

TNO 2025 R11348

Comparison of future cost of renewable energy between regions

Energy for industrial processes: chlor-alkali and syncrude production

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2 July 2025

Final version



Competitiveness of energy-intensive industries

In 2023, the Dutch government launched the National Program for Industry Sustainability (NPVI) to accelerate the transition towards a sustainable industrial sector. Amid growing concerns about the competitiveness of the energy-intensive industry in The Netherlands, the NPVI has identified a need to explore how sustainable energy solutions can enhance industrial competitiveness.

Recognizing that competitiveness has multiple dimensions, the NPVI has engaged various stakeholders to provide insights from their areas of expertise on the long-term competitive position of energy-intensive industries. This collaborative effort involves contributions from Roland Berger (RB), The Hague Centre for Strategic Studies (HCSS) and TNO, under the supervision of a NPVI advisory board. RB and HCSS report their results separately. This **TNO technical report** addresses the techno-economic perspective of current and future renewable energy production cost for two different product chains, chlor-alkali and syncrude production, and two geographical regions, i.e. The Netherlands and Saudi Arabia.

Acknowledgement

The study described in this report is funded by program funding provided by the Ministry of Climate Policy and Green Growth.

The principal authors of this report are Alejandro Martin Gil, Arie Kalkman, Javier Fatou Gomez, Leonard Eblé, and Remko Detz from the TNO unit Energy and Materials Transition. The report greatly benefitted from review contributions from TNO colleagues Christiaan van den Berg, Iratxe Gonzalez Aparicio, Martijn de Graaff, Martin Scheepers, and Marcel Weeda.

Further useful feedback to improve the quality of the report has been received from Roland Berger and the NPVI advisory board.

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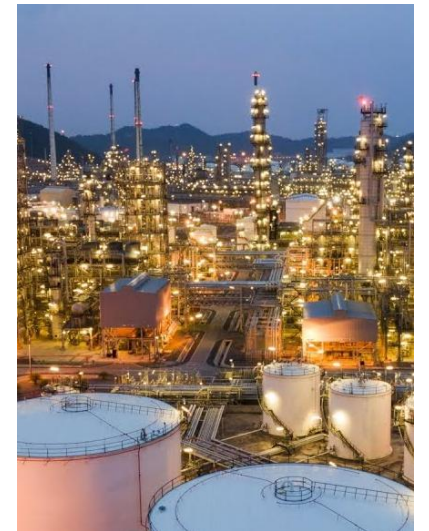
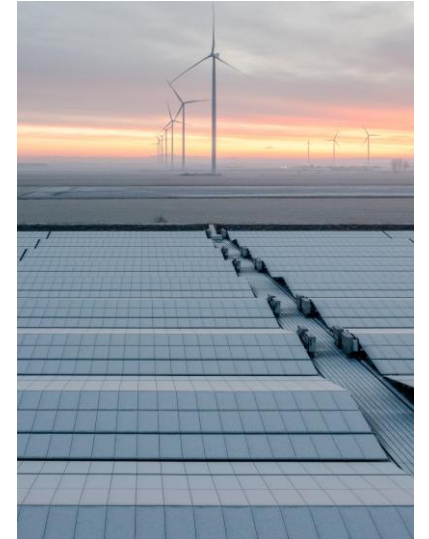
Renewable energy for industrial processes

Energy costs play an increasingly important role in the competitiveness of the energy-intensive industry. In recent years, costs of energy, such as electricity and natural gas, are relatively high in The Netherlands compared to other regions in the world. These costs largely depend on fossil fuel prices, but this dependence may change in the future when renewable electricity supply increases, which has triggered the **main research question** addressed in this report:

How may the competitiveness of the energy-intensive industry change in a future where they no longer rely on fossil fuels but harvest all the energy needed from sustainable sources?

To address this research question, **an artificial situation** is considered where a mix of sustainable sources supplies renewable electricity to a specific energy-intensive industrial process, supported by as much storage as is necessary to fulfil the energy demand of the process. The entire value chain from sustainable energy generation to product is modelled in isolation, thus, without any connections to the outside world. This allows for a clean and fair comparison of the costs of the system but excludes effects from interactions and synergies to other processes outside of the system boundaries. For this **island system model**, the levelised costs for energy provision for the industrial process are optimised to identify the combination of assets and their capacities that result in the lowest cost. The focus lies on comparing the industrial production costs and, more specifically, the contribution of energy costs, while other factors, such as transport costs, are not studied.

Energy-intensive industrial processes can have **different degrees of flexibility in operation and energy requirements**. This level of flexibility and the type of energy required will likely affect the outcome of the cost optimisation in that different assets and capacities are required to provide the energy for a specific process. In this study, two different industrial processes are addressed, chlor-alkali and syncrude production. The chlor-alkali product chain studied has a significant degree of flexibility and only requires electricity as energy, as compared to the syncrude (a precursor for fuels and chemicals) process chain which operates at baseload conditions and uses both electricity and hydrogen as energy. This gives a first impression of how the flexibility and energy requirements of industrial processes affect their respective energy cost.



Comparison of costs between regions and years

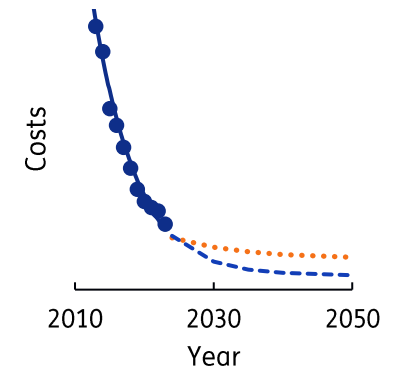
In the island model, renewable electricity can be generated by onshore and offshore wind and solar PV plants. As the availability of wind and solar energy is location dependent, **different geographical locations** will likely lead to different costs of energy. In this study, the energy cost in The Netherlands (NL), with a large potential for offshore wind energy, are compared to a geographical location with abundant solar energy and less wind, in this case Saudi Arabia (SA). This gives a first impression of how the geographical location affects the energy costs for industrial processes.

The data that is used to describe the different assets in the model largely determines the results. **Performance and cost data** of the different assets are generally ranging significantly and may proof to be location dependent. For ease of comparison is assumed that no differences in performance and investment costs exist between NL and SA. The only factor that is changed and directly affects the costs are the costs for capital investments, represented by the discount rate, which is lower in NL than in SA. As base value, the global weighted average of total installed costs of solar PV, onshore wind, offshore wind, and stationary battery electric storage is used. Cost reductions for these technologies are projections for 2040 based on extrapolation of their historical **learning curves**. Costs reduce faster when more of the technology is deployed and, thus, more learning happens. The growth scenarios are based on the Stated Policies scenario (STEPS, conservative deployment) and the Net Zero Emissions scenario (NZE, optimistic deployment) from the IEA. Notably, the reported levelised cost of energy are integrated system cost of the island model.

Renewable energy cost in 2024. For both chlor-alkali and syncrude production, costs of renewable energy do not differ substantially between regions in 2024. In NL, offshore wind has the largest share, while in SA, solar energy dominates the energy supply. For chlor-alkali, a relatively flexible process that mainly depends on electricity supply, costs amount to 113 EUR/MWh in NL and 110 EUR/MWh in SA. Syncrude production is not flexible and uses mainly hydrogen as energy supply. This results in costs that are more as twice as high, namely 254 and 291 EUR/MWh for NL and SA, resp.



Learning Curve Solar PV



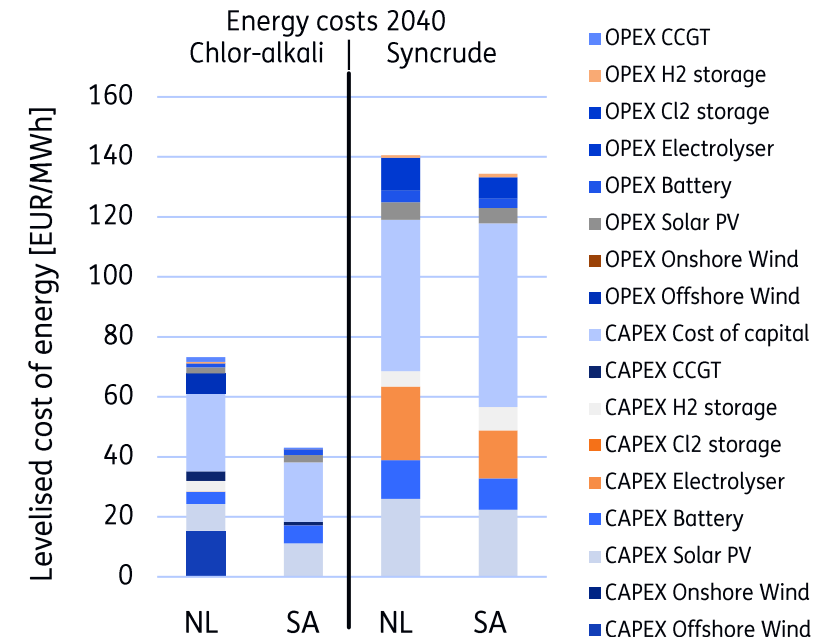
Comparison of renewable energy costs for industry between regions

Renewable energy cost in 2040. Thanks to the technology learning curves, costs towards 2040 reduce for all cases studied. Energy costs for chlor-alkali amount to 73 EUR/MWh for NL and, around 40% lower, 43 EUR/MWh for SA. For syncrude production, the costs for energy are higher but differ only slightly with 141 EUR/MWh for NL and 134 EUR/MWh for SA. As solar PV is expected to decline in costs at a higher rate than wind energy, solar energy becomes more favourable in 2040. In NL, for chlor-alkali production offshore wind is still implemented but for syncrude production solar PV supplies all energy. Implications of spatial constraints or social/political resistance are excluded from the calculations but can affect the allowable installed capacity. Such constraints may lead to higher costs, and it is recommendable to investigate these aspects in more detail.

Production costs. For chlor-alkali, energy costs varied substantially between NL and SA. The relative difference in chlorine production costs is, however, less substantial and costs are roughly 8% lower in SA for the base case. Syncrude production costs are not calculated but rely on several other factors besides energy, such as investment costs and feedstocks.

Impact of value chain flexibility. The results illustrate that the type of value chain and the level of flexible operation has a significant impact on the costs of energy and, also, on the observed difference between regions. The CA chain, with at its core a process that can operate between 40-100% and deploy one-and-a-half-day product storage is more flexible and has significantly lower energy costs than the unflexible syncrude chain.

Other relevant aspects. Other parameters, such as, for instance, different weather profiles or spatial constraints, are not investigated and can have a substantial effect on the outcome. Comparing two different value chains and regions already gives interesting insights but more processes and locations need to be studied to create a more complete picture. It is recommendable to investigate these aspects in more detail.



Cost of renewable energy for industry

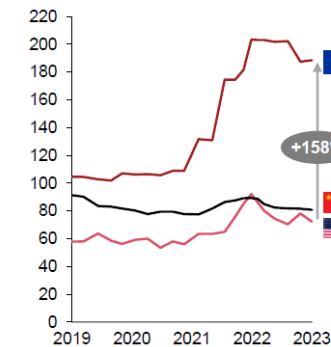
Energy costs play an increasingly important role in the competitiveness of the energy-intensive industry. In recent years, costs of energy, such as electricity and natural gas, are relatively high in The Netherlands compared to other regions in the world. These costs largely depend on fossil fuel prices, but this dependence may change in the future when renewable electricity supply increases, which has triggered the **main research question** addressed in this report:

How may the competitiveness of the energy-intensive industry change in a future where they no longer rely on fossil fuels but harvest all the energy needed from sustainable sources?

