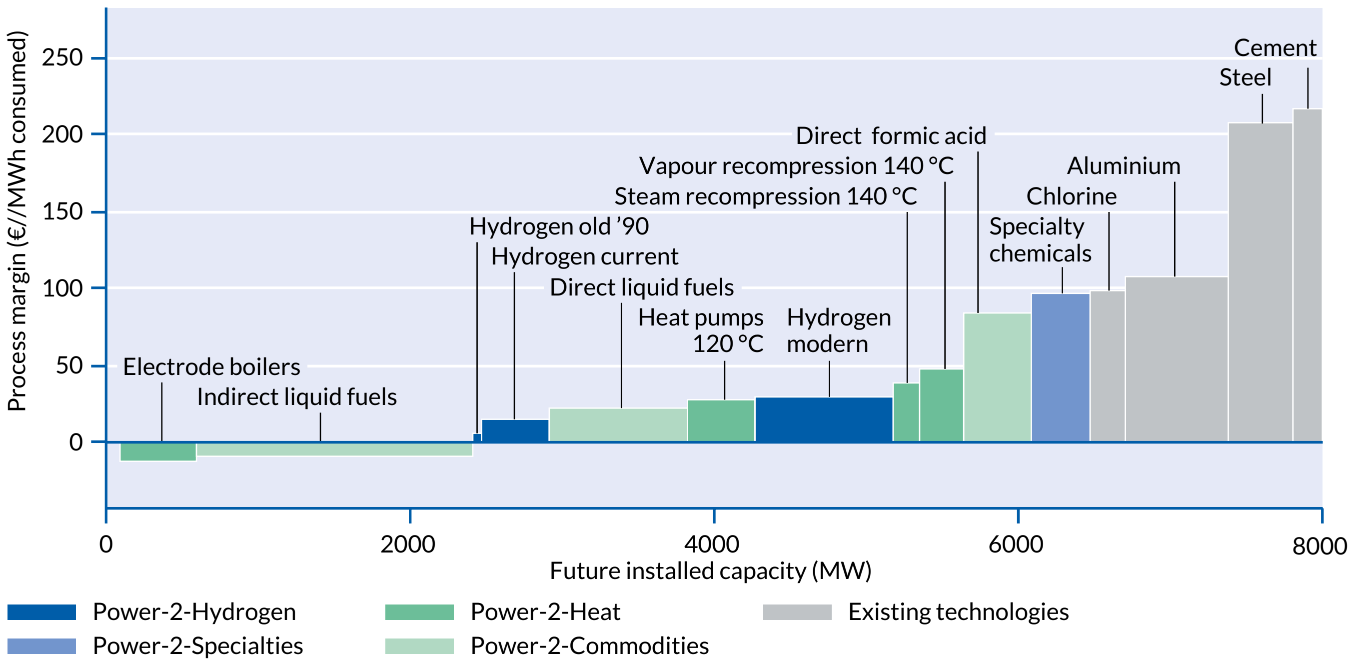
THE POTENTIAL VALUE OF ELECTRIFICATION TO THE CHEMICAL INDUSTRY IS SIGNIFICANT

In order to assess the future economic potential of electrification in more detail, a merit order study was performed. In this merit order, a number of applications of electrification have been ranked based on their operational margin. In the study, a future scenario for fifteen electrification options was defined for the Netherlands. The merit order provides insight into the operational margin in €/MWh for each option (vertical axis) and the capacity for load balancing (horizontal axis). The study was based on an assumed base load power price of € 32/MWh. Without going into the details of the study here, the results are shown in the graph.

At the right side of the merit order, a number of applications were identified that are already operational in the cement, steel and aluminium industries. In the chemical industry, the production of chlorine is already operational. Their high operational margins make them candidates for load shedding, but not for load shifting: these processes would only be shut down in case of serious electricity shortages, since the value of lost load is high. As shown in the figure, this also applies for specialty chemicals, direct formic acid, and to a lesser extent for a number of Power-2-Heat options.

Applications on the left side of the merit order appear to have a lower or even negative operational margin. Though they may seem economically unattractive at first sight, these options may become attractive by applying load shifting: by making use of moments with low electricity prices, the operational margin will increase. Also, when the base load power price goes below the assumed price of € 32/MWh, the operational margin will become higher.

In this merit order study, CAPEX and fixed OPEX were not taken into account and not all required technologies are available yet. Also, the economic potential of the different electrification options was not compared to the costs of traditional processes. Therefore, this merit order study is not appropriate for making investment decisions, but the study does provide an interesting indication of the economic potential of the different electrification options at different electricity price levels. For example, hydrogen production that employs currently available commercial technology



Future theoretical merit order of electrification options.

('Hydrogen current' in the figure) has an operational margin of 15 €/MWh of consumed electricity. If electricity prices increase, this margin will decrease. At a certain electricity price, it is economically more attractive to shut down the process. At a later time, when energy demand becomes lower and electricity prices decrease, hydrogen production will start again. This will thus shift the load and level out electricity demand, thereby balancing production and consumption of electricity.

Several electrification options have an attractive operational margin

For the chemical industry, the figure shows that several electrification options have an attractive operational margin. Especially for the options on the right side of the merit order, it is interesting to further explore economic feasibility in a business case. The options on the left may become economically feasible at lower energy prices, for example at moments when renewable energy is abundantly available.

For the energy sector, the merit order indicates that electrification of the chemical industry offers interesting capacity for load shifting (on the left side) and load shedding (on the right side).

