A first order roadmap for Electrification of the Dutch Industry

Commissioned by RVO (under number TSE1706004) on behalf of the TKI E&I and
prepared by Arend de Groot and Yvonne van Delft (ECN)

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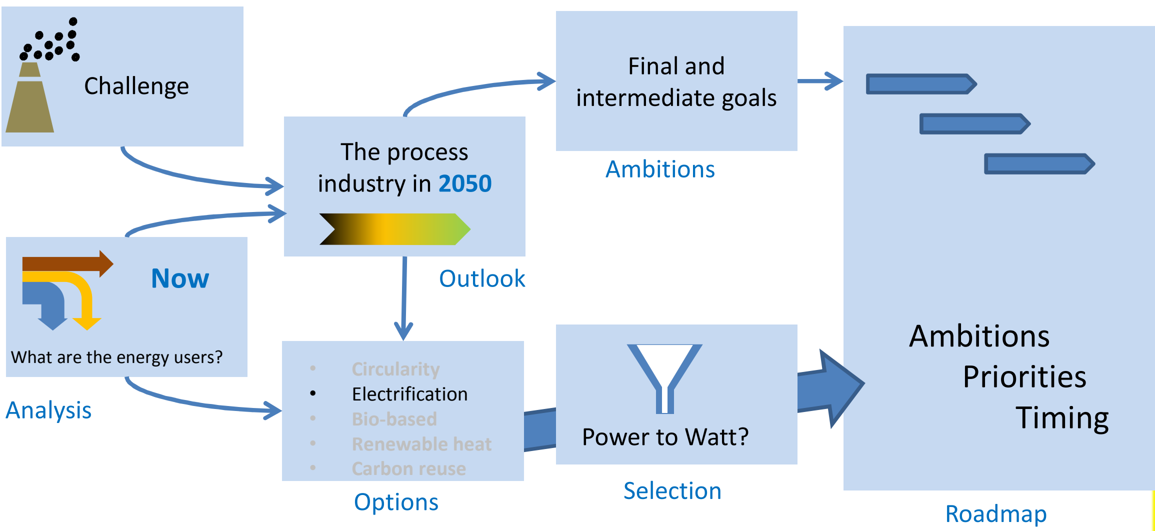
The Canvas



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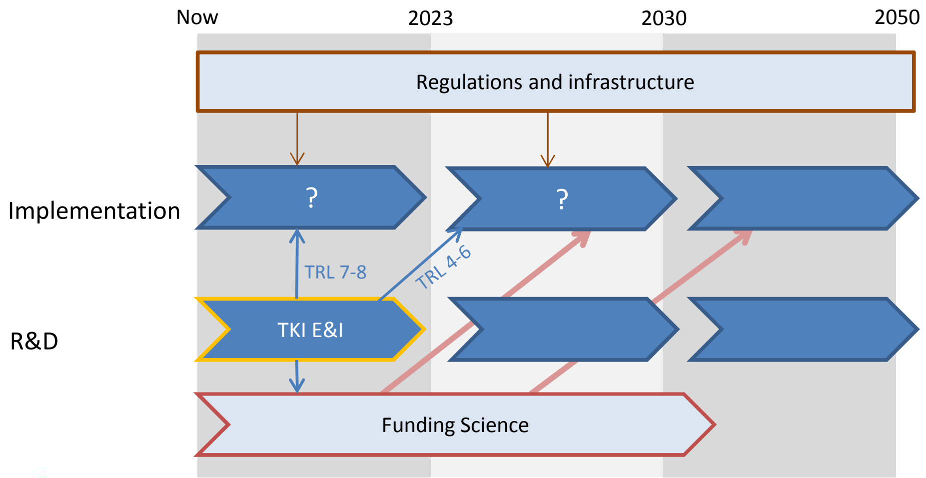
Roadmap structure



Key role of the TKI is to support technology RD&D with both a focus on implementation of technology on the short term and development of technology which can be implemented on the mid-term (2030)

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THE CHALLENGE

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The challenge

The government of the Netherlands is committed to reduce its total CO_2 emissions in 2050 by 80-95% compared to 2005.

For the Dutch process industry to contribute to this challenge, requires a major transition from a fossil to a renewable based industry.
To achieve deep decarbonisation in 2050 requires different approaches:

- Energy efficiency focussing on reduction of the heat demand
- Use of renewable heat, e.g. biomass for high temperature heat and geothermal energy for medium temperature heat
- Use of biomass feedstock and carbon capture and reuse (CCUS) to provide the carbon backbone of the chemical products and liquid fuels.
- Finally **Electrification** will play an important role to replace current fossil energy carriers and feedstock by (renewable electricity).

While CO_2 emission reduction to limit climate change is one of the primary challenges, reducing the dependency on fossil energy carriers is also of utmost importance to the competitiveness of the Dutch and European industry

The challenge

TKI Energie en Industrie carries out a successful innovation program with three main theme's:

- Process heat
- Circularity
- System integration

The topic **Electrification** is part of the System integration topic. The TKI Energy and Industry has expressed the need for a technology roadmap Electrification which describes the diversity of technological options. This roadmap will be used to shape the innovation program and innovation policy of the TKI.

A previous study[a] identified electrification options. The TKI now needs a roadmap which forms a coherent vision of the electrification and allows the TKI to determine ambitions, priorities and timing for the innovation program. The technological potential, status of the technology and remaining technical barriers to overcome and the rate at which technology can be brought to maturity form the basis for such a roadmap.

This study intends to make a first draft of such a roadmap which will be detailed and verified in the follow-up process

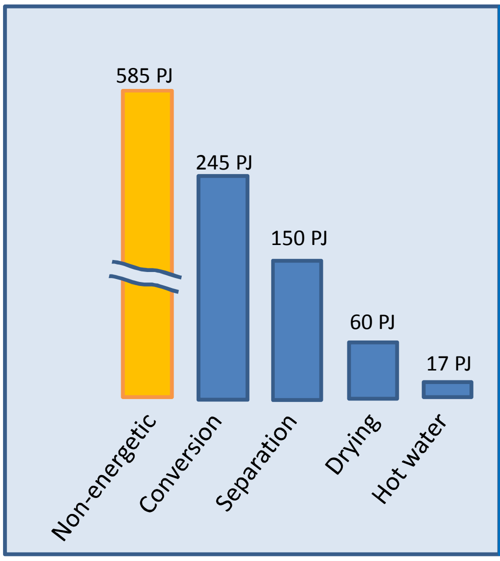
[a] *Berenschot, Electrification in the Dutch process industry, 2017*



Energy use and functions

THE CURRENT PROCESS INDUSTRY

Energy functions: current energy use



The figures on the left show the distribution of the energy use in the Dutch Process Industry based on the Berenschot study. The energy demand consists mainly of heat for different application. In addition mainly in the petrochemical industry energy carriers are used as feedstock, for example natural gas to produce hydrogen.