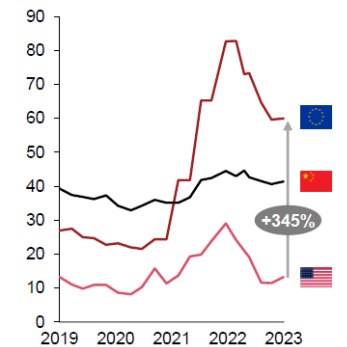
These changes likely differ per region and depend on the type of renewable energy supply (e.g. based on solar and/or wind power), and the kind of energy required by the industry (e.g. electricity and/or hydrogen). A more detailed understanding of the future renewable energy costs and the differences per region may improve strategies and decision making today. To further address this research question, **an artificial situation** is considered where a mix of sustainable sources supplies renewable electricity to a specific energy-intensive industrial process, supported by as much storage as is necessary to fulfil the energy demand of the process. The entire value chain from sustainable energy generation to product is modelled in isolation, thus, without any connections to the outside world. This allows for a clean and fair comparison of the costs of the system but excludes effects from interactions and synergies to other processes outside of the system boundaries. For this **island system model**, the levelised costs for energy provision for the industrial process are optimised to identify the combination of assets and their capacities that result in the lowest cost. The focus lies on comparing the industrial production costs and, more specifically, the contribution of energy costs, while other factors, such as transport costs, are not studied.



Industrial retail power prices
(2019 – 2023, in €/MWh)



Industrial gas prices
(2019 – 2023, in €/MWh)



Strategy&, 2024.

Scope and industrial value chains

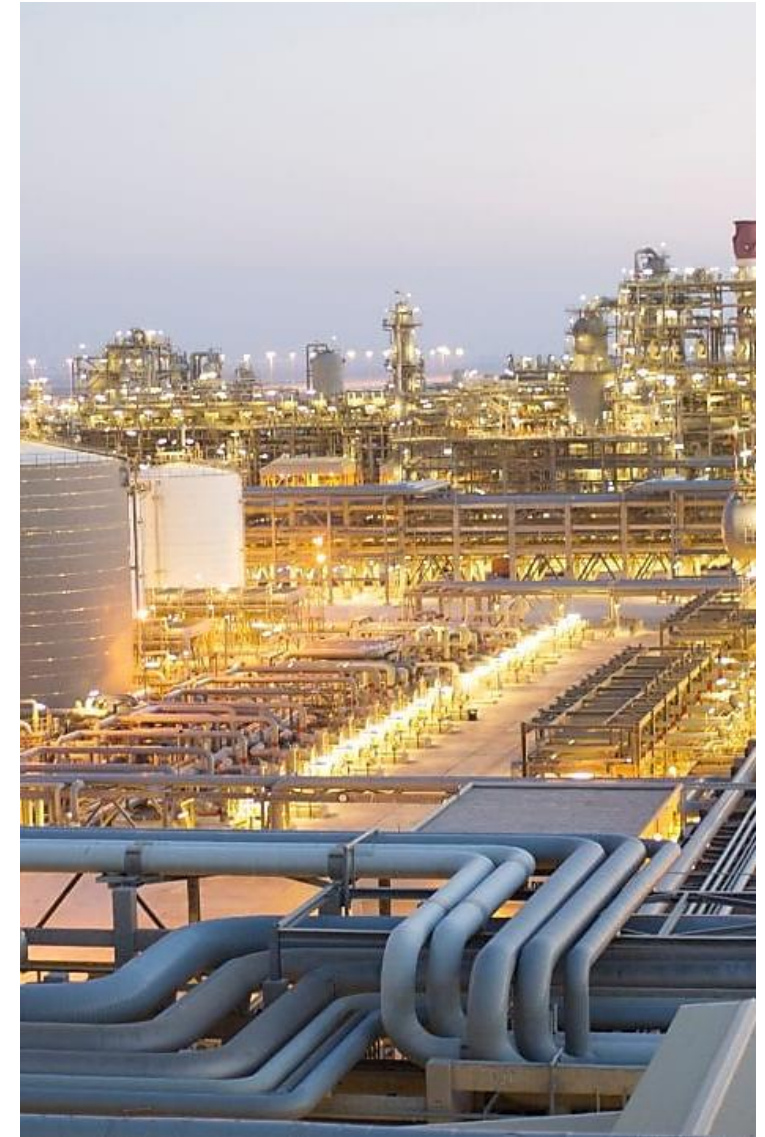
Energy-intensive industrial processes can have **different degrees of flexibility in operation and energy requirements**. This level of flexibility and the type of energy required will likely affect the outcome of the cost optimisation in that different assets and capacities are required to provide the energy for a specific process. In this study, two industrial processes are analysed:

1. Chlor-alkali production
2. Syncrude production via waste gasification and Fischer-Tropsch synthesis.

The chlor-alkali product chain studied has a significant degree of flexibility and only requires electricity as energy, as compared to the syncrude process chain which operates at baseload conditions and uses both electricity and hydrogen as energy. This gives a first impression of how the flexibility and energy requirements of industrial processes affect their respective energy cost.

The energy supply for the two process chains is modelled and optimized for both 2024 and 2040 to determine the **lowest (future) cost of energy** for the production of either chlorine or syncrude (syncrude is an intermediate product that can be converted into fuel or chemicals, e.g. aviation fuel). A key aspect of the analysis is that these energy costs for the industrial processes are compared between two regions: Rotterdam (The Netherlands) and Yanbu (Saudi Arabia).

The defined energy system fully depends on supply of renewable energy from either solar PV and/or wind turbines. Energy storage is afforded through battery electric storage and/or hydrogen storage. The annual production and industrial plant size is kept the same between regions. This results in the same costs for use of feedstocks and fixed operation and maintenance (excl. costs for energy use). Other factors, such as up- and downstream processing and transport costs, also influence the competitiveness of these industrial value chains for supply to the Western European market but these are not studied here.



Data and modelling

To analyse the costs of energy for the two case studies, an energy system model is setup in which the different energy supply options are connected with energy storage technologies and the industrial process itself. The operational and cost data of these technologies and the required infrastructure is collected based on publicly available sources, expert judgement and own analysis. The costs for all assets and infrastructure, which are required to construct the system, are determined for 2024 and projected for 2040 by applying, when possible, technology learning curves.

For both case studies, the costs are determined for both 2024 and 2040 to illustrate the changes that appear in terms of costs and installed capacities. This would imply that such a renewable “island” system can be realised today, which is likely not realistic as, for instance, no hydrogen network including cavern storage exists currently in The Netherlands. Notably, the analysis for 2024 does not indicate the current costs of energy in the specific regions but only the calculated costs for the “island” system based on solely renewable energy sources. The costs and operational parameters of various assets are determined and used in an “island-type” model of an industrial production process. The “island” approach is followed to avoid interaction with costs of systems that are influenced by (fossil-based) prices and tariffs, which may also depend on specific regulations and policies.

The model is mainly set up to find the optimal cost of energy that is supplied to the industrial process using renewable energy profiles on an hourly basis. The analysis approach should enable to study the implications of operating a chemical process flexibly, at least to some extent. To do so, an optimization model has been setup based on linear programming. This approach allows full flexibility to the variables being optimized, as long as a set of hard constraints are satisfied. The capacities of several assets, such as the wind farm, single axis tracking solar PV, utility scale battery storage and hydrogen cavern (in NL) or tank (in SA) storage, combined-cycle gas turbine (CCGT), and an electrolyser plant (only for the syncrude case), are optimized over the entire lifetime of the industrial plant (with perfect foresight in future weather patterns) to generate the lowest levelised cost of energy¹.

More details on the model, the techno-economic data, and the modelling results can also be found in the appendix.

¹ Equations and explanation on the calculated costs of energy is provided in Appendix B

Costs of renewable energy supply

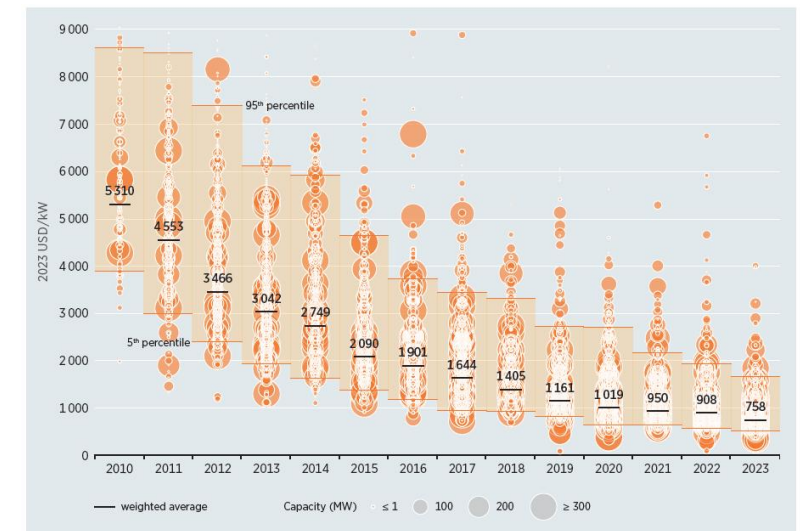
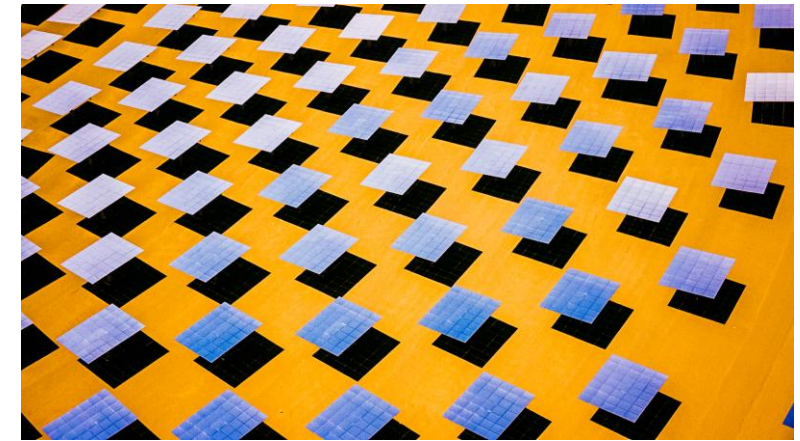
IRENA publishes every year an update of the global weighted average total installed costs of solar PV, onshore wind, offshore wind, and stationary battery electric storage. The data includes costs of all regions in the world. As also visible in the figure at the right for utility-scale solar PV, the costs range substantially between projects and may vary up to around a factor 4 starting from the average.

Cost projections for 2040 are based on extrapolation of the historical learning curve of the global weighted average of the total installed costs for solar PV, onshore wind, offshore wind, and stationary battery electric storage. The projected cumulative installed capacity of these assets is based on either the Stated Policies scenario (STEPS, conservative deployment) or the Net Zero Emissions scenario (NZE, optimistic deployment) of the IEA.

With the lack of a historical learning curve for electrolysis, the starting point for the current costs is based on a recent market consultation and the learning rate (LR) is varied between 9 and 20% to project the costs up to 2040. The projected cumulative installed electrolyser capacity is again based on the IEA scenarios.