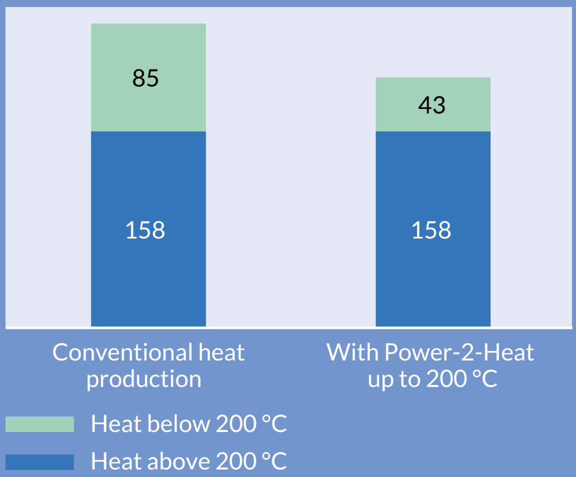
ELECTRIFICATION OF THE CHEMICAL INDUSTRY CAN CONTRIBUTE TO FLEXIBILITY IN THE ELECTRICITY SYSTEM

Electrification of the energy demand in the chemical industry through Power-2-Heat, Power-2-Hydrogen, Power-2-Specialties and Power-2-Commodities offers clear potential benefits for the energy sector. Therefore, exploring and exploiting the opportunities requires close cooperation between the chemical industry and the energy sector.

POTENTIAL IMPACT OF POWER-2-HEAT FOR THE DUTCH CHEMICAL INDUSTRY

Power-2-Heat in the chemical industry could result in about 15-20% energy savings for heat production
In 2013, the final energy use for heat in the chemical industry amounted to 243 PJ. About 35% of the required energy is for heat at temperatures up to 200 °C. These temperatures can be obtained by heat pumps and upgrading of residual steam by mechanical vapor recompression. It is estimated that a 50% energy savings is possible through application of these technologies, resulting in 15-20% savings on energy for heat demand, as shown in the figure below.

Full deployment of Power-2-Heat technologies for generating heat up to 200 °C could lead to a reduction in CO_2 emissions in the chemical industry of about 6 Mtonne. The maximum effect is achieved if all of the electricity is produced by additional generation capacity based on wind and solar photovoltaics.



Power-2-Heat could offer an important source of adjustable load for demand response schemes at local scales
When operating at full load, a Power-2-Heat capacity of more than 1 GW is required. This represents more than 25% of the currently installed 3.9 GW of wind turbines and PV-panels, and about 4% of the expected 30 GW of installed wind and solar-based generation capacity in 2030. Clearly, this presents a significant source of adjustable load to help compensate for fluctuations in intermittent supply on a national level, and in particular on local or regional levels. It could thus contribute to minimising investments in expansion of the electricity grid associated with the deployment of intermittent renewables.

During the industrial consultation, representatives from the energy sector named the following potential benefits of electrification:

- A considerable and concentrated increase of controllable load in the electricity system. This can be used to better align demand with the fluctuating supply of electricity, and thus reduce volatility in market conditions. To this end, the deployment of hybrid systems can also be considered, in particular for heating, which can switch between fossil fuels and electricity. This may serve as an outlet at moments when the oversupply of electricity is looming.
- Optimisation of required infrastructure investments to absorb fluctuating renewables into the energy system. Electrification offers additional possibilities to match local supply with local demand, thus potentially reducing the need for extending and upgrading of the electricity grid to transport large amounts of locally produced energy to other locations.

The merit order study above covered a significant capacity of almost 8 GW of controllable load. To quantify the contribution of electrification to flexibility in the electricity system further, two cases were elaborated (see text boxes). It is expected that electrification of demand for heat below 200 °C from the chemical industry in the Netherlands has the potential to present a significant source of flexibility on local or regional level. Electrification of hydrogen production in the Netherlands represents a significant source of adjustable load at the national scale.

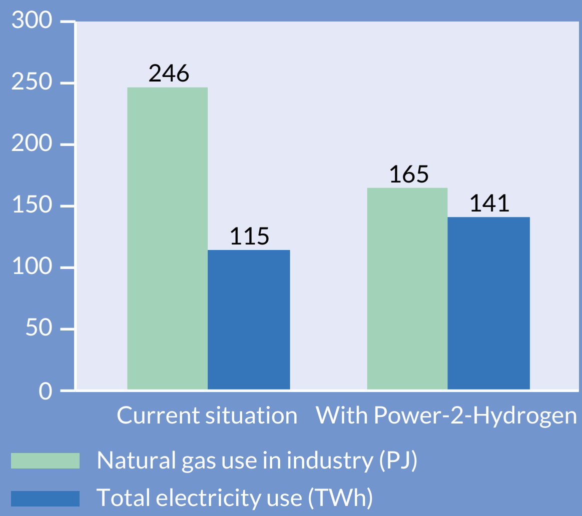
Electrification offers interesting opportunities for load shifting

POTENTIAL IMPACT OF POWER-2-HYDROGEN FOR THE DUTCH CHEMICAL INDUSTRY

Replacement of natural gas-based production through electrolysis requires 26 TWh of electricity

Annual industrial consumption of hydrogen in the Netherlands is about 63 PJ (based on LHV). Production of this requires 81 PJ of natural gas as feedstock (based on LHV), taking into account a conversion efficiency from natural gas to hydrogen of 75-80%. The production of this amount of hydrogen through electrolysis would require roughly 26 TWh of electricity, leading to a considerable increase in electricity demand and reduction in natural gas demand.