Conversion:

- Includes transformations requiring activation such as (endothermal) chemical reactions, reduction of iron ore and production of cement
- Other energy intensive processes include melting, casting.

Separation:

- Mainly thermally driven process: distillation, absorption, extraction
- High energy use in chemical industry is associated with non-selective processes.

Non-energetic is use of energy carriers as feedstock, e.g. natural gas for hydrogen production, naphtha or LPG for cracking, etc.

Current energy use Dutch Process industry

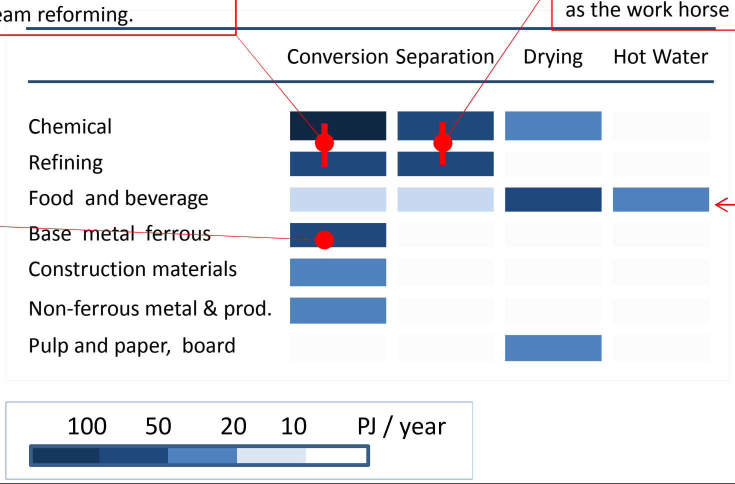
Energy demand per sector

HT heat for conversion in the petrochemical industry for endothermal chemical reactions such as cracking and steam reforming.

Separation processes are important in the chemical and refining sector, with distillation as the work horse in both sectors

Steel production requires HT heat for the conversion of ore to iron.

The energy demand in the food sector is diverse, with the largest demand for drying.



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Current energy use Dutch Process industry

Temperature level of heat demand

The heat demand is different per sector, but the temperature of the heat required as well. A recent extensive study by ECN[a] considers quantitatively the temperature at which heat is needed in industry and temperature levels at which waste heat is available. The study identified a total cumulative industrial heat demand identified for the Netherlands is about 550 PJ.

Lower temperature heat (<200 °C) is used in the food and beverages and in the paper industry for a wide variety of processes including drying. In most cases heat is provided to processes in the form of steam or hot water. More than 35% of the total heat demand is below 200°C.

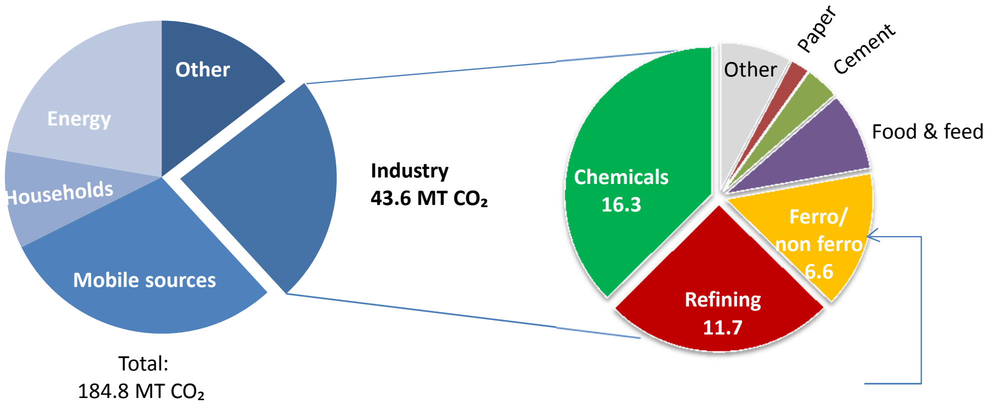
In the petrochemical industry and ferrous/non-ferrous metal sectors, heat of higher temperature is used as well.
A substantial part of the heat demand in these sectors is above 400 °C:

- Refinery processes (crude distillation, vacuum distillation, hydro-treating and naphtha reforming) dominate the heat demand between 400°C and 1000°C (32% of total industrial heat demand);
- 27% of the total industrial heat demand is above 1000°C. Main high temperature heat demanding processes are steel production, base chemical production, naphtha cracking

The ECN study is based on the evaluation of a large number of individual processes.

[a] High Temperature Heat in the Dutch Industry - heat demand and waste heat recovery potential, H.A. Zondag & S.F. Smeding, ECN 2017

Current Direct CO_2 emissions Dutch Process industry



Direct CO_2 emissions from the Dutch industry confirm the dominance of steel, refining and (bulk-)chemical processes and the need to achieve very substantial reductions of emissions [CBS, 2015] *Note: this does not take into account the indirect emissions allocated to Tata Steel as a result of the use of waste gasses from the steel production in electricity production (6 Mt) and indirect emissions related to electricity production (appr. 16 MT)*

Energy intensive processes in the Netherlands
Steel production and refineries

Steel production

Two main routes for:

- In Blast Furnace (BF)/Basic Oxygen Furnace (BOF) route, pig iron is produced using primarily iron ore (70-100%) and coke in a blast furnace, and then turned into steel in a basic oxygen furnace. Highly energy intensive, also due to coke making and sintering operations.
- Electric arc furnace (EAF) using primarily scrap for the iron input and has significantly lower energy intensity compared to the BF/BOF route due to the omission of coke making and iron making processes;

In the Netherlands the CO_2 emissions in the ferro/non-ferro sector are mainly caused by the BF/BOF process of steelmaking at Tata IJmuiden.

Refineries

- Shell Pernis Refinery (Royal Dutch Shell)
- Botlek (ExxonMobil) Rotterdam
- BP Rotterdam Refinery (BP)
- Gunvor Refinery Europoort (Gunvor)
- Koch HC Partnership Refinery (Koch Industries)
- Zeeland Refinery (Total/Lukoil)

With 6 refineries with a joint refining capacity of 1320 x 10^3 barrels/day, the Netherland harbours almost 10% of the European Union refining capacity

Energy intensive processes in the Netherlands
Key petrochemical processes

Base chemicals

Production of base chemicals methanol and ammonia uses hydrogen as a feedstock. Steam methane reforming of natural gas is used in the Netherlands for hydrogen production. CO_2 emissions of the production process are almost fully linked to the hydrogen production process. In the case of ammonia production for urea manufacturing, CO_2 is partially captured and used in the urea process.

In the steam reformer natural gas reacts to hydrogen at a temperature of approximately 900 °C in the catalyst bed corresponding to heat supply at 1100 °C. Further more heat is used at low(er) temperatures for steam production and CO_2 removal.