Two base cases are explored in this study. In the first one, the analysis is based on the current cost estimates for all assets required in the optimisation. If applicable, these costs are based on the global weighted average from IRENA.

The second base case involves a cost projection for 2040 based on the projected costs that follow an average learning rate and average deployment scenario. The low and high side of the determined ranges from the learning curves in the year 2040 (or an even larger range) are used for the sensitivity analysis.



Notes: MW = megawatt; kW = kilowatt.

IRENA: Total installed cost of utility-scale solar PV by project and weighted average for utility-scale systems, 2010-2023
([Renewable Power Generation Costs in 2023](#))

Onshore Wind Costs

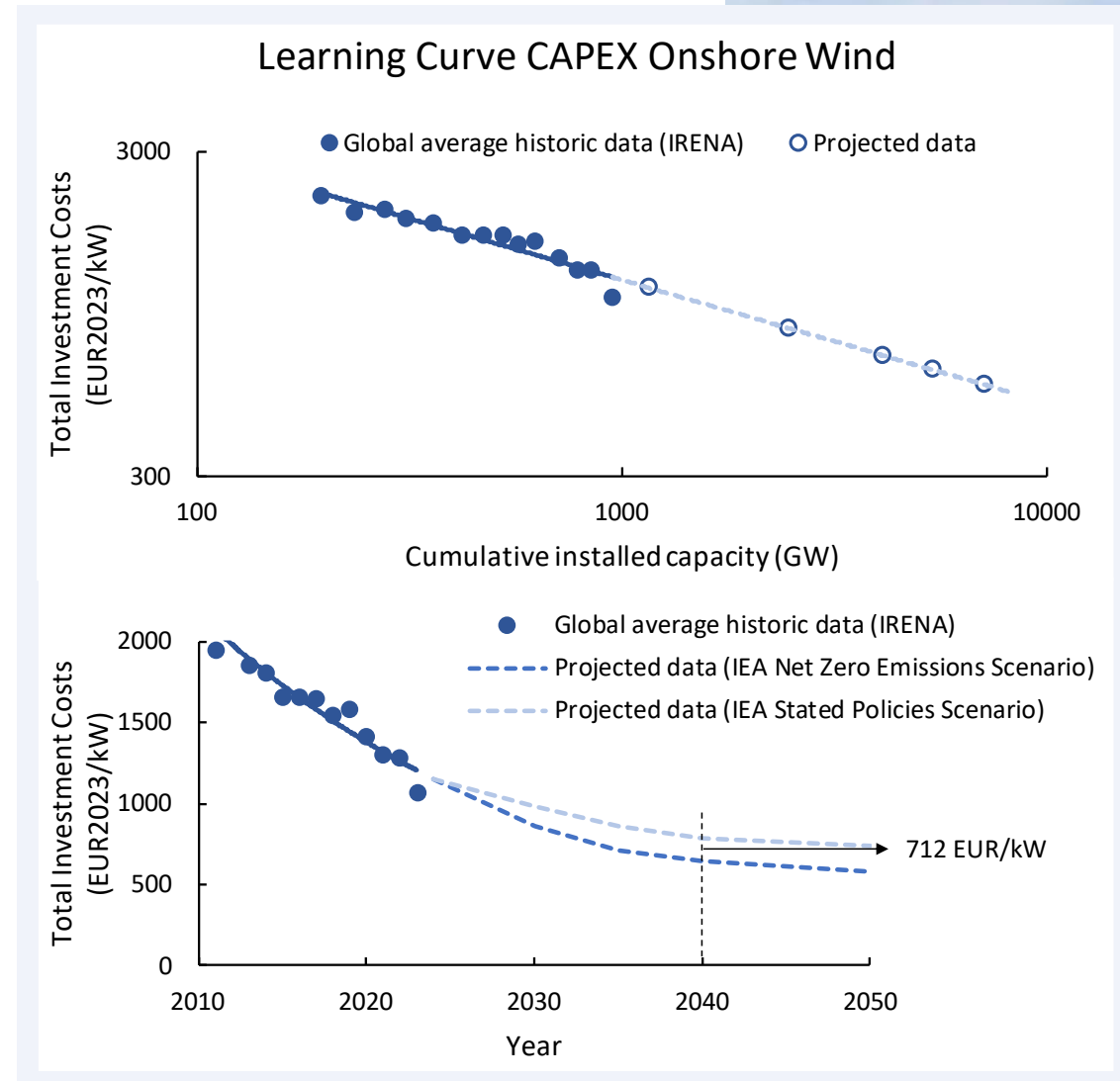
- Total installed costs for onshore wind are reported by IRENA
- Global average weighted costs from 2010 to 2023 are used to determine the learning curve of onshore wind CAPEX
- Historical learning rate since 2010 is 23%
- Based on projected capacities from the two IEA scenarios, the learning curve has been extrapolated with an LR of 23%
- Costs in 2040 range between 641 and 783 EUR/kW, with 712 EUR/kW as average (excl. infrastructure costs)

Sources:

GWEC annual reports ([Reports and resources](#)) – existing capacity

IRENA Renewable power generation costs in 2023 ([Renewable Power Generation Costs in 2023](#)) – investment costs

IEA World Energy Outlook 2024 ([World Energy Outlook 2024 – Analysis – IEA](#)) – 90% of projected wind capacity



Offshore Wind Costs

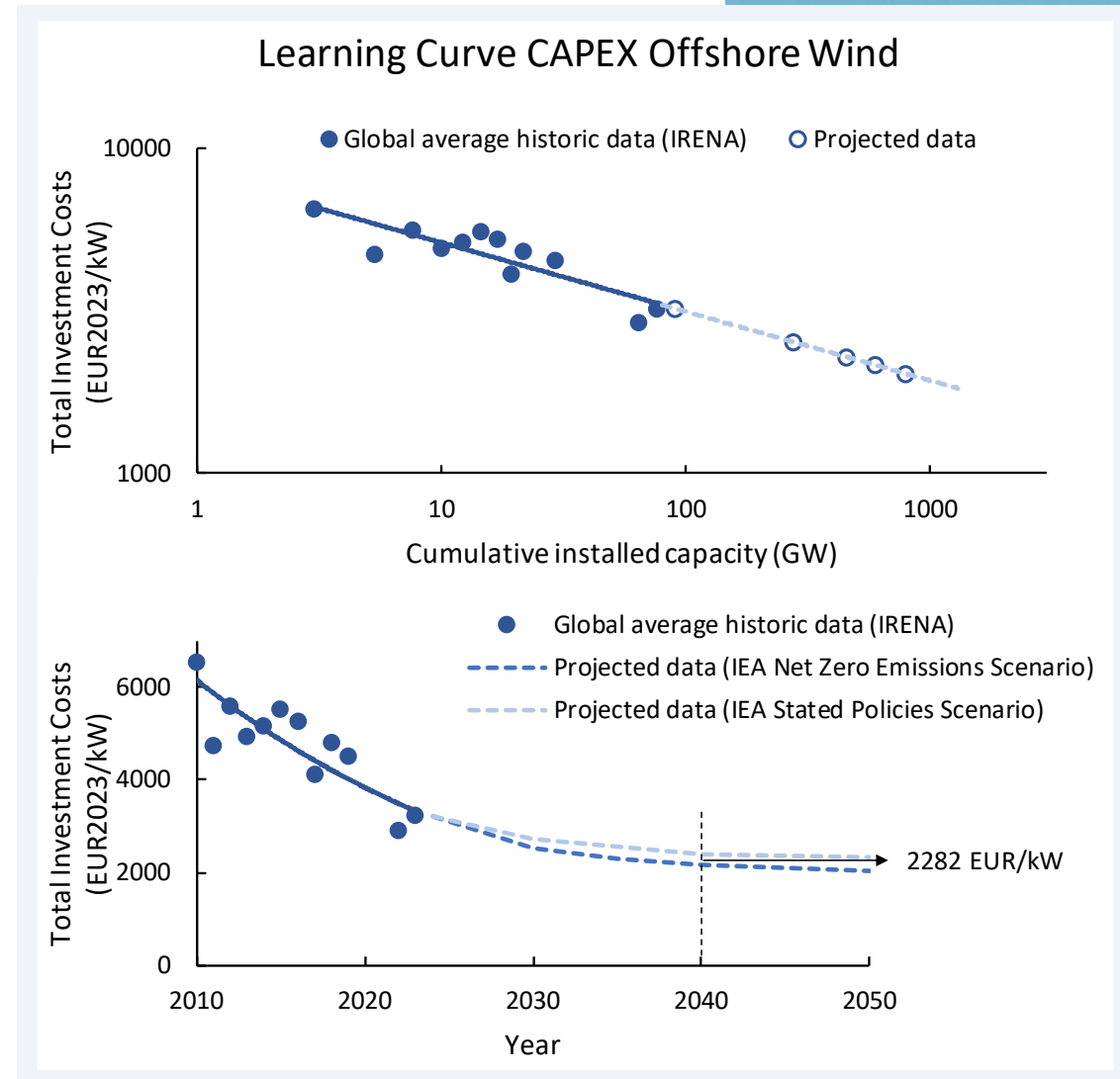
- Total installed costs for offshore wind are reported by IRENA
- Global average weighted costs from 2010 to 2023 are used to determine the learning curve of offshore wind CAPEX
- Historical learning rate since 2010 is 14%
- Based on projected capacities from the two IEA scenarios (assuming 10% of the capacity is deployed offshore), the learning curve has been extrapolated with an LR of 14%
- Costs in 2040 range between 2154 and 2410 EUR/kW, with 2282 EUR/kW as average (excl. infrastructure costs)

Sources:

GWEC annual reports ([Reports and resources](#)) – existing capacity

IRENA Renewable power generation costs in 2023 ([Renewable Power Generation Costs in 2023](#)) – investment costs

IEA World Energy Outlook 2024 ([World Energy Outlook 2024 – Analysis – IEA](#)) – 10% of projected wind capacity