Full replacement of hydrogen production using natural gas by electrolysis would lead to a CO_2 emissions reduction in the chemical industry up to 4.1 Mtonne.



Electrolysis could represent a significant source of adjustable load for demand response schemes at national level

To fully implement Power-2-Hydrogen, the corresponding installed capacity of electrolysers depends on the average annual full load hours of the units that are used. While continuous full load operation would be desirable from an investment standpoint, use of the electrolysers in demand response schemes would require an overcapacity. At an average of 50% full load hours, twice the required installed capacity would be required, amounting to 6 GW. Installed wind and solar generation capacity is expected to grow to around 30 GW in 2030, up from 3.9 GW in 2014. Water electrolysis could thus represent a significant source of adjustable load to help compensate for fluctuations in supply of electricity from wind and solar and balance the electricity grid.

TECHNICAL DEVELOPMENTS WILL BRING DOWN CAPITAL AND OPERATIONAL COSTS AND DRIVE IMPLEMENTATION OF ELECTRIFICATION

The different forms of electrification all have the potential to significantly impact the EU chemical industry when certain technical hurdles are overcome. Although quite some niche applications have been realised already, it is expected that electrification will accelerate drastically in the coming decade due to several important scientific and technological developments worldwide. These developments are driven by reducing capital investment and operating costs while at the same time allowing the technologies to interface better with the evolving electricity supply. Four main categories of technological interest have been identified and are discussed in more detail below. These are:

- Increased operating flexibility
- Extension of operating windows
- Improved system components and design
- Disruptive technologies

INCREASED OPERATING FLEXIBILITY

To take full advantage of fluctuating electricity prices, technologies for each of the types of electrification should be able to operate flexibly. Quick start-up and shutdown times coupled with high efficiencies over varying loads are needed. This is in contrast to current processes, which are designed to run continuously with high efficiency at their operating design point, typically close to 100% load.

Applying the concept of flexibility in Power-2-Heat requires multifunctional equipment which can be driven by either natural gas or electricity, depending on the prevailing energy prices. Industrial end-users then have the ability to operate with the cheapest energy carrier. To this end, technology concepts are being developed, including control strategies. Another level of flexibility, although not yet available, is operating Power-2-Heat systems in a reversible way. Heat is produced by an electrically driven heat pump at low electricity prices. Should electricity prices be high compared to natural gas prices, the same technology could be used in reverse to produce electrical power.

When applied to Power-2-Hydrogen and Power-2-Commodity technologies, flexibility will require start-stop and dynamic operation with high efficiencies across much of the load curve. Simultaneously maintaining and improving lifetime and high efficiency with flexible operation requires much better knowledge of the future requirements of electro-chemical systems. Projects designed specifically to gather data on these factors are being started and will be essential to allow for the correct design of flexible electrochemical systems. Examples of such projects are the ELECTRE project from the Shared Innovation Program VoltaChem, involving ECN and Hydrogen Energy[14] and the CO2RRECT project with Siemens, Bayer Technology Services, and others. Siemens has now partnered with Linde and Energiepark Mainz to scale up their electrolyser technology to a 6 MW_P system, the largest of its kind in the world.

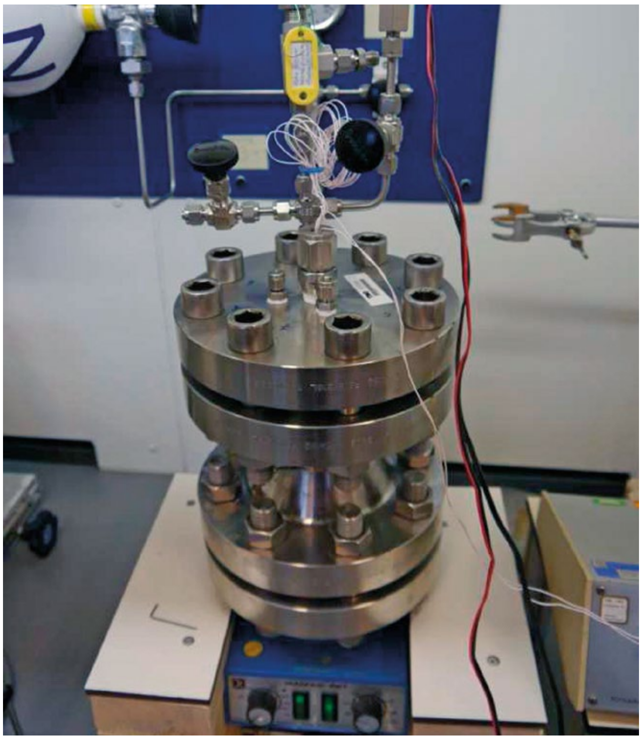
EXTENSION OF OPERATING WINDOWS

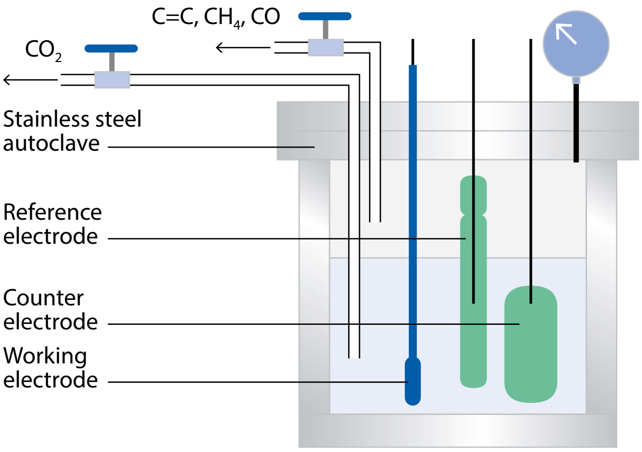
By developing technologies which can operate over a wider range of operating conditions, such as temperature and pressure, they become applicable in more processes and have improved business cases. This is essential for increased implementation of electrification.