Naphtha cracking

The naphtha-fed steam cracker is the link between the refinery and the chemical industry with ethylene and propylene as major products. Typical for the cracking process are the high temperature (800 °C process temperature) and the low selectivity of the process, leading to a range of products besides the desired main products, including, hydrogen, methane and higher hydrocarbons. As a result the energy use of the cracker process is determined by a series of highly energy intensive separation processes.

The current process industry: Key messages

A relatively small number of processes, including steel production, methane reforming (ammonia, methanol) and naphtha cracking have a large impact on CO_2 emissions and energy consumption. The roadmap should at minimum offer robust options to reduce CO_2 emissions and energy use in these areas. Energy use is largely in the form of high temperature heat.

Low temperature processes (<200 °C) are found in the chemical industry, but also a large number of processes in the food and beverages and in the paper industry. Although the number of different types of processes in these sectors is very large, the energy technology to deliver heat in the form of heat and/or steam using boilers and CHP systems is largely generic.

THE PROCESS INDUSTRY IN 2050 ?

Source: Veolia

Key changes in the Process Industry by 2050

Many studies have been carried out to assess how deep decarbonisation of the Dutch industry can be achieved. For example a very recent study [McKinsey, 2017] assessed the cost to reduce CO_2 emissions from industry by 60% in 2040 and by 80 to 95% by 2050. They identified 6 major changes required to achieve these goals:

- Efficiency improvement
- Electrification
- Change of feedstock
- Increasing reuse, remanufacturing or recycling
- Change in the steel production process
- Carbon capture and storage or usage (CCS/CCU)

Another very thorough study by PBL/ECN [Ros, 2017] demonstrated that for a national 80/95% goal the industry will probably have to reduce its emissions more than average by 2050.

Key message for the evaluation of electrification technologies for the longer term is not only what the energy savings and/or business case is for the near future, but also in a changed energy system. Therefore we consider how the (industrial) energy system could change.

Key changes in the **Petro-chemical** industry 2050

Current energy use	Key challenges for the petrochemical industry	Impact on the energy functions in 2050
In chemical industry most energy-intensive conversion processes are cracking and making base chemicals (MeOH, NH_3, H_2) for further use in building complex molecules. Large fraction of energy use for separation due to unselective processes (oxidations, cracking, etc)	Replacing fossil heat by renewable heat Carbon reuse / CCU fuels and hydrogen Circularity: closing the loop, e.g. for solvents, activators (catalyst, chlorine, etc) and water. Bio-based materials providing carbon	Increased energy demand (electricity) for CO_2 based fuels Heat for distillation and drying largely replaced by renewable heat (heat pumps, RE). Increasing separation processes for circular economy.

Key changes in the **Food** & **Paper** industry in 2050

Current energy use	Key changes in the food and paper Industry	Impact on the energy functions in 2050
Most energy required for separation, in particular drying and hot water. Feedstock biomaterial is (currently) not considered in the energy balance	Biorefinery concepts, using the whole plant are expected to create valuable product streams in addition to the primary product Circularity, including recycling essential elements back to farmland and recovery of valuable products from waste stream will become standard practice Drastic reduction of water use paper industry	Links/overlap with other clusters including chemicals and transportation Increased need for separation, including recovery of low-concentration compounds to close cycles, often from dilute streams

Key changes in the **Steel** & **Cement** industry in 2050

Current energy use	Key changes in the steel and cement Industry	Impact on the energy functions in 2050
Mainly very high temperature heat (>1000 °C) Linked to very large process related CO_2 emissions (cokes, fuel for cement furnace)	New process such as direct reduction of steel and different cement chemistries [1] will be used Part of the sector may still be using existing processes, but capture and reuse [2] of CO_2 is necessary to avoid CO_2 emission cost.	High energy use for transformation processes expected to remain important. Reuse of CO_2 requires efficient separation from flue gas or other process flows .

[1] *The cement sector is not directly relevant for the Netherlands as the last cement furnace is expected to close in 2019*

[2] *CO_2 is (re-)utilized where use of carbon is unavoidable, such as aviation fuel and polymers*

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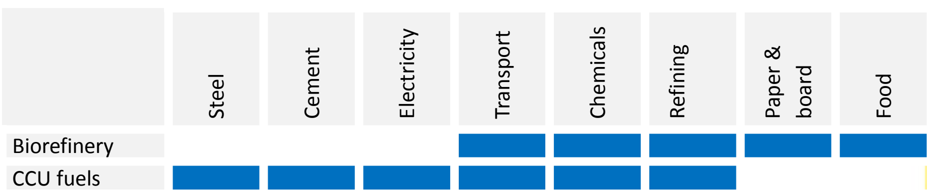
Key changes for the Process Industry **towards 2050**

Process industry In **2050**

Key transitions in the process industry:

- Process heat is produced largely renewably, using electricity, renewable hydrogen, biomass waste streams and geothermal energy.
- Increased energy demand for separations due to circular economy & re-use of CO_2
- High energy-intensity needed for activation remains in different sectors (e.g. steel, fuel)
- Biorefinery and carbon capture and re-use require novel technical solutions and business models across the current sectoral boundaries.
- Heat demand and waste heat availability of the Dutch industry changes as current high-temperature processes have been replaced

Cross sector themes emerging



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Key changes for the Process Industry towards 2050

Because the process industry in 2050 is a completely different industry from today, technology should be developed which can reduce emissions today, but also in a future industry.
Even more important is to avoid **Lock-in** by implementing technology on the shorter term which creates barriers for further innovation

Potential **lock-in** effects:

- Investments in infrastructure and downstream processing which depend on (waste) flows from processes (heat, CO_2) hinder investments in innovation of the core process
- Replacing (partially) current high temperature activation processes by more efficient processes or renewable based processes will change the demand for high temperature heat and the temperature at which waste heat becomes available strongly.
- Decline in refinery capacity, expected to impact Europe already on the short to middle term [CIEP, 2016] will have an impact on availability of feedstock for the chemical industry, waste gases for combustion, and availability of CO_2.
- Concentrated CO_2 emissions, viewed currently as a source for carbon for production of fuels and materials, will not be available for re-use if more efficient process for steel making will be applied and hydrogen production is largely based on electrolysis

Long-Term prospects for Northwest European refining, van den Bergh etal. CIEP, 2016

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SELECTING TECHNOLOGIES

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Technology options for electrification (criteria)

What technology options are available which use electricity instead of fossil fuels to fill in the energy demand in the process industry?
Criteria to determine if a technology is suitable:

- **Impact**: Potential to reduce CO_2 emissions by renewable energy (electricity)
- **Efficiency**: does it save primary energy?
- **Balancing**: can it be used cost-effectively as a flexible process operating when electricity prices are low?
- **Full load**: can it be operated continuously economically
- **TRL** (technology readiness level): What is the technology maturity

Currently most processes are thermally driven. Electrification can follow two different tracks.
The **heat demand** can be fulfilled using electricity or the function (activation, separation) can be carried out directly using **electricity as driving force**.