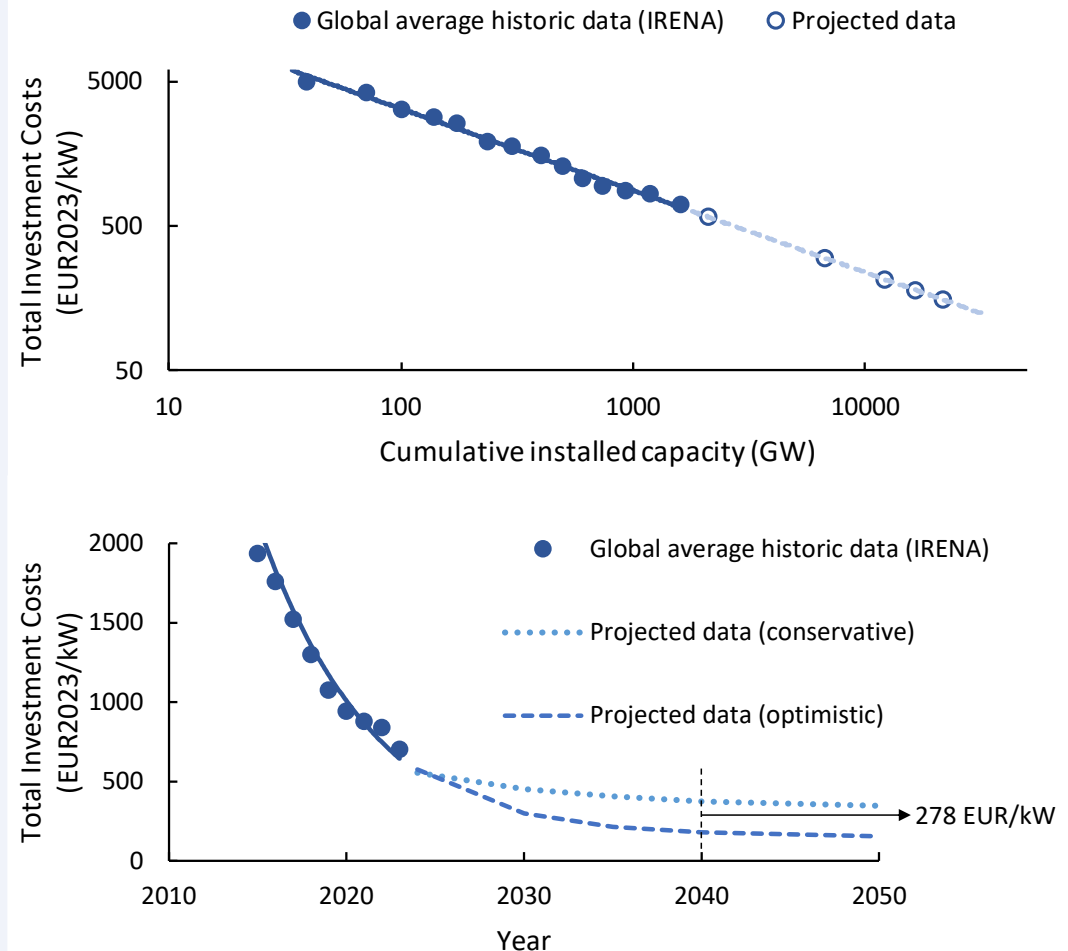
Solar PV Costs

- Total installed costs for solar PV are reported by IRENA
- Global average weighted costs from 2010 to 2023 are used to determine the learning curve of solar PV CAPEX
- Notably, IRENA includes costs for fixed tilt, as well as single and dual axis tracking systems in their range. For the analysis, no distinction is made between the costs for the different systems, although in reality costs appear around 10% higher for single axis tracking compared to fixed tilt.
- Historical learning rate since 2010 is 32%
- For the optimistic projection, the learning curve has been extrapolated with an LR of 32% and follows the capacities from the IEA NZE scenario, while for the more conservative case, the IEA STEPS scenario is used with an LR of 16%.
- Costs in 2040 range between 180 and 376 EUR/kW, with 278 EUR/kW as average (excl. infrastructure costs)

Sources: IRENA Renewable power generation costs in 2023 ([Renewable Power Generation Costs in 2023](#)) – investment costs

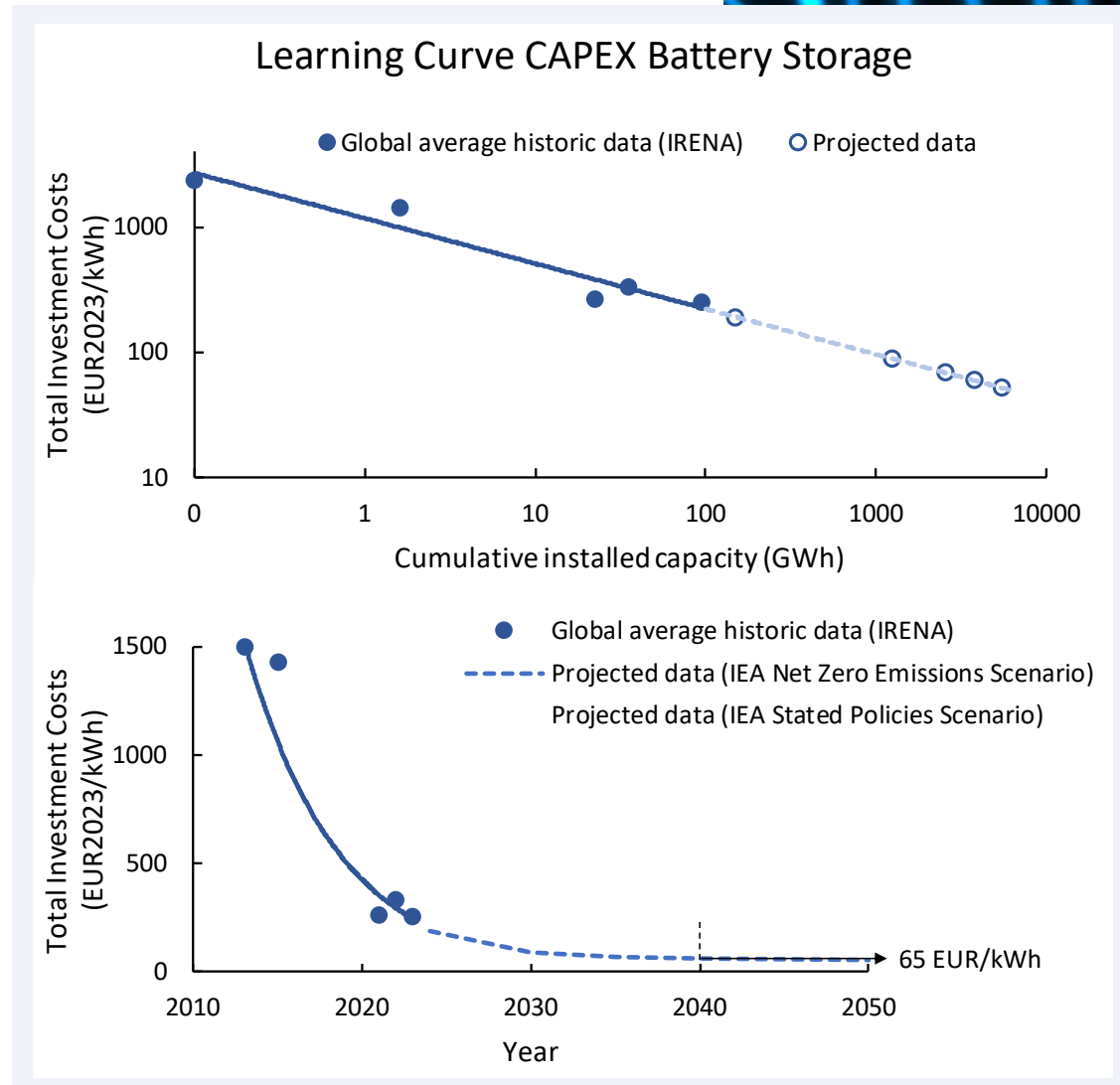
IEA World Energy Outlook 2024 ([World Energy Outlook 2024 – Analysis – IEA](#)) – existing and projected capacity

Learning Curve CAPEX Solar PV



Battery Storage Costs

- Total installed costs for battery storage are reported by IRENA
- Global average weighted costs from 2010 to 2023 are used to determine the learning curve of battery storage CAPEX
- Historical learning rate since 2010 is 22%
- Based on projected capacities from the two IEA scenarios, the learning curve has been extrapolated with an LR of 22%
- Costs in 2040 range between 59 and 71 EUR/kWh, with 65 EUR/kWh as average

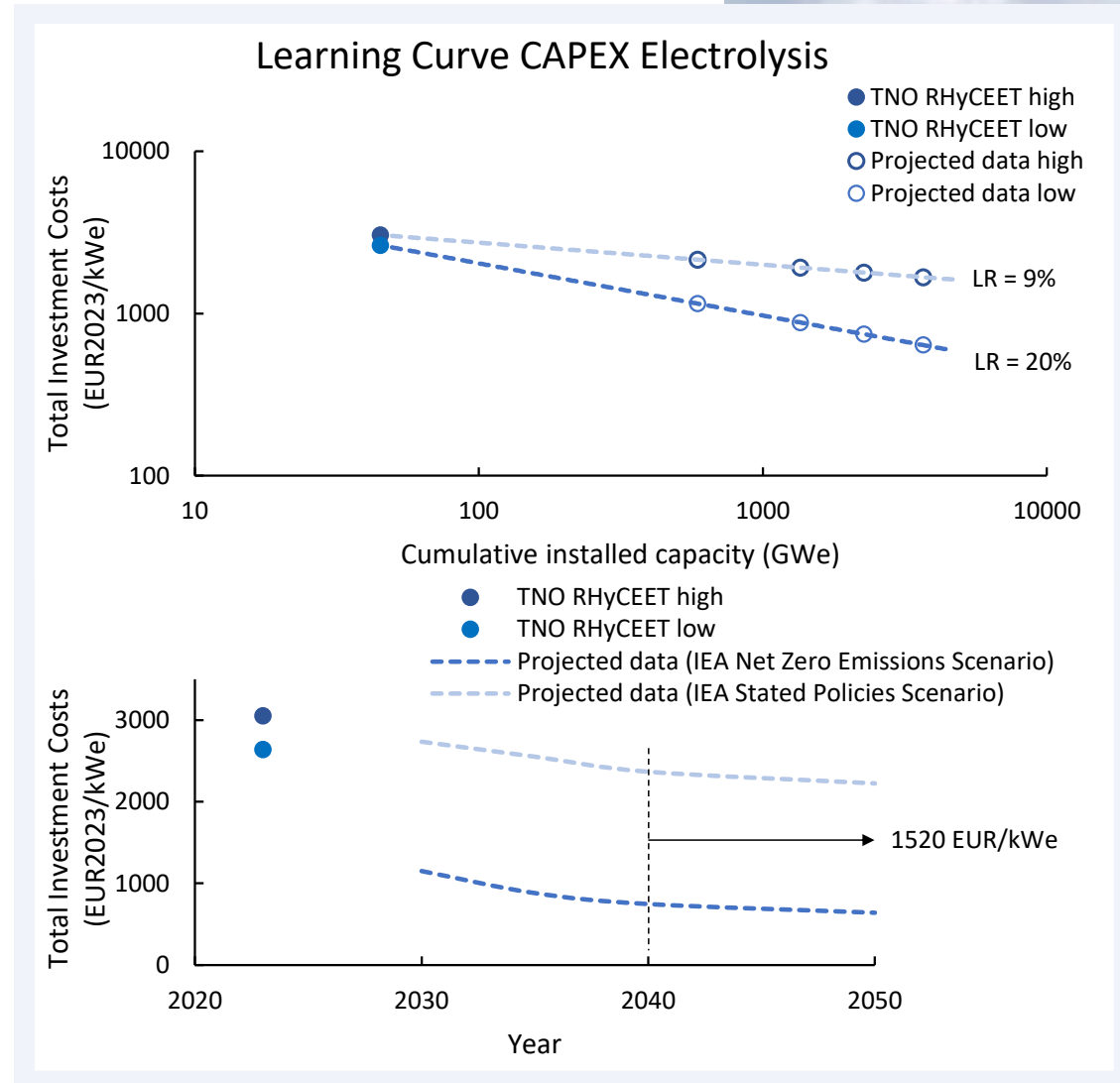


Sources: IRENA Renewable power generation costs in 2023 ([Renewable Power Generation Costs in 2023](#)) – investment costs