To realise the commercial potential for Power-2-Heat technologies, higher temperature levels must be achieved in order to reach the elevated temperatures required by many chemical processes. Electrically driven heat pumps can provide solutions for upgrading heat to temperatures up to 250 °C. Developments are on-going to extend the operating window of these systems by new working media and compressors. Other developments are based on gaseous working media.

10 kW bench scale electrically driven thermo-acoustic heat pump, which uses waste heat at 50-120 °C to deliver process heat 100-200 °C. Developed by ECN together with Bronswerk.

New working media at ECN.





High pressure electrochemical reactor at TNO for the production of ethylene from CO_2 and water (above) and schematic view of a high pressure reactor at the University of Twente.

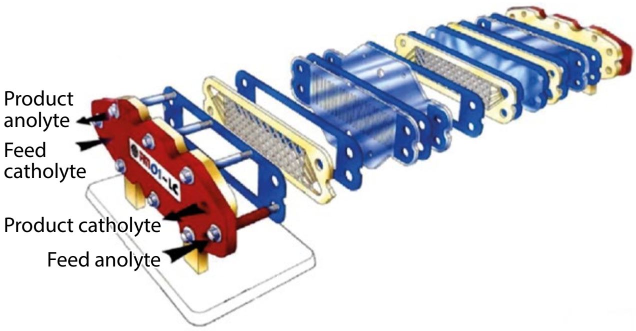
At the same time, electrochemical processes are being developed with new materials and a better understanding of electrochemistry. This allows for the use of operating parameters, such as temperature, pressure and pH, to influence the reactions and improve activity and selectivity. This is also required to enable the product flexibility that can dramatically improve the business case for Power-2-Specialties and especially Power-2-Commodities. For example, the University of Twente has shown that by changing either the pH or the pressure of an electrochemical reactor for the conversion of CO_2, the product selectivity can be tuned from producing mostly C1 molecules, such as methane, to producing almost only C2 molecules, namely ethylene[15].

IMPROVED SYSTEM COMPONENTS AND DESIGN

The operating costs of an electrochemical system can be reduced through introducing flexibility, integration with other systems, and increased energy efficiency. However, the capital investments of these technologies are too often prohibitive in the cases of Power-2-Hydrogen, Power-2-Specialties, and Power-2-Commodities. Improved electrocatalysts, in-situ product separation, and reduction in processing steps are all ways in which capital investments can be reduced and the business case for electrochemical systems can be improved.

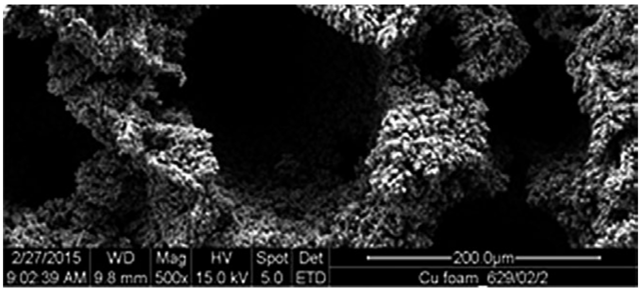
For Power-2-Hydrogen, one of the biggest challenges is maintaining the lifetime and appropriately high efficiency. With the current state-of-the-art, hydrogen produced by electrolysis is at least twice as expensive as hydrogen produced from fossil fuels. New electrolyser technologies, such as anion exchange membrane ('alkaline PEM') and solid oxide electrolysers, are still in development, but could realise significant improvements over the more mature technologies. Each has promise for cost reduction and the solid oxide system, which operates at high temperatures, could produce hydrogen with much lower electricity input than conventional electrolysers.

Volume production and supply chain development will occur in parallel with increased deployment of electrolyser systems. However, technology innovations are needed that can enable the mass fabrication of standardised low cost components e.g. by roll to roll techniques or the use of standardised low cost components already in mass manufacture. Recent studies predict a reduction in capital cost beyond 2020 of a factor 2 for alkaline electrolyser systems up to 4 for polymer electrolyte membrane (PEM) electrolyser systems.



Schematic overview of a commercially available FM01-LC electrochemical cell showing the several components that are involved in the fabrication. *Source: www.sciencedirect.com/science/article/pii/S2213343713001796.*

For Power-2-Specialties and Power-2-Commodities, the focus of research is on achieving high performance with cheaper and more stable materials and novel electrocatalysts. One approach to making improvements is through alloying different metals together to make bimetallic catalysts, thereby affecting the electronic nature of the material and its function. Next to this is modifying the shape of catalytic nanoparticles. As the activity and selectivity are strongly facet dependent, tuning the nanoparticle size can have a strong influence on the total reactor performance. This is a parameter that can today be controlled relatively easily. Even more interesting and challenging is to control the shape of the nanoparticles. This allows for preferentially exposing specific crystal facets, where each facet can be selective for a different product.