Heat demand:
- High temperature heat (>200 °C)
- Medium temperature heat (120 – 200 °C)
- Low temperature heat (<120 °C)

Processes using electricity as driving force.
- Activation
- Separation
- Sterilisation and pasteurisation
- Etc.

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Technology options for electrification (criteria)

Efficiency:

In the current energy system, electricity is still **largely based on fossil energy**. Technologies which replace fossil fuels with low efficiency lead to an increase of primary fossil fuel and higher CO_2 emissions in continuously operated processes.

Whether a technology saves CO_2 depends on:

- The CO_2 footprint of the current process
- The efficiency or coefficient of performance (output/kWh) of the electrified process
- The energy mix used to generate electricity

Technologies which are currently not attractive as a continuous options because of a lower efficiency, may become attractive on the longer term, as the fraction of renewable electricity in the mix increases. Other options are already effective to reduce CO_2 emissions with the current mix.

There is an order of merit for technologies with respect to the CO_2 footprint of the electricity they require to reduce CO_2 emissions compared to the current technology. Technologies which reduce CO_2 in continuous operation (even) with a "grey" electricity mix (e.g. heat pumps) are candidates for early implementation.

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Technology options for electrification (criteria)

The order of merit is valid for technologies which are operated continuously. Technologies and processes which can be operated discontinuously using excess (renewable) electricity will have merit even if the overall energy mix is grey

Technology Flexibility:

Technologies which have a higher CAPEX than the technology they replace are generally not economic when operated only when electricity prices are (substantially) below average cost.

Process Flexibility:

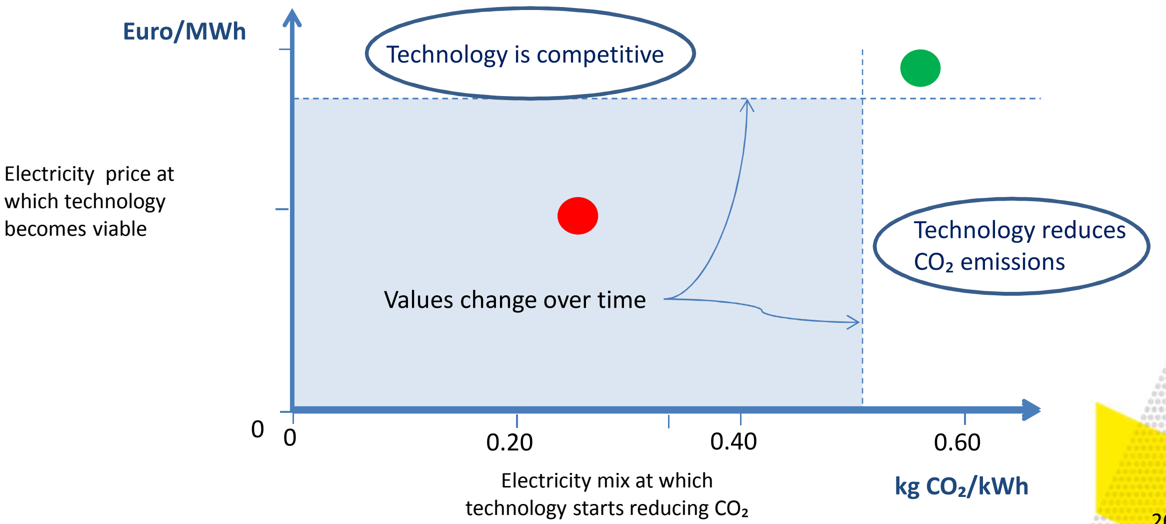
In addition a condition for flexibility is that the process in which it is used can be operated in a discontinuous manner or that storage or hybrid solutions can be found to allow the process to operate continuously.

Storage or hybrid solution

If the process cannot be made continuous it may be possible to decouple the process and energy supply by using storage (e.g. heat, hydrogen, liquid product).

These criteria determine whether the option can be used intermittently in an economic way

A framework for ranking options on impact



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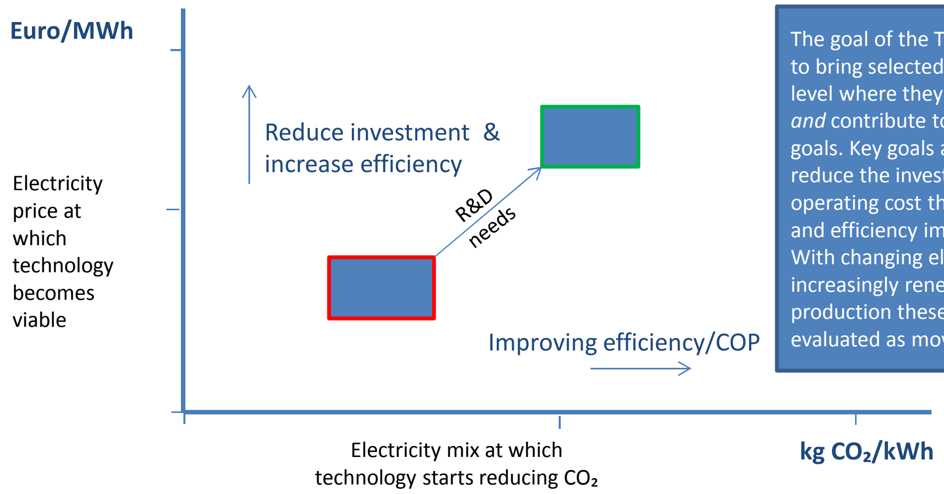
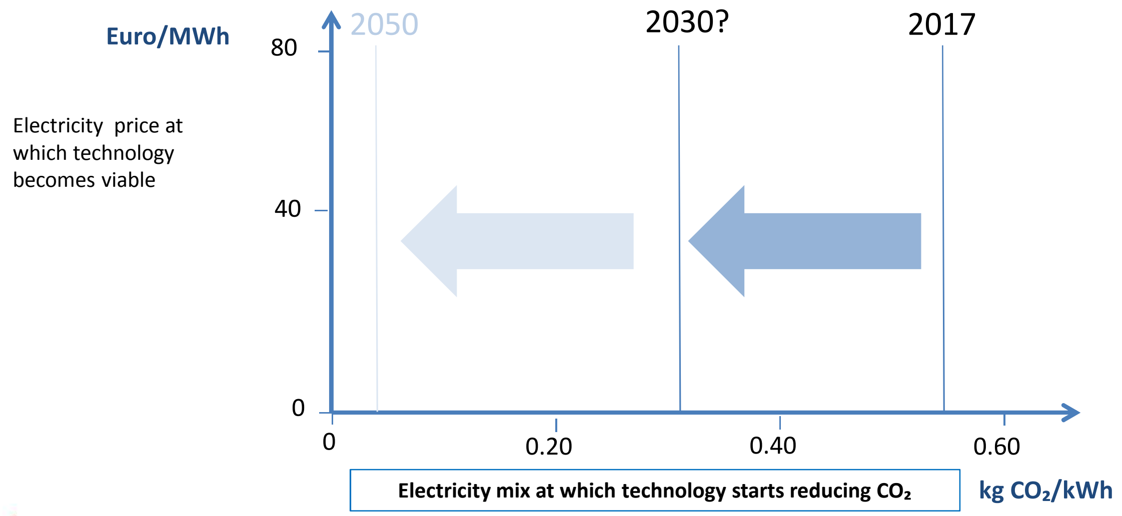
Framework for ranking options on impact