IEA World Energy Outlook 2024 ([World Energy Outlook 2024 – Analysis – IEA](#)) – existing and projected capacity

Electrolysis Costs

- Total installed costs for an electrolysis plant are reported by Eblé & Weeda (2024)
- Learning rates are based on previous work by Detz & Weeda (2022)
- Based on projected capacities from the two IEA scenarios, the learning curve has been projected with an LR ranging between 9 and 20%
- Costs in 2040 range between 747 and 2368 EUR/kW, with 1520 EUR/kW as average



Sources: Eblé, L. F. J., Weeda, M. (2024). ([TNO 2024 R10766](#)) – investment costs

Detz, R., Weeda, M. (2022). ([TNO 2022 P10111](#)) – learning rates

IEA World Energy Outlook 2024 ([World Energy Outlook 2024 – Analysis – IEA](#)) – existing and projected capacity

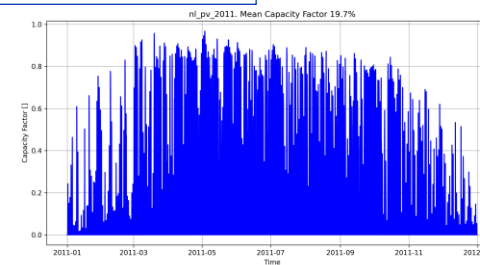
Energy profiles

An important difference between regions is the profile of renewable energy supply. For this study, arbitrarily selected weather profiles of the **year 2011**, from renewables.ninja (MERRA-2 dataset) are used for the entire plant lifetime. The MERRA-2 dataset is a global dataset with a spatial resolution of about 50 km in the latitudinal direction.¹ For both regions and for both sun and wind, this weather year seems rather average in terms of its annual capacity factor. Notably, these profiles do have a significant impact on the outcome of the results and selecting another weather year may lead to different results. The solar profile in NL demonstrates a strong seasonal dependency with peak capacity during the summer (annual capacity factor of 19.7%), while for SA the irradiation is higher and more equally distributed along the year (annual capacity factor of 30.4%). Offshore wind has a substantially higher annual capacity factor of 53.8% in NL, onshore wind in SA shows an annual capacity factor of 22.2%.

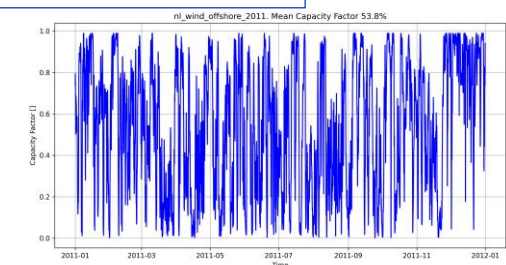
These capacity factors indicate the percentage of the time that the specific asset (a single axis solar PV system or a wind turbine) can operate at full capacity, i.e. that the distribution over the year can be very different as shown by the hourly profiles below.



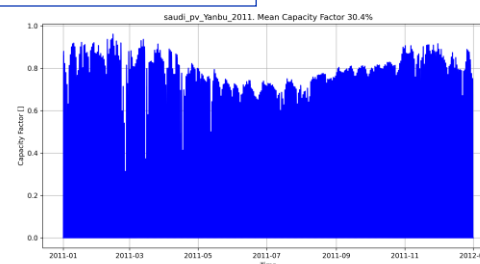
NL PV



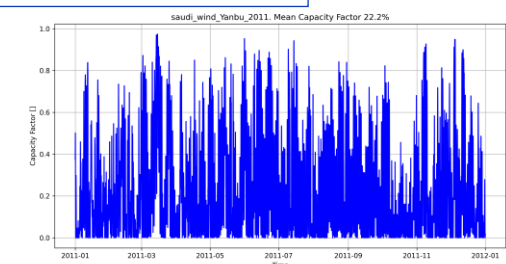
NL Offshore Wind



SA PV



SA Onshore Wind



¹ More information on MERRA-2 can be found here: [MERRA-2](#)

Regional differences (base case)

In The Netherlands, renewable energy can be supplied by solar PV (single axis tracking) and/or offshore wind (no onshore wind is allowed). In Saudi Arabia, no offshore wind is allowed but onshore wind is included as a renewable energy supply option, next to single axis tracking solar PV. In both regions, hydrogen can be converted into electricity through a CCGT, and electricity can be stored in a battery. In NL, hydrogen can be stored in caverns, while in SA hydrogen can only be stored in tanks.

As indicated previously, the profiles for renewable energy production through solar and/or wind differ between regions. This is one of the key variables between regions.

Another important difference exist of the selected discount rate (or WACC). The WACC is generally lower in regions with lower investment risks, such as NL.

Investment costs are generally also depending on the region but for this study is assumed that no differences exist. The same approach is followed for the OPEX (excluding costs of energy).

For the chlorine production case, the CA plant and Cl₂ storage are kept identical in both regions. For the syncrude production case, the Fischer-Tropsch plant and electrolyser are also the same in both regions. No electrolyser is present for the chlorine production case as hydrogen is produced by the CA plant.

Assets (base case)	NL	SA
Onshore Wind Farm	-	x
Offshore Wind Farm	x	-
Solar PV	x	x
CCGT	x	x
Battery Electric Storage	x	x
H ₂ Tank Storage	-	x
H ₂ Cavern Storage	x	-
Renewable energy profiles	for NL	for SA
WACC (for all assets)	7.2%	10.4%
CAPEX	same	
Fixed OPEX	same	
Chlor-Alkali Plant	x	x
Cl ₂ Tank Storage	x	x
Fischer-Tropsch Plant	x	x
Electrolyser	x	x

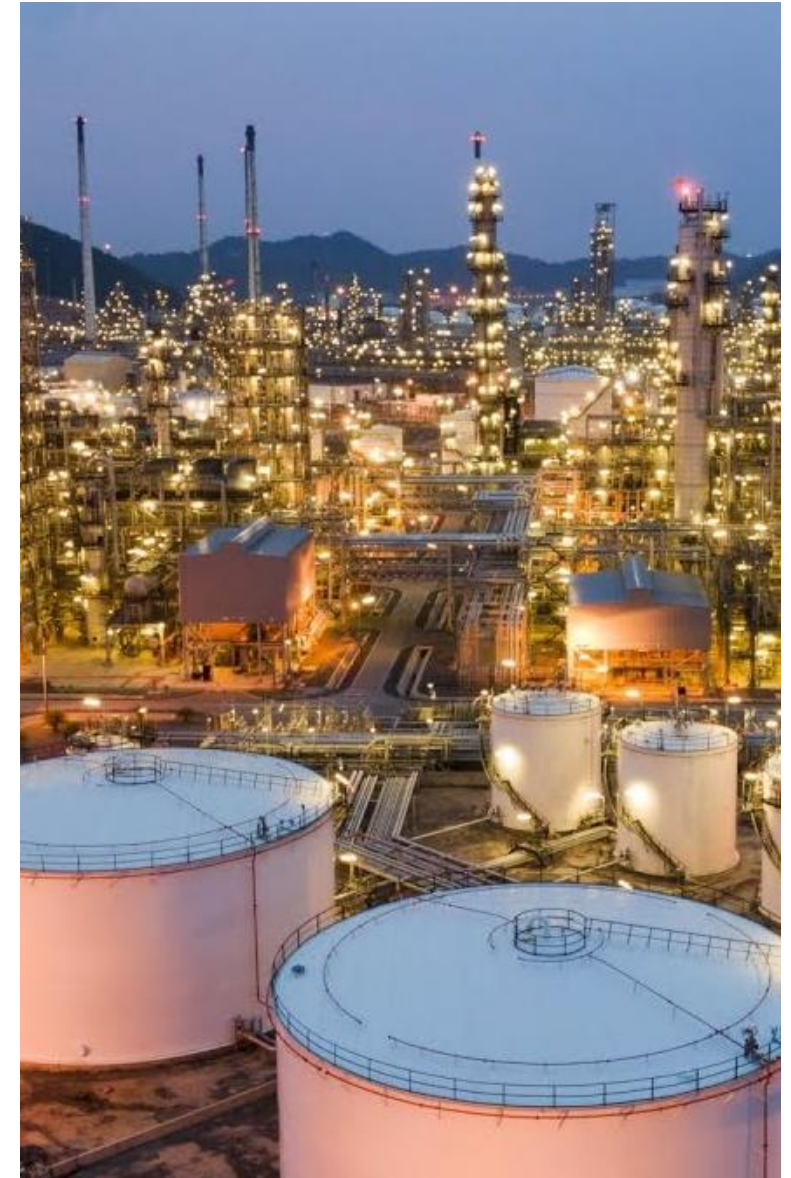
Chlor-alkali production

The first industrial value chain that is analysed is chlor-alkali production. The chlor-alkali (CA) production plant converts salt and water into chlorine, caustic soda and hydrogen in an electrochemical process. The plant mainly consumes electricity and some steam.

In this study, the costs the electricity and steam used by the CA plant are optimized. The CA plant itself is also part of the model as the produced hydrogen can be used as a mean to store energy. The chlorine storage facility at the plant is modelled as well to provide additional operational flexibility.

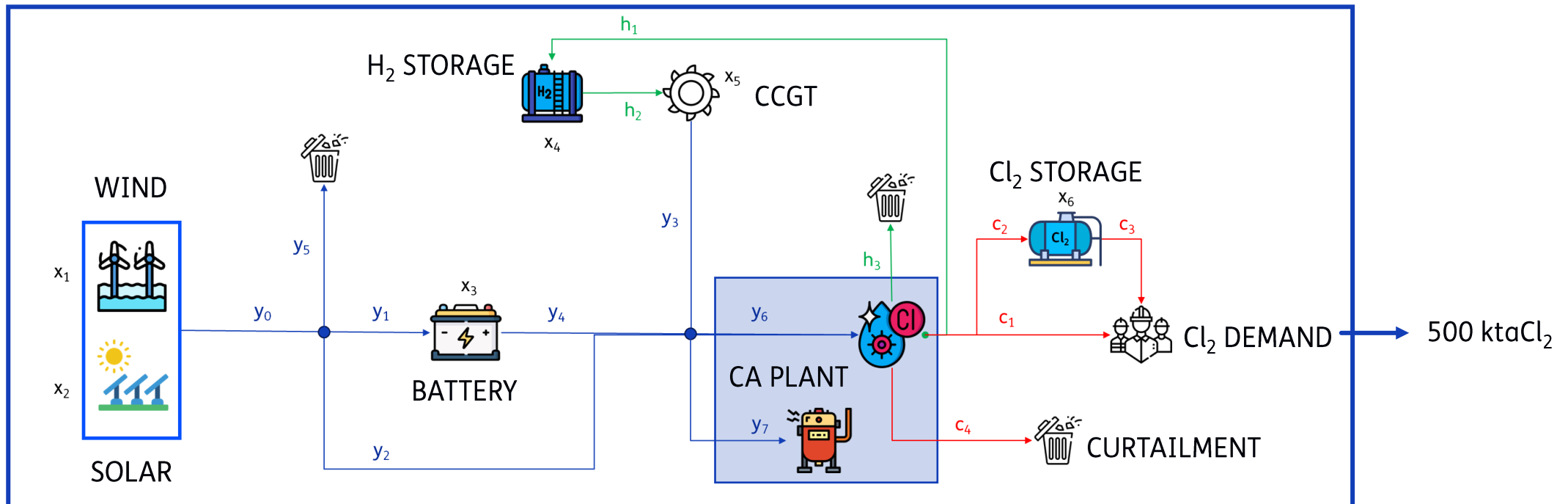
The CA plant can be operated flexibly between 40% and 100%, but not been shut down entirely. The plant can produce the annual demand when it operates at 90% capacity over the entire year. At 100% capacity it has to store the excess of chlorine in the storage facility (if space is available). The plant has a fixed hourly demand of 95% as well. This demand can be produced directly or be provided from the storage. For the base case, the chlorine storage is fixed at 1.5 days of storage (up to 2 kt Cl_2) because of safety constraints.