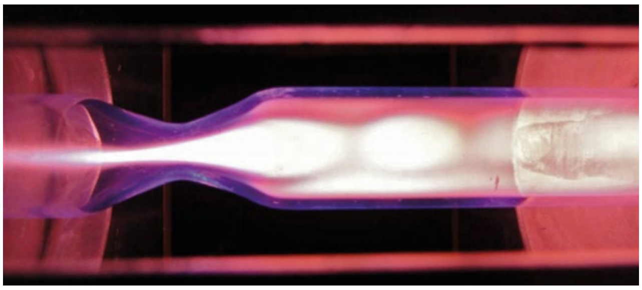


Nanostructured copper foam used to increase the electrocatalytic surface area by a factor of 10. *Source: TNO.*

In the past couple of decades, components such as catalytic electrodes, membranes, and stable gasket materials have become available off the shelf. While this has drastically reduced the costs of developing electrochemical processes, further advancements are still needed. Ensuring a high specific surface area is achieved with highly porous electrode materials, such as metal foams, porous carbon particles, and nano-structures. When these are combined with novel electrocatalysts, the overall performance of the electrochemical process can be significantly improved.

DISRUPTIVE TECHNOLOGIES

The focus of Power-2-Hydrogen, Power-2-Specialties and Power-2-Commodities has been on the direct use of electricity for the chemical conversion. It should be noted, however, that the means of using electricity in chemical conversions, possibly other than direct electrochemistry, is also a part of the design. Technologies such as plasma, microwave and photocatalysis can have key benefits over conventional electrochemistry for certain processes. These technologies might lead to higher energy efficiencies and product yields by activating the molecules in different ways than electro-chemistry or conventional thermochemical processes, such as through generation of free radicals or specific vibrational excitation. These technologies are especially applicable to highly stable molecules, such as CO_2. While mostly in earlier stages of development than the other technologies mentioned here, with successful implementation in the future, these would be game-changers in the field of electrification for the chemical industry.



Plasma reactor for producing CO from CO_2 at DIFFER in the Netherlands. *www.differ.nl/news/new_regime_in_dissociating_CO2_for_clean _fuels.*

OUTLOOK

It is expected that these scientific and technological developments will heavily impact the business potential and timeline of the electrification options under consideration. The relevance of the different areas of focus in current research is summarised in the table for each of the types of electrification. Power-2-Heat can already have a positive business case today, but further developments will expand the applicability. Calculations on the business case of Power-2-Hydrogen, Power-2-Specialties and Power-2-Commodities technologies often show negative net present values, but the required developments to make these systems commercially attractive are clear and in the coming decades important steps will certainly be made in research labs all over the world in the coming decades.

Industrial driver	Flexibility in operation	Extension of operating windows	Improved system components	Disruptive technologies
Cost reduction	Important	Important	Relevant	Not important
Power-2-Hydrogen	Important	Not important	Important	Relevant
Power-2-Specialties	Not important	Relevant	Important	Important
Power-2-Commodities	Important	Important	Important	Important

A COLLABORATIVE EFFORT OF ALL STAKEHOLDERS CAN ACCELERATE ELECTRIFICATION

In conclusion, it can be stated that implementation of electrification technologies has the potential to make the EU chemical industry more competitive and sustainable. Electrification creates interesting opportunities for the chemical industry to improve the business case for the production of bulk chemicals and specialties by reducing costs. Electrification also offers possibilities to develop new products, mainly in higher value segments. Improved sustainability can be achieved by using renewable energy instead of fossils and by using bio-based feedstocks and CO_2 as building blocks for chemicals. Besides chemical companies, other stakeholders will also benefit when electrification takes off.