The goal of the TKI is support R&DD to bring selected technologies to the level where they are both economic *and* contribute to CO_2 reduction goals. Key goals are therefore to reduce the investment cost and operating cost through cost reduction and efficiency improvements.
With changing electricity prices and increasingly renewable electricity production these goals should be evaluated as moving targets

Framework for ranking options on impact



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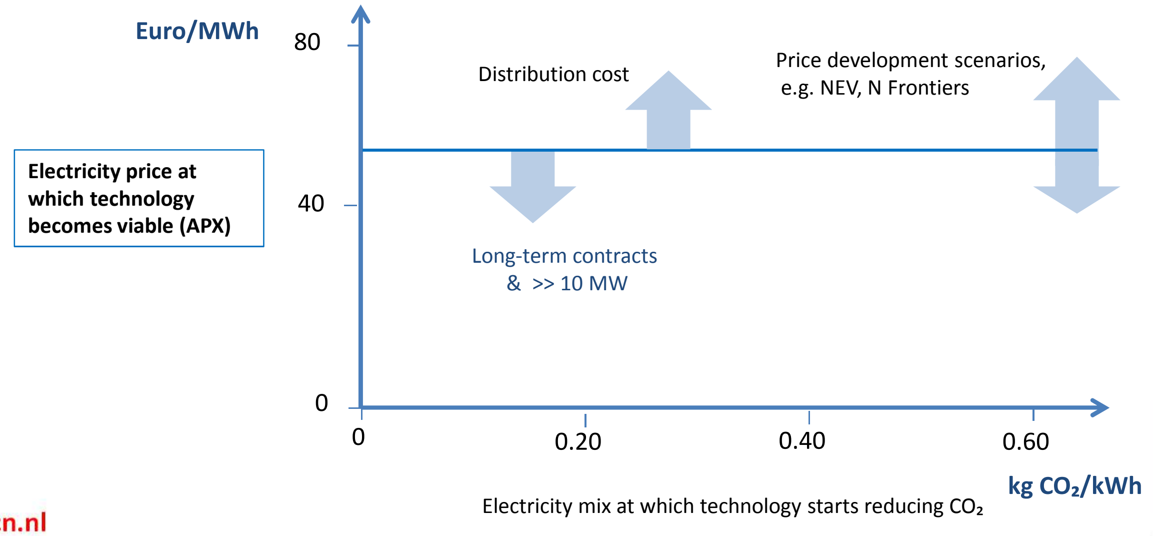
Framework for ranking options on impact



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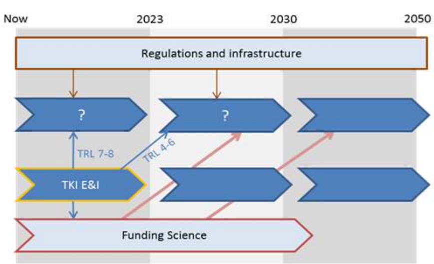
Framework for ranking options on impact

Goals and targets for RD&D depend on the implementation timeframe. This determines whether the technology should be competitive / reduce emissions assuming current or future conditions. A framework for analysis depending on the time to implementation is needed



Now - 2023

- No R&D but implementation -> DEI
- R&D based on targets based on CO_2 reduction and business case with current mix and electricity prices
- Impact (ton CO_2) and identify potential lock-in effect

2023-2030

- R&D based on targets which will realize CO_2 reduction against 2030 mix and business case against process
- Define needs/limitation in infrastructure
- Define competition (e.g. for energy carriers)

Beyond 2030 -> define conditions under which the technology will contribute to further CO_2 reduction taking into account earlier technologies have been implemented.

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TECHNOLOGY OPTIONS

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Overview of electrification options

Electric heating	Group of technologies which convert electricity into different forms of heat, including infrared, microwave, induction heating.
Heat pumps	Deliver heat to the (existing) process using thermodynamic cycle, characterized by a coefficient of performance (COP) > 1.
Electrochemical H_2 as feedstock	Processes using electrolytic hydrogen to activate a reaction, for example chemical processes such as methanol and ammonia production and direct reduction of iron ore using hydrogen.
Electrically driven separation	Using electricity directly (e.g. capacitive deionization, electro-dialysis) or by providing mechanical force (reverse osmosis, pressure driven membrane processes, pressing) .
Electric activation (direct)	Technologies which use electrical energy directly to drive a reaction, including electrochemical processes
Other functions	Other processes where electricity is used directly as a driving force to fulfill a function currently performed by high temperature, e.g. UV sterilization

To create insight into the potential of different electrifications options, we have grouped them into categories of technologies which have similar application characteristics

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Electrification options: **Electrical heating**

Opportunities and limitations	The coefficient-of-performance (COP) of electrical heating is smaller than unity (1 kJ of heat per kJ of electricity). Taking into account conversion efficiencies for the production of electricity, 1 kJ of heat from electricity requires considerably more primary energy than 1 kJ of heat directly from fossil fuel. For both fossil-based and heat pump technology, efficiency of heat generation depends on the temperature of the heat. High temperature heat requires more effort (heat losses and recovery, investments) to generate. For low and medium temperature heat, a boiler and/or heat pump are more efficient than electrical heating. Application of electric heating can nonetheless have a positive business case in a number of cases: • Heating technologies with relatively low CAPEX, such as resistance and electric arc heating, can be operated flexibly to utilize periodic low electricity prices. • Using highly targeted heat input, the efficiency of processes can be improved by achieving the same effect with less heat input • Heating can be effective for high temperatures (e.g. > 800 °C) because of the cost and losses in the conventional process (furnace).