The total power consumption of the plant amounts to approximately 180 MW_e. The annual energy input to produce 500 kt of chlorine is nearly 1.5 TWh electricity (of which approximately 80% is for the electroconversion process). Additionally, around 850 kt of salt is used as feedstock. Besides chlorine, the facility produces around 550 kt of caustic soda and 10 kt of hydrogen.



Chlor-alkali production

Below a schematic of the model scope is illustrated for the chlor-alkali process:

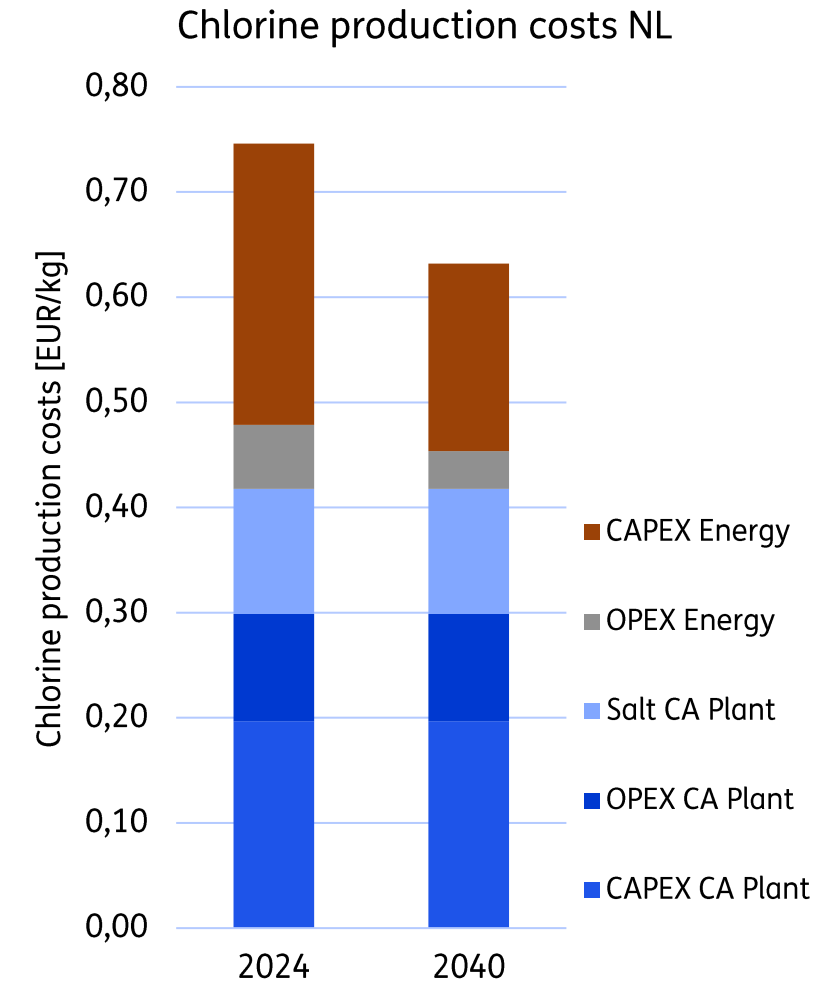


Production costs - NL

The cost optimisation is performed based on the current (2024) and the projected costs for 2040 of the different assets to illustrate the differences. As already mentioned on page 7, the 2024 case does not represent the actual situation, but the “island” system based on renewable energy costs of today. Notably, some of the requirements for the analysis, such as hydrogen cavern storage and flexible operation of the chlor-alkali plant are not realistic today.

For The Netherlands, cost optimization results in chlorine production costs of 0.75 EUR/kg. Around 56% of these costs is directly associated to investments, operation, and salt feedstock for the plant, while 44% can be ascribed to energy provision.

Thanks to lower energy costs towards 2040, the production costs may decline from 0.75 to 0.63 EUR/kg. The relative contribution of energy to the chlorine production costs has now declined to 34%.

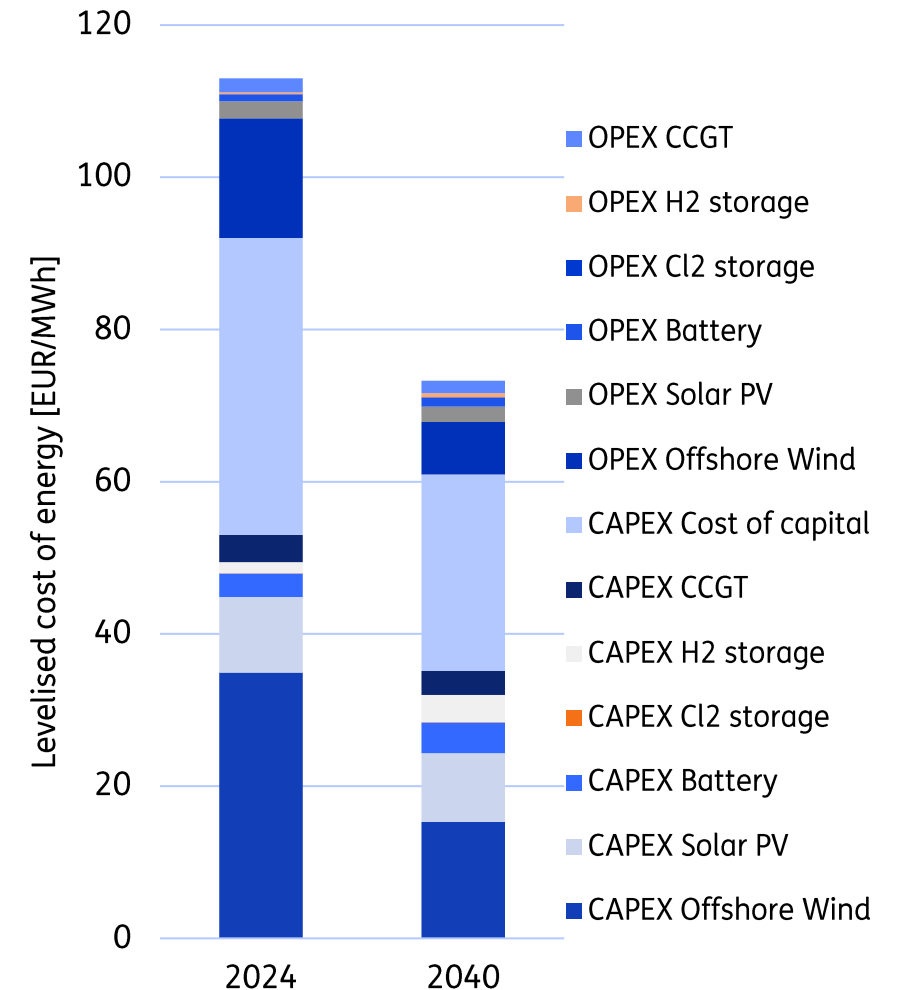


Renewable energy costs – NL

For The Netherlands, the costs of the supplied energy to the CA plant amount to 113 EUR/MWh. To achieve this, an installed capacity for solar PV and offshore wind of 283 and 201 MW_e, resp., is required. Additionally, a battery storage capacity of 267 MWh and nearly 2.7 kt of hydrogen cavern storage is needed. All of the hydrogen that is produced by the CA plant is converted by a 81 MW CCGT plant to provide part of the electricity for the CA plant. This is explained in that, for the model, the hydrogen has no value and its use results in lower chlorine production costs as it will avoid additional electricity supply. In reality, the hydrogen may have a higher value as additional electricity supply may cost but this effect is not further explored. Wind supplies roughly twice the amount of energy compared to solar PV. Only 9% of the supplied electricity from solar and wind together is curtailed.

For 2040, the relatively high cost reductions that are projected for solar PV and battery storage result in a shift in the installed capacities. The wind capacity reduces to 118 MW_e while both the capacity of solar PV and batteries increase to 588 MW_e and 1366 MWh. Also the hydrogen storage increases to 6.5 kt (approximately the capacity of a single cavern). Not surprisingly, the cost reductions result in lower cost of energy of 73 EUR/MWh. Most of the energy is now produced by solar PV (964 GWh/yr), with offshore wind providing 526 GWh/yr. Curtailment increases to 12%.

The influence of the discount rate of 7.2% is indicated by the “Cost of capital” category, as the discount rate varies typically among different regions.



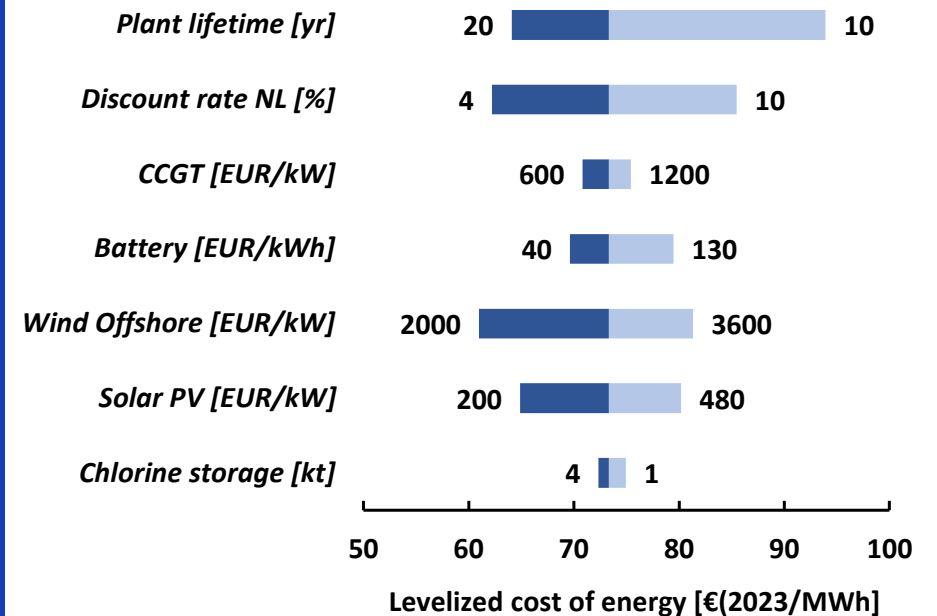
Sensitivity analysis for NL

How different parameters affect the costs is explored through sensitivity analysis in which the effect of changing a single parameter is indicated. Only the influence on the cost of energy is investigated for the 2040 projection. The effect on chlorine production costs is not specifically examined and these costs will be affected by even a larger number of parameters, such as CAPEX of the CA plant and salt costs.

The plant lifetime has a significant impact on the energy costs. The base case of 15 years is mainly based on the CA plant but is for simplicity reasons kept the same for all assets. Solar panels and wind turbines, for example, may last longer, which will reduce costs. Renewable energy is capital intensive and the discount rate has a substantial influence. A rate of 10% would increase the costs to 85 EUR/MWh, while a low rate of 4% leads to energy costs of 62 EUR/MWh.