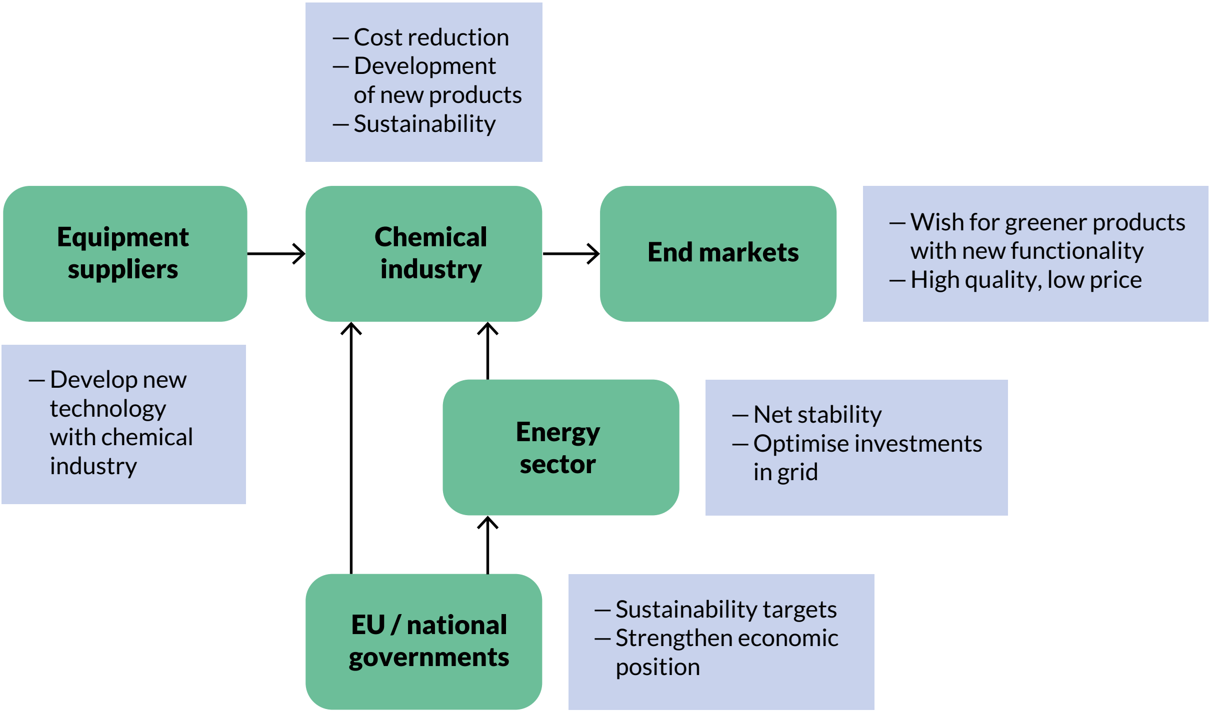
INTERESTS OF STAKEHOLDERS

The interests of the chemical industry and the energy sector were discussed in previous chapters. Though they are the main stakeholders, also equipment suppliers, end markets (both business customers and consumers) and governments have an important role. The interests of these stakeholders are shown in the figure below:

- For the **energy sector**, electrification offers a very interesting opportunity to stabilise the electricity grids, considering the growing share of intermittent renewable energy. Implementation of load-response options and matching local supply and demand may prevent unnecessary investments in the electricity grid.
- **Equipment suppliers** have interest in developing and supplying the necessary technologies to enable electrification.
- **Governments** have interest in reaching sustainability targets and utilising the opportunities to strengthen the economy.
- **Users of chemical products and fuels**, both consumers and businesses, have a desire for greener products with new functionalities. A condition is that these products have at least the same quality as and are not more expensive than the comparative conventional products.

Besides the stakeholders named above, new players may appear in the value web. For example, bulk chemical companies may want to outsource heat supply when they make use of Power-2-Heat. New players can fill in this role, offering flexibility towards the energy sector and continuity towards chemical companies.

New players may appear in the value web



Stakeholders and their interests in electrification.

OVERCOMING THE BARRIERS

To maintain the competitive position of the EU chemical industry, and to fully utilise the potential of electrification, innovation and implementation should be accelerated. To achieve this, a number of barriers need to be overcome. The table below presents the barriers that were named during the industry consultation and suggestions of how to overcome these barriers.

To fully utilise the potential of electrification, innovation and implementation should be accelerated

	Barriers	How to overcome
Economic	– High CAPEX does not match required payback periods of 2-3 years – Depreciation of existing assets; e.g. plants are built for 30-50 years – Uncertainty regarding future development of energy prices – Electricity connections for high capacity are expensive	– Investigate what business cases are already viable – Utilise local renewable energy supply – Develop new products in high value markets together with customers – The energy sector could co-invest in electrification to prevent unnecessary grid investments – Adapt electricity tariff structures for high capacity connections – Develop and apply financial constructions to mitigate uncertainty of future energy prices – Develop new business models
Technical	– Technology not proven yet for many cases, while preventing downtime is essential – Some technologies are unavailable on industrial scale or still too expensive (e.g. electrolysers) compared to traditional technologies – Technology supplying SMEs have innovative ideas, but little room for investments	– Develop technologies that: · have high availability · are applicable at industrial scale · are low cost – Attract venture capital to finance promising technology development
Organisational	– Cultural: resistance to change – Collaboration: equipment providers will only invest when there is demand from industry – Large scale demos and pilots too expensive and uncertain for a single company – Interests of different stakeholders not yet aligned with each other	– Involve people from all parts of the organisation – Close cooperation between equipment providers and chemical companies – Set up innovation communities and joint ventures
Regulatory	– Fossil fuels and CO_2 emissions are too inexpensive, preventing companies from choosing more sustainable alternatives – No global level playing field for sustainability	– Support pilots and commercial deployment of sustainable initiatives – Create a global level playing field with international policy alignment – Targeted EU or national policy to stimulate production of sustainable chemicals