Electrification options: Electrical heating

Technology overview (1)	Systems with wide application for production hot water and/or steam using electricity • Electric boiler or electrode boiler • Hybrid gas fired/electrode boiler A large number of processes uses conventional electrical heating principles. • Resistance heating (direct/indirect) • Arc heating (direct, indirect, plasma) These technologies are used for example in furnaces in the production of ceramics, metals, etc. These electrification technologies are characterized by: • **Low cost** • **Rapid response** • **Maturity: commercial technologies**

Electrification options: Electrical heating

Technology overview (2)	In addition a large number of advanced technologies are used • Radiant (IR, UV) typically heats the surface of an object. • Induction heating uses electromagnetic waves to create eddies which enables a uniform heating of an object • Electron beam • Dielectric (microwave, radiofrequency) systems can create a high (MW) to very high (radiofrequency) heat input (energy/area) Typically these technologies are used in specific (niche) application. For application in the energy-intensive industry the technology needs to be developed. Compared to conventional technologies these technologies are characterized by: • **Higher investment cost** • **Potential to improve the process by precise (location, timing) heating** • **Need for R&D to bring the technology to maturity (TRL 3-5)**

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Electrification options: Electrical heating

Research, development & demonstration agenda	Accelerating implementation: • Demonstration of hybrid systems, e.g. for hot water or steam production Key R&D needs • Development of hybrid systems and or electricity driven high temperature activation processes (such as reforming, cracking) • Developing advanced high temperature intensified technologies for high selectivity for high temperature activation processes • Development of heat storage suited for industrial scale heat storage (> 100 °C)
Potential lock-in and uncertainties	• Uncertainty over electricity price development, both load curve and long-term electricity/ natural gas price ratio. • Lock-in: CO_2 emission reduction is limited (if positive at all), but investments may block more sustainable solutions such as heat pump because of its impact on electricity pricing and stranded investments

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Electrification options: **Heat pumps**

Opportunities and limitations	Application of heat pumps in industrial processes in general requires a much higher temperature lift than heat pumps used in space heating. As the temperature lift becomes higher, the coefficient-of-performance (COP) decreases. Heat pumps are therefore used most efficiently if useful heat is produced from waste heat at an appropriate temperature level. There are different types of heat pumps using a number of principles. An important characterisation of a heat pump is the temperature at which the heat is rejected and the temperature lift. There is no general classification • Low temperature heat pumps (<100 °C) producing hot water / space heating • Medium temperature heat pumps (100 - 200 °C) • High temperature heat pumps (>200 °C) Heat pumps are generally suited for a specific temperature range. For example compression heat pump has a large application potential for low to medium, but will not address high temperature applications.

Electrification options: Heat pumps

Technology overview (1)	Heat pumps can be stand-alone, delivering heat to a process, but also process integrated. Examples of process integrated heat pump technology includes vapour recompression (VRC) and the heat-integrated distillation column (HIDiC). Steam recompression can also be used in a process as a heat pump. Compression heat pumps are commercially available, although the business case for application in an industrial environment requires further cost reduction to reach acceptable pay-back times. Application is limited to the medium temperature range both due the availability of compressor and suitable media. Other heat pump types are able to reach much higher temperatures. However, these heat pumps are not commercially available and RD&D effort is needed for their implementation. Types of heat pumps with potential as high temperature heat pumps: • Thermo-acoustic (TA) heat pump • Stirling heat pump • Brayton heat pump • Adsorption/resorption heat pump

Electrification options: Heat pumps

Technology overview (2)	Process integrated heat pumps include: • Steam recompression / Vapour recompression • Vapour recompression distillation column (VRC) • Heat integrated distillation (HIDiC) The last two options are specifically integrated with distillations. Steam recompression or more general vapour recompression can be used in any process where it is useful to increase the temperature level of the condensation heat .

Electrification options: Heat pumps

Research, development & demonstration agenda	**Accelerating implementation:** • Implement existing heat pump technology for **low-temperature** applications in all sectors (mainly for hot water production). • Carry out demonstrations for **medium temperature** industrial heat pumps **Key R&D needs** • Reducing investment cost by technology development and standardisation. Development target is 200 €/kW. • Development of high temperature heat pumps (>200 °C) • Develop robust methods for heat recovery from “difficult” process flows including solids-containing and corrosive flows.
Potential lock-in and uncertainties	• Uncertainty is waste heat availability for medium and for high temperature heat pumps • Potential lock-in can occur if more efficient processes become available but waste heat from the existing process is used

Electrification options: Electrolytic H_2 as feedstock

Opportunities and limitations (1)	**(Near) Commercially available electrolysers** To convert electric energy into chemical energy, hydrogen production through water electrolysis is the most direct process. Low-temperature electrolysis (Alkaline, PEM) is available as a (near-) commercial technology, but economic only for small-scale applications. For large-scale application (e.g. replacing steam methane reforming) a considerable decrease in cost of hydrogen is necessary. Cost of hydrogen from electrolysis for continuous production is determined by both the cost of electricity (OPEX) and the investment cost (CAPEX). For continuous operation the cost of hydrogen is mainly determined by the cost of electricity. For flexible operation the CAPEX becomes the limiting factor. A strong trade-off exists between the two: a system can be optimized towards lower capex or high efficiency. R&DD targets both reduction of the investment cost as well as increase in efficiency while achieving a required lifetime. Further development of both alkaline and PEM electrolysers is strongly supported in H2020 by the PPP on hydrogen technology (FCH-JU)

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Electrification options: Electrolytic H_2 as feedstock

Opportunities and limitations (2)	**Other electrolysers types** Several other types of electrolysers are being developed but are currently at a lower TRL level. High temperature electrolysis or solid oxide (SOE) promises higher efficiencies and thus lower OPEX. Typically the SOE will be process integrated, enabling the use of heat and oxygen produced in the downstream conversion process such as steel making or base chemicals manufacturing. The technology is however at a lower TRL level Anion exchange membrane (AEM) electrolysis and the battolyser offer perspective of a much lower CAPEX, but are also at a very early stage of development **Use of electrolytic hydrogen** Hydrogen is already widely used as a reactant in the chemical industry and food industry. Processes to produce a wide variety of chemicals using hydrogen are commercially available. Production of methanol and ammonia are two major hydrogen using processes. Use of hydrogen to reduce iron ore is very attractive from an energetic and carbon footprint point of view.

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Electrification options: Electrolytic H_2 as feedstock

Technology overview	**Production of hydrogen using electrolysis**	
	• Alkaline water electrolysis • PEM water electrolysis	Commercially available, rapid response possible, but investment cost currently prohibitive for operation during periods of low-electricity prices only
	• Solid Oxide water electrolysis	High efficiency (low OPEX) option for large-scale continuous operation e.g. in steel production or base chemical production.
	• Anion exchange membrane water electrolysis • Battolyser	Prospective technologies for low CAPEX, currently at low TRL level (3-4)

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Electrification options: Electrolytic H_2 as feedstock

Technology overview

There are many state-of-the-art **processes using hydrogen**:

- Base chemicals and fuels (MeOH, NH3)
- Fischer-Tropsch synthesis
- Desulphurisation and hydrogenation processes in refining.