A change in CAPEX of the CCGT and battery indicates a relatively modest impact. If investment costs for offshore wind reduce more as projected for the base case, costs of energy may go down to 61 EUR/MWh (for offshore wind CAPEX of 2000 EUR/kW_e). This would also shift the installed capacity from 118 to 191 MW_e. Solar capacity would decline from 588 to 298 MW_e and battery capacity from 1366 to 421 MWh. A different CAPEX for solar PV also has a substantial impact but less severe as for wind. When a lower or higher chlorine storage capacity is allowed in the optimisation, no significant effect on the energy costs is observed.

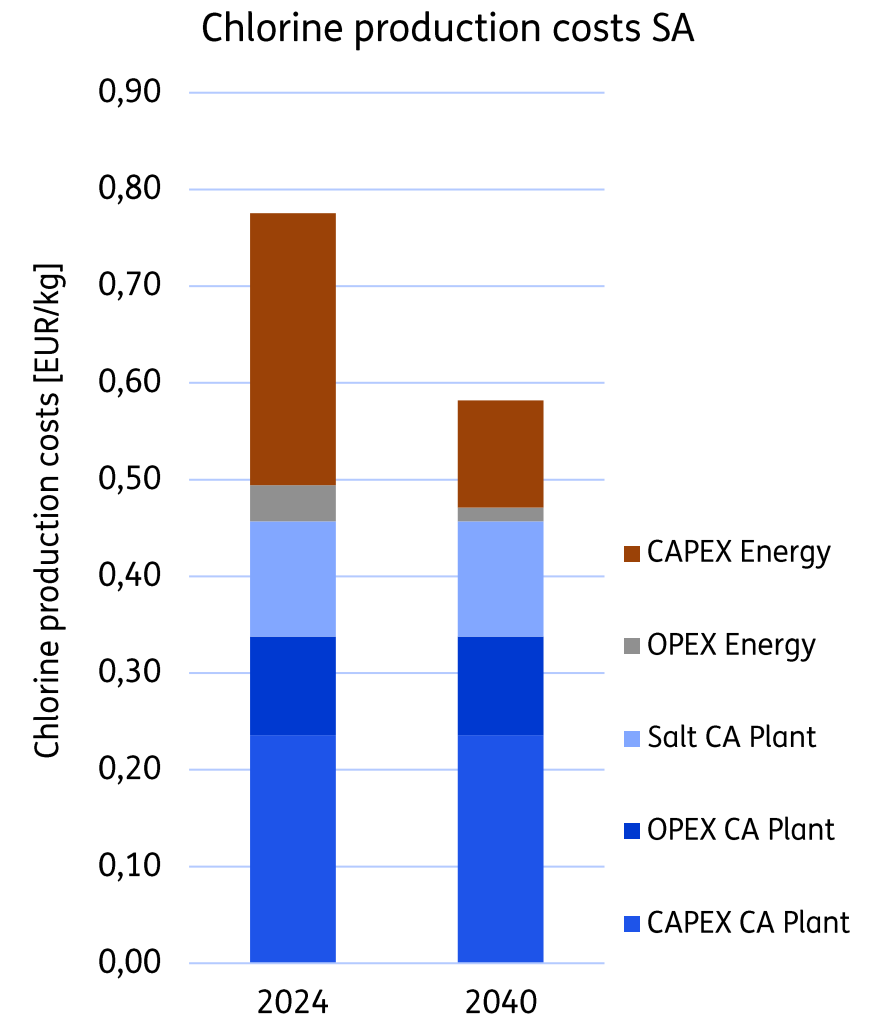
CA - Sensitivity NL



Production costs - SA

For Saudi Arabia, cost optimization results in chlorine production costs of 0.78 EUR/kg. Approximately 59% of these costs is directly associated to investments, operation, and salt feedstock for the plant, while the remaining can be ascribed to energy provision.

Thanks to lower energy costs towards 2040, the production costs may decline from 0.78 to 0.58 EUR/kg. The relative contribution of energy to the chlorine production costs amounts to barely 22%.



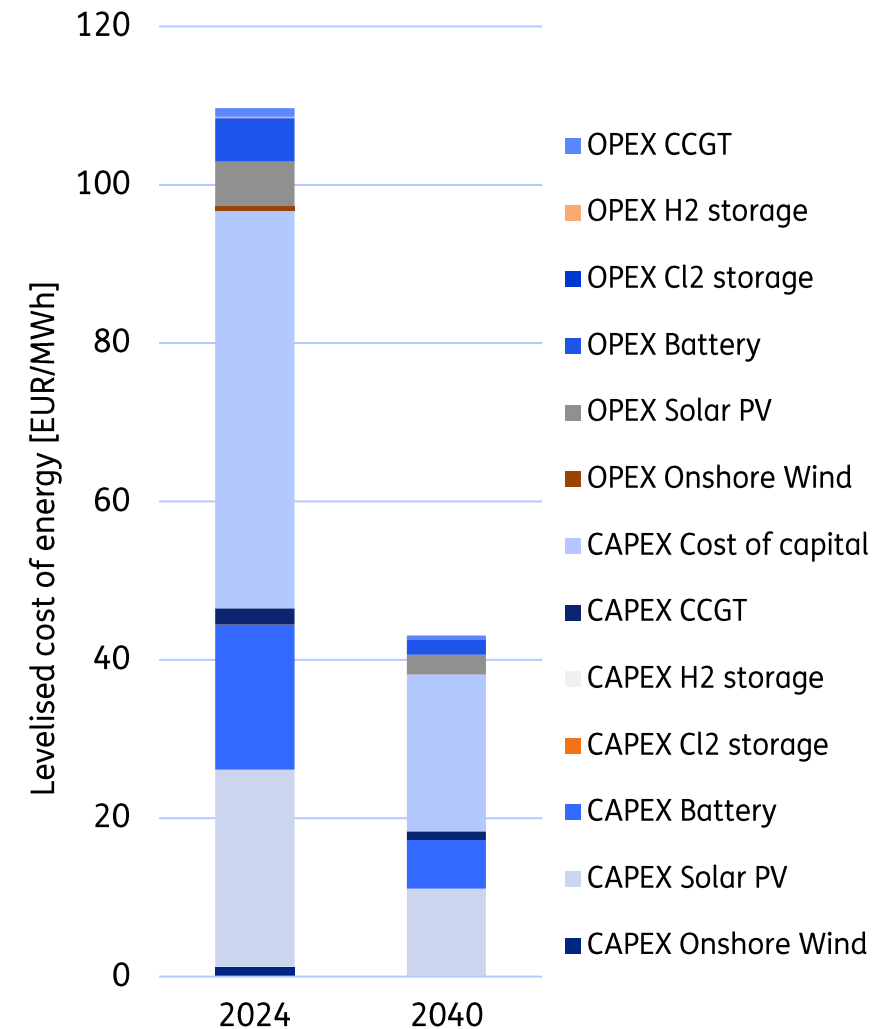
Renewable energy costs – SA

In Saudi Arabia, the base case costs of the supplied renewable energy to the CA plant amount to 110 EUR/MWh in 2024. To achieve this, an installed capacity for solar PV and onshore wind of 713 and 23 MW_e, resp., is required. Additionally, a battery storage capacity of 1576 MWh and less than 0.02 kt of hydrogen tank storage is needed. 81% of the hydrogen that is produced by the CA plant is converted by a 47 MW CCGT plant to provide part of the electricity for the CA plant.

Nearly all energy is supplied by solar PV, which together with battery storage is perfectly capable to cope with the daily rhythm of the solar energy supply. Thanks to the relatively large battery, barely any hydrogen tank storage is required as this is costly. 24% of the supplied electricity is curtailed.

For 2040, the relatively high cost reductions that are projected for solar PV and battery storage result in a significant reduction of the energy costs to 43 EUR/MWh. Solar capacity remains nearly the same. No wind capacity is installed but instead the battery capacity increases from 1576 to 2058 MWh. This allows for less hydrogen use (41%) and less need for hydrogen storage and conversion. All energy is now produced by solar PV (1816 GWh/yr) of which 286 GWh/yr is curtailed (16%).

The influence of the discount rate of 10.4% is indicated by the “Cost of capital” category, as the discount rate varies typically among different regions.



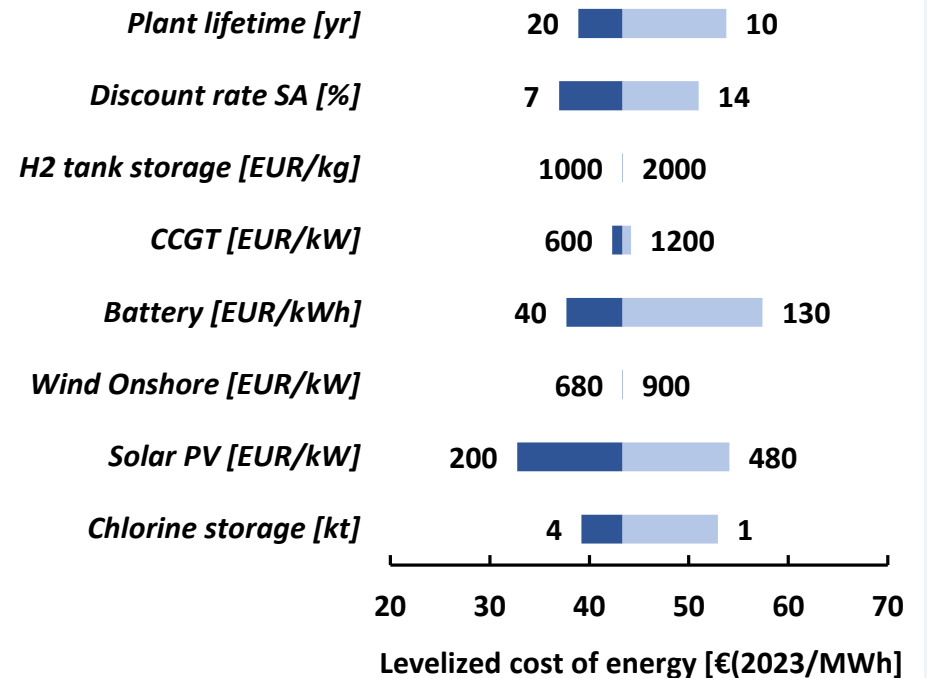
Sensitivity analysis for SA

Also for the chlor-alkali case in Saudi Arabia a sensitivity analysis is performed to explore the influence of several parameters on the cost of energy in 2040. The plant lifetime has a significant impact on the energy costs. A five year higher or lower lifetime results in a range of the energy costs between 39 and 54 EUR/MWh. Also for SA, the discount rate has a substantial influence. When a discount rate similar to that in NL is applied, cost of energy reduce to 37 EUR/MWh, while a higher rate of 14% results in costs of 51 EUR/MWh.

A change in CAPEX of the H₂ tank storage and CCGT indicate a relatively minor impact due to the low contribution of hydrogen to provide storage in SA. Energy is dominantly stored in the battery and a change in battery CAPEX results in substantial impact. Lower battery costs of 40 EUR/kWh would bring the energy costs down to 38 EUR/MWh. If battery investment costs will reduce less quickly, e.g. to 130 EUR/kWh, costs of energy would amount to 57 EUR/MWh. Interestingly, this case in the sensitivity analysis is the only one in which the optimal cost requires onshore wind capacity (18 MW_e) to allow a reduction in battery capacity to 1685 MWh.