A ROADMAP FOR INNOVATION

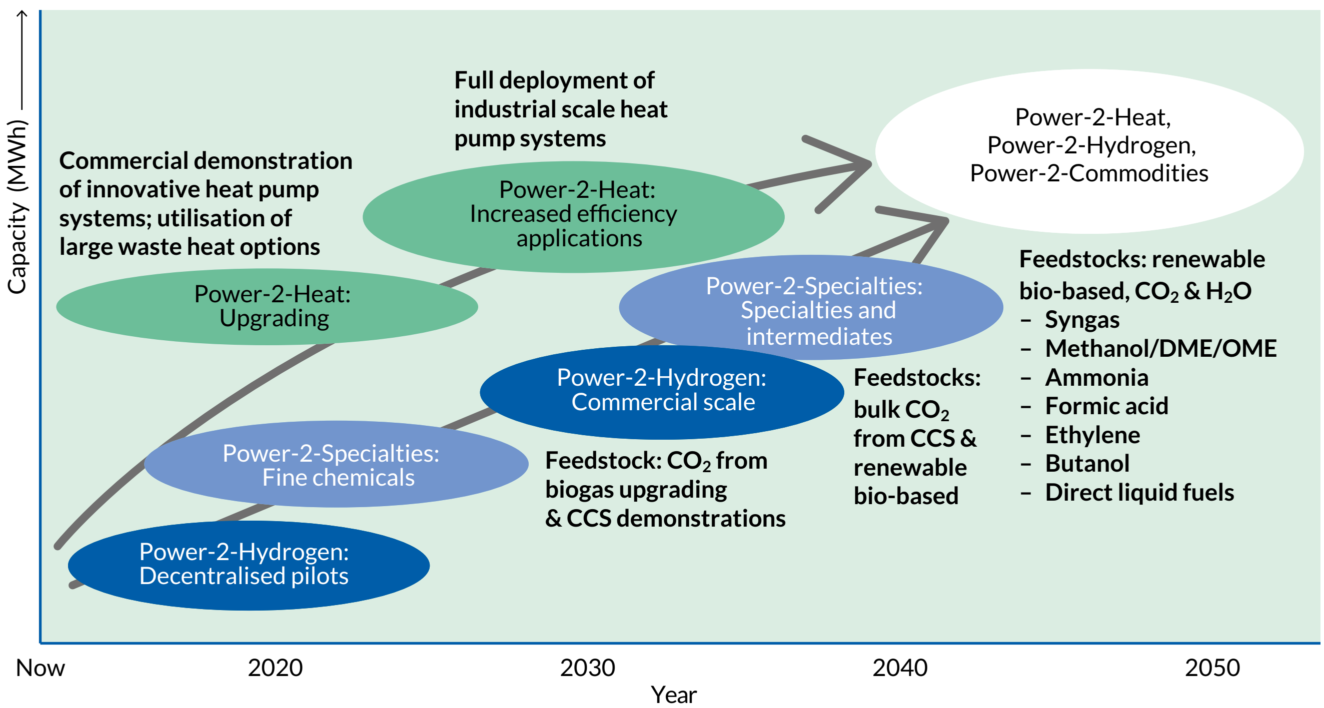
For successful commercial deployment of electrification, it is obvious that close cooperation between the stakeholders is essential. The interests of the stakeholders need to be balanced in order to get the flywheel up to speed. Open innovation communities can provide the imperative governance, stimulating open innovation and demonstration projects, with the goal to drive the development of a circular ecosystem. In such communities, the stakeholders can work together on the following topics:

- Taking advantage of 'low hanging fruit' and identifying short term opportunities for cooperation in electrification projects.
- Continuous business and technology scouting.
- Joint innovation on technology and effective use of research infrastructure.
- Assessment of economic feasibility and comparison of options regarding total cost-of-ownership and cost-to-implementation.
- Development of innovative business models.
- Development of future price scenarios for energy, feedstocks, commodities and final products.
- Development of (load-response) merit orders.

The roadmap in the picture below was developed, based on a realistic growth scenario of the different electrification options in view of technical maturity levels and wide-ranging business cases.

The first applications of electrification are already visible in the market. Especially in Power-2-Heat and Power-2-Hydrogen, numerous pilots have been realised in Europe and quite some applications in operational settings do exist. With respect to Power-2-Specialties, several niche applications have been proven and implemented. Electrochemical production of commodities is already seen nowadays in specific cases, like the production of chlorine.

Close cooperation between the stakeholders is essential

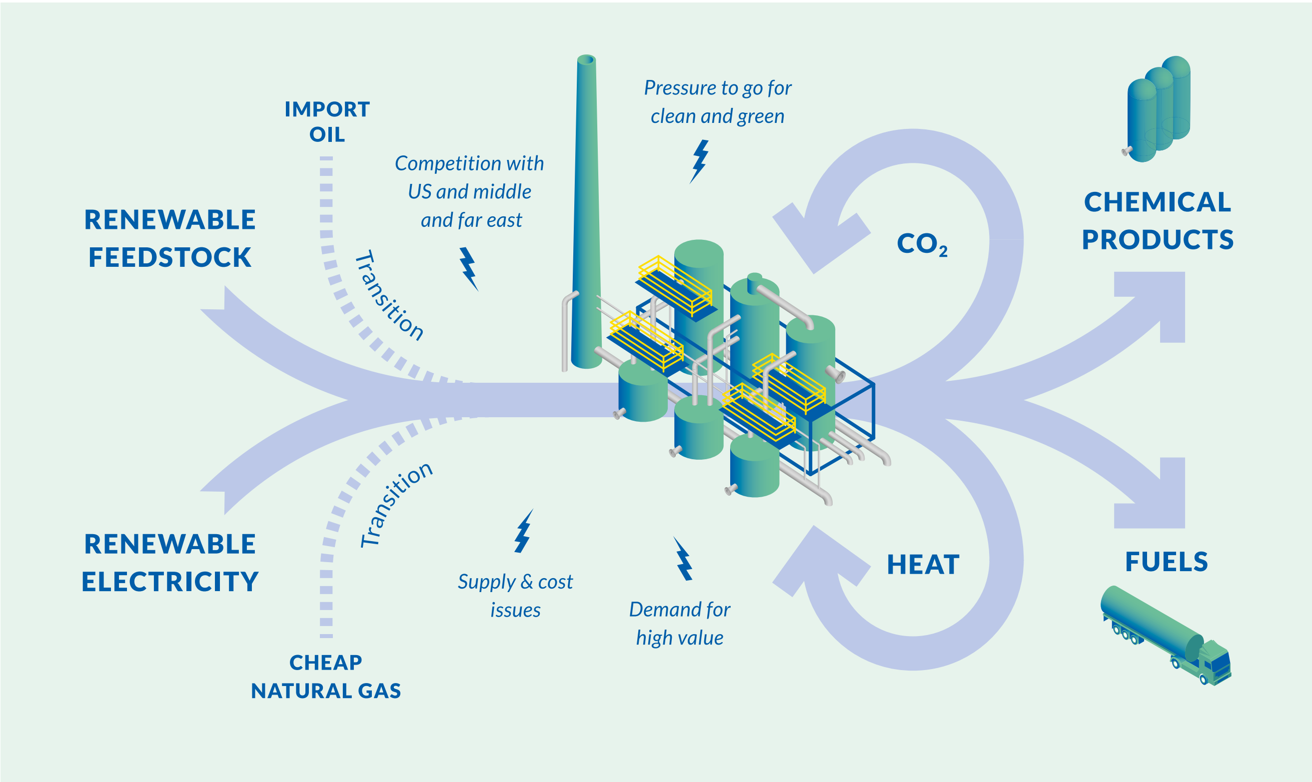


Roadmap for electrification.