These processes are generally carried out at very large scale (> 100 MW of thermal energy input), partly because the fossil-based hydrogen production process has a very strong economy-of-scale. In addition, because much waste heat is produced in the fossil-based hydrogen production, as a rule there is a strong degree of integration between hydrogen production and the downstream process. Smaller scale processes, not relying on heat integration with hydrogen production, could however be required if hydrogen is produced by electrolysis.

In addition **future processes** with a much lower CO_2 intensity to produce steel and chemicals are foreseen using hydrogen in for example:

- Production of base chemicals from H_2 and CO_2 (CCU)
- Direct reduction of iron ore with hydrogen to produce iron
- Top-recycling of CO from hydrogen and CO_2 to the blast furnace in steel manufacturing.

Therefore, although there are many processes currently using hydrogen, there is much RD&D effort required to create future hydrogen-using processes fitting in a low CO_2 emitting industry.

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Electrification options: Electrolytic H_2 as feedstock

Research, development and demonstration agenda	**Implementation** • Development of demonstration of electrolysis to assess actual capabilities and cost of electrolyser systems integrated in industrial processes **Key R&D needs** • Reducing investment cost for low temperature electrolysis. Target is 300 €/kW @ 75% efficiency (2-2.5 €/kg H_2) with "industrial" durability (e.g. 100 000 hours or business case based on cell replacement) [FCH-JU, 2015] • Develop efficient processes schemes and technologies for re-use of CO_2 using green hydrogen • Develop break-through technologies for production of base chemicals such as MeOH and NH_3 having high efficiency and increased flexibility at a smaller scale.
Barriers and potential breakthroughs	Potential lock-in for CCU: availability of CO_2 on the longer term from existing industrial plants, for example by replacement of CO_2 intensive processes such as hydrogen production and blast furnaces by other processes.

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Electrification options: Electrically driven separation

Opportunities and limitations (1)	**Electrically driven separation (EDS) technology today** Electrical driven technologies focus mainly on separation of low-concentration components from liquid flows using **non-thermal** methods. The most energy-intensive separation processes are currently carried out mainly by distillation. Major energy-intensive separation are found in bulk processes with low selectivity, such as the cracker downstream and large-scale oxidation processes. EDS technologies are not expected to displace a substantial part of current (large) distillation columns. Electrically driven separations today do not have a large impact on the CO_2 emissions and energy use of the industry. Generally application is limited to selected applications such as recovery of specific metals, removal of low concentrations of salts from aqueous flows etc. **Future needs** However, a process industry based on bio-refinery and circularity has a need for efficient technology to recover low concentrations compounds from liquid streams.

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Electrification options: Electrically driven separation

Opportunities and limitations (2)	Two specific future expected developments leading to a demand for electrically driven separation technology • **Circularity:** increasingly valuable components which are currently discharged need to be brought back into the process. For high concentrations of recoverable components conventional technologies are available or novel technology is being developed. However for bulk process flows containing low concentrations of recoverable components require more selective technologies • **Biorefinery:** Economics of non-thermal routes (such as gasification) rely on recovery of a wide range of components. In particular biochemical routes create dilute flows. Efficient and selective processes for recovery of value components are essential to avoid high CO_2 emissions from the recovery processes.

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Electrification options: Electrically driven separation

Technology overview	There are many technologies relying on electrical fields or currents to achieve separation • Dialysis • Electro-refining / Electro-winning / Electro-plating • Capacitive deionisation • Pressure driven filtration / molecular separation In many cases technology is available commercially but the application is **limited to very specific markets**. For these technologies to play a role in energy-intensive processes in the current and future industry, it is necessary to develop novel applications. In many cases this includes technological development to improve efficiency and effectivity, reduce cost, etc. In addition there are also technologies at lower TRL, including electrostatic techniques, electro crystallisation and others, which have the potential to offer effective solutions.
Research, development and demonstration agenda	Research and development is needed to extend application of existing technologies (such as the above) to applications which have a considerable impact on the current energy use and CO_2 emissions or have the potential to avoid future CO_2 emissions. This requires application oriented R&D at TRL level 4-6. In addition more fundament research (TRL 3-4) is necessary to assess the potential of novel EDS approaches

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Electrification options: **Electrical activation (direct)**

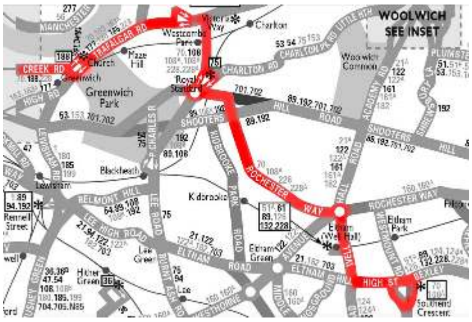
Opportunities and limitations	Several electrochemical processes are used in the chemical industry today. The chlor-alkali technology is the most used process. In principle a much large number of thermodynamically "up-hill" reactions can be carried out using electricity as driving force. A large number of reactions has been investigated on lab-scale. However, this research is generally at low TRL. Key parameters which determine the competiveness of an electrochemical technology include current density and required potential for the design of the electrochemical process, while the conversion and selectivity have a large impact on the process design. In many of the work done on lab-scale, product concentrations and current densities are still orders of magnitude lower than required for commercial applications. In addition to electrochemical processes, much research has been done on other activation principles such as the use for plasma. For application in the energy-intensive industry these technologies are still at an early stage of development. Outside of the chemical industry, electrochemical processes to produce iron (electrochemical reduction of iron oxides) is possible. This technology is however still at a very low TRL.

Electrification options: Electrical activation (direct)

Technology overview	There are many different approaches to be found, these include: • Direct conversion of CO_2 by electrochemical reduction (e.g. to formic acid, CO, ethane) • Electrochemical reactors (Electrochemical conversion of X to Y) • Electrochemical reduction of iron • Direct electrochemical ammonia production • Plasma chemistry At the current level of development, which requires break-through's in selectivity and energy intensity, it is not yet possible to distinguish which approaches will lead to viable mature processes
Research, development and demonstration agenda	**Key R&D needs** • Development of direct electrochemical process for industrially relevant electrochemical reactions with a focus on realistic selectivities and down-stream processing requirements • Development of direct electrochemical process reduction of CO_2 to potential platform chemicals (MeOH, formic acid, CO) with a focus on realistic selectivities and down-stream processing requirements • Break-through technologies for direct electrochemical conversions, such as direct ammonia production, electrochemical reduction of iron, etc.