The roadmap exemplifies a fast growing development of Power-2-Heat options initially, mainly based on the current favourable market conditions and technology maturity of the different heat upgrading technologies. At a later stage, higher efficiency applications at industrial scale will be deployed. For Power-2-Hydrogen and Power-2-Specialties, a steady evolutionary growth of new improved electrification options is expected, increasing the load-response capacity. New emerging technologies and innovative developments are imperative to reach broader applicability of Power-2-Commodities.

Though this will take time, maybe decades, the long term perspective of a highly electrified commodities industry is very appealing: it brings the dream of a sustainable chemical industry – where fossil feedstocks are replaced by renewable feedstocks and electricity, and CO_2 and heat are part of a circular process – a step closer to reality.

The long-term perspective of a highly electrified commodities industry is very appealing



The dream of a sustainable, circular chemical industry.

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REFERENCES

The European Chemical Industry, Facts and Figures 2014, CEFIC

Industrial heat pumps in the Netherlands, IEA Heat Pump Programme Annex 35, May 2014

'Power to Products, over de resultaten, conclusies en vervolgstappen', sept. 2015, Berenschot, CE Delft en ISPT

www.carbonrecycling.is/

www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Smarter-business/Smart-energy/power-to-gas,t=model-commercialization-projects-in-germany,did=547394.html

www.bmbf.de/pub/Power_to_Gas_engl.pdf and cleantechnica.com/2014/10/20/7-5-megawatt-wind-turbines-power-gas-pilot-project-germany-video

www.provinciegroningen.nl/fileadmin/user_upload/Documenten/Brief/2014-12171bijlage.pdf

www.sunfire.de/en/produkte/fuel/power-to-liquids and www.sunfire.de/wp-content/uploads/PtL_Bilfinger_EN.pdf

www.akzonobel.com/ic/products/chlorine/production_process

www.wacker.com/cms/en/100years/people/kallinger.jsp

www.youtube.com/watch?v=tnn2u4siwsM

A First Course in Electrode Processes, Derek Pletcher, Royal Society of Chemistry, 2009

Energy Technology Perspectives 2014 - Harnessing Electricity's Potential

Study on development of water electrolysis in the EU: Final Report, E4tech Sàrl with Element Energy Ltd for the Fuel Cells and Hydrogen Joint Undertaking, February 2014

NOTES

1 The European Chemical Industry, Facts & Figures 2016
2 The European Chemical Industry, Facts and Figures 2013, CEFIC
3 EU outspends e.g. US and China in chemicals R&D. Source: The European Chemical Industry, Facts and Figures 2014, CEFIC
4 ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm
5 www.wbcsd.org/action2020.aspx
6 www.cefic.org/Facts-and-Figures
7 'Power to Products, over de resultaten, conclusies en vervolgstappen', sept 2015, Berenschot, CE Delft en ISPT
8 E.g. see www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Smarter-business/Smart-energy/power-to-gas,t=model-commercialization-projects-in-germany,did=547394.html, www.bmbf.de/pub/Power_to_Gas_engl.pdf and cleantechnica.com/2014/10/20/7-5-megawatt-wind-turbines-power-gas-pilot-project-germany-video
9 www.nuon.com/nieuws/nieuws/2016/nuon-en-tu-delft-onderzoeken-opslag-windenergie-in-nieuwe-superbatterij, gtr.rcuk.ac.uk/projects?ref=971289
10 www.provinciegroningen.nl/fileadmin/user_upload/Documenten/Brief/2014-12171bijlage.pdf
11 www.akzonobel.com/ic/products/chlorine/production_process
12 www.wacker.com/cms/en/100years/people/kallinger.jsp
13 www.youtube.com/watch?v=tnn2u4siwsM
14 www.ecn.nl/news/item/start-of-electre-project-driving-down-electrolyser-cost-by-improving-durability
15 Kas, et al., ChemElectroChem 2015, 2, 354-358

THE VOLTACHEM SHARED INNOVATION PROGRAM

VoltaChem is a business-driven Shared Innovation Program that connects the electricity sector to the chemical industry. New technologies are developed and implemented that focus on the conversion of renewable energy from solar and wind to heat, hydrogen and chemicals. These technologies are incorporated within three program lines: Power-2-Heat, Power-2-Hydrogen, and Power-2-Chemicals (including fine, specialty, and commodity chemicals). VoltaChem serves and works with the industry within each of these program lines to strengthen its competitive position and that of its suppliers.

VoltaChem invites organisations to join its community with stakeholders from the chemical industry, electricity sector, high-tech industry and public sector. This community is an excellent platform to meet relevant stakeholders across the entire value chain, exchange knowledge and explore business opportunities together.

www.voltachem.com

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TNO Sustainable Chemical Industry

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