The roadmap

- How to get there



The roadmap in the following sheets defines steps to realize the desired CO_2 reduction in the Dutch process industry through electrification.
It is a first concept which needs further refining and consultation. Nonetheless, it defines the structure of the final roadmap based on the technology families and the relevant time frames (short, mid and long term). It defines:

- Expected market development (Application)
- Required support from the government (Support)
- Ambition for each of the technology families (Goals and Targets)

Roadmap: application

	2017-2023	2023-2030	2030-2050
Electric heating	Hybrid systems for heating implemented	Slow growth, increasing competition from heat pumps (COP)	Niche markets, other markets covered by heat pumps
	High temperature heating in research phase	First applications of high temperature heating developing	Key processes (e.g. cracking) electrified
Heat pumps	Heat pumps for low and medium temperature moving from demo to commercial	Steady growth in number of applications	Fully developed market
Electrochemical H2 as feedstock	Business cases electrolysis move from niche to commercial in limited markets	Steady growth due to developing links with other sectors (energy, transport)	H_2 from electrolysis competitive with SMR
Electrically driven separation	Novel markets for existing technologies (MCDI, dialysis, etc.) explored	Applications growing from niche to commercial applications, a.o. in biobased systems	Expanding impact due to growth bio-based fuels and products
Electric activation (direct)	Proof-of-principle demonstrated for selected chemicals (e.g. FA), fundamental for bulk chemicals	Commercialisation in smaller markets	Commercial application in CO_2 re-use and specific reactions

Roadmap: goals and targets

	2017-2023	2023-2030	2030-2050
Electric heating	Demo's and first systems with cumulative installed capacity > 10 MW (2020)		-
	Technology needs identified for 2030 business cases	Implementation of at leas 1 large scale application (>50 MW)	Commercial deployment
Heat pumps	200 €/kW compression heat pump commercially available (2023)	HT heat pump demo 5 MW (2030) Pilot advanced process integrated HP (VRC, HIDiC) for medium-scale distillation process (2025)	Commercial deployment
Electrochemical H2 as feedstock	Demonstration of large-scale electrolysis (>10 MW) for industrial application (2020) Achieve 500 €/kWe cost target for low temperature electrolysis (2023)		Commercial deployment
Electrically driven separation	Development of at least one robust, efficient EDS technology to remove salt/organic from industrial wastewater (2020)	Large-scale demo's for novel technologies recovery of valuable components	Commercial deployment
Electric activation (direct)	Selective CO_2 reduction to target (bulk-chemical) molecule on lab-scale at current density > 100 mA/cm²	3 showcases highly selective electrochemical reactions (@TRL7), Demonstrate CO_2 reuse at 10% of commercial scale	

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Roadmap: support

	2017-2023	2023-2030	2030-2050
Electric heating	Development and Demo for hybrid systems	Generic instruments	
	Feasibility and R&D	RD&D	Generic instruments
Heat pumps	Development and demo for L&MT, R&D for HT	Development and demo for HT	Generic instruments
Electrochemical H2 as feedstock	RD&D	Infrastructure development (demo, generic)	
Electrically driven separation	Feasibility, development, future markets	RD&D	Generic
Electric activation	R&D	Demo	Generic, RD&D base chemicals

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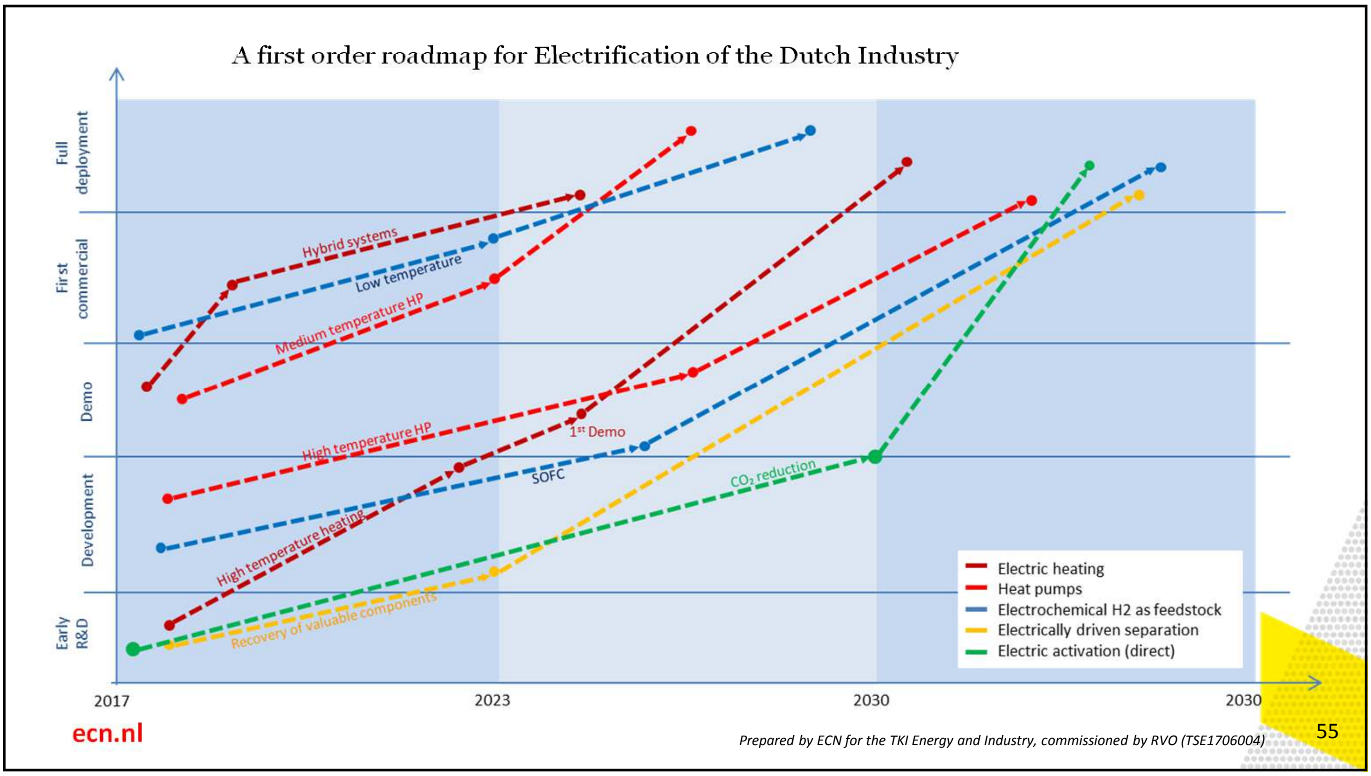

A first order roadmap for Electrification of the Dutch Industry
Full deployment
First commercial
Demo
Development
Early R&D
Hybrid systems
Low temperature
Medium temperature HP
High temperature HP
1st Demo
SOFC
High temperature heating
CO2 reduction
Recovery of valuable components
Electric heating
Heat pumps
Electrochemical H2 as feedstock
Electrically driven separation
Electric activation (direct)
2017
2023
2030
2030
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