A different CAPEX for onshore wind has no effect as its capacity remains zero. As solar PV dominates the energy production, its CAPEX has a substantial impact on the energy costs. Remarkably, the installed capacities do barely differ when the CAPEX of solar PV is changed between 200 and 480 EUR/kW_e. In contrast to NL, a lower or higher chlorine storage capacity demonstrate in SA a significant impact on the energy costs. If the capacity is only half that of the base case, roughly 200 MW_e of solar PV and 500 MWh of battery capacity is additionally required. A doubling in Cl₂ storage would require more than 100 MW_e solar PV less.

CA - Sensitivity SA



Comparison of regions

One of the main tasks of this study is to understand the difference in energy costs for industrial processes between regions. For the chlor-alkali case, the results of the base case for 2024 indicate that the energy costs are very similar between NL and SA, namely 113 and 110 EUR/MWh.

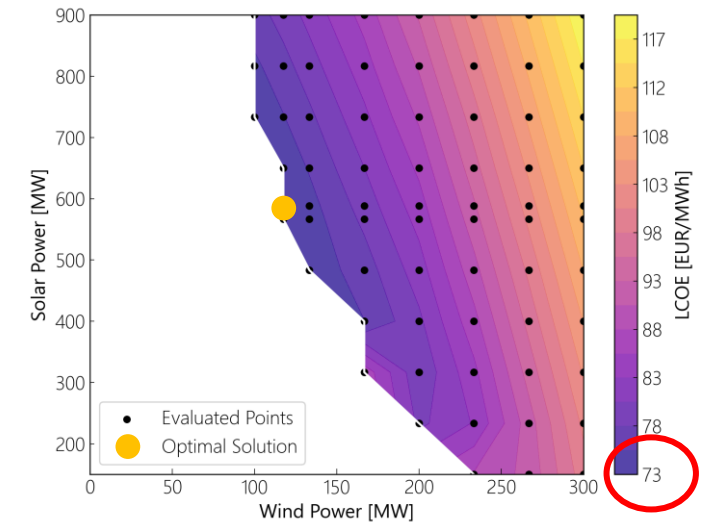
Thanks to cost reductions for many of the technologies involved, projected energy costs reduce for both regions to 73 EUR/MWh in NL and 43 EUR/MWh in SA. This indicates that for the base scenario the energy costs are around 40% lower in SA compared to NL. The difference is mainly caused by the projected learning curves, which are steeper for solar PV and battery storage than for offshore wind. These cost reductions are more beneficial for sunny regions without strong seasonal influences.

One aspect that has a strong influence is the flexibility of the chlor-alkali process itself, which can operate between 40 and 100% of its load. Also, the chlorine storage has a significant impact on especially the energy costs in SA. Flexibility and storage in NL is mainly solved by hydrogen cavern storage. Modelling indicates (results not shown) that without cavern storage the cost of energy increases by at least 10%.

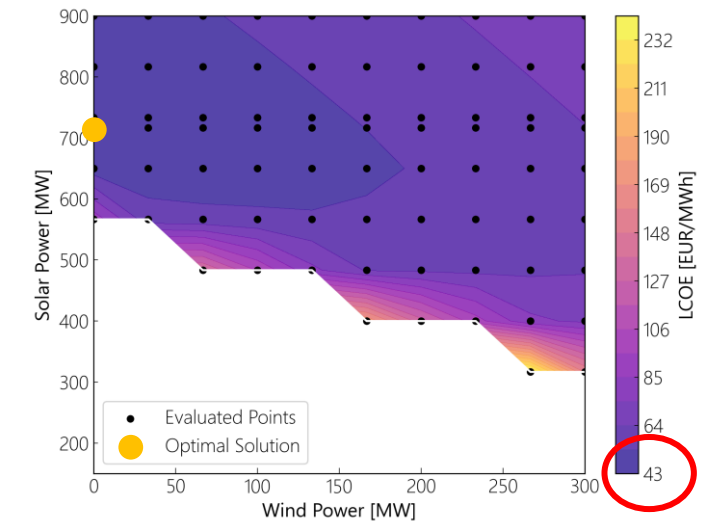
In the contour plots at the right, the LCOE is indicated for different combinations of installed solar and wind power. It can be seen that in NL at least around 100 MWe of offshore wind is required to enable energy production for the CA plant as otherwise no solution could be found for solar PV capacities below 900 MW_e (white area). Additional wind power, however, results rapidly in higher costs. This gradient is less severe for the SA case unless at least around 400 MW_e of solar PV is installed.

Base case 2040

NL



SA



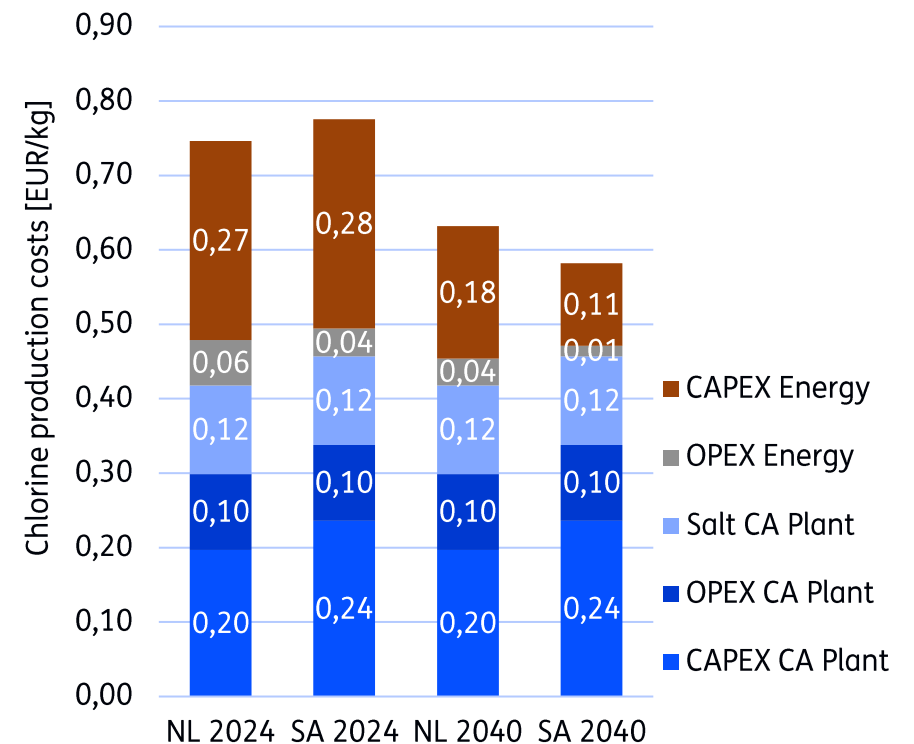
Comparison of regions

Not only energy costs contribute to the production costs of the industrial process. Despite that energy costs are lower towards 2040 in SA than in NL, the chlorine production costs reveal a substantially smaller relative difference. For 2024, the base case values amount to 0.75 EUR/kg in NL and even slightly higher in SA 0.78 EUR/kg.

This difference is of course induced by the assumed regional differences, which are mainly the weather profiles and the cost of capital. The first parameter mostly impacts the energy production, but the cost of capital (included in CAPEX categories) also directly affect the CAPEX of the CA plant, which is higher in SA.

Thanks to lower costs of energy, the 2040 base case in SA results in lower chlorine production costs of 0.58 EUR/kg versus 0.63 EUR/kg in NL. So, while the costs of energy are around 40% lower in SA compared to NL, the production costs are 8% lower. Considering all uncertainty in the analysis and assumptions, such a small difference seems not a decisive parameter for selecting SA as more promising than NL. Other factors that are not analysed in this study, such as connection to markets, feedstock availability, strategic and regulatory aspects, and existing infrastructure and assets, will likely be of equal importance.

Comparison of chlorine production costs between regions

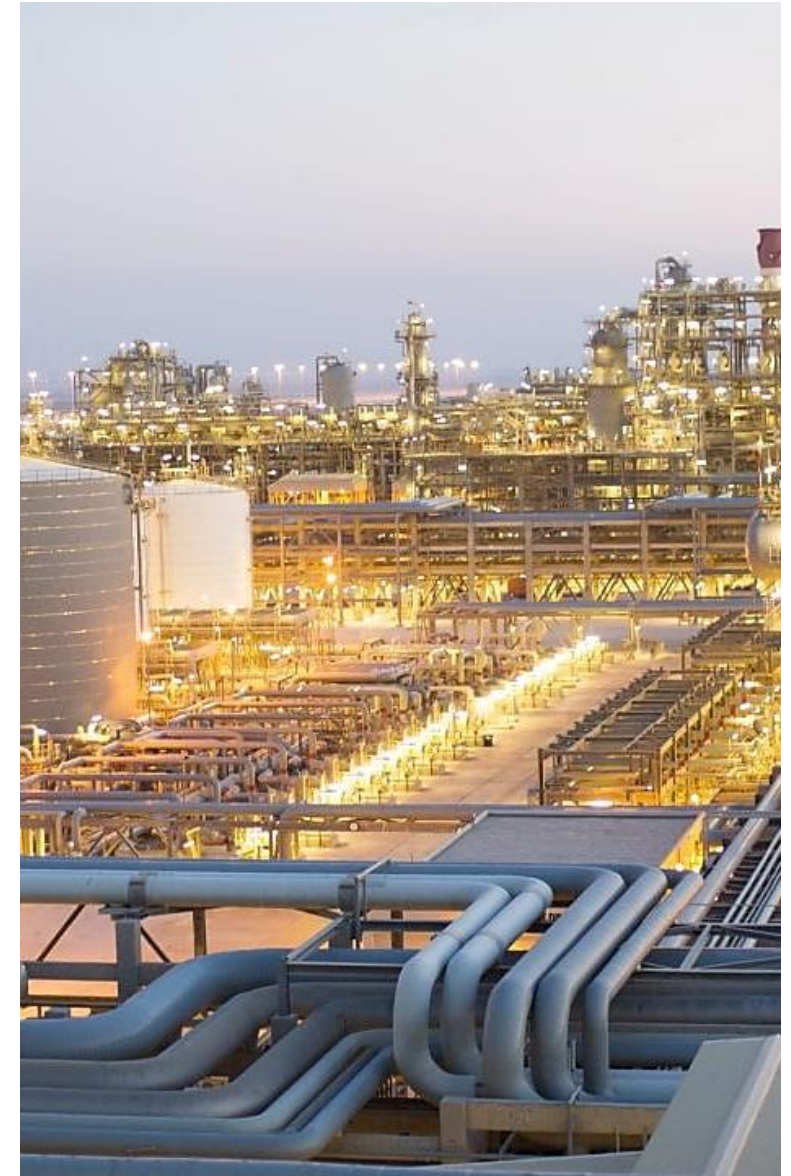


Syncrude production

The second industrial value chain that is analysed is syncrude production. The syncrude production plant combines municipal solid waste gasification with Fischer-Tropsch synthesis to produce a syncrude, which subsequently can be upgraded into, for instance, aviation fuel. The gasification process generates a syngas to which additional hydrogen is added from electrolysis. The plant also consumes some electricity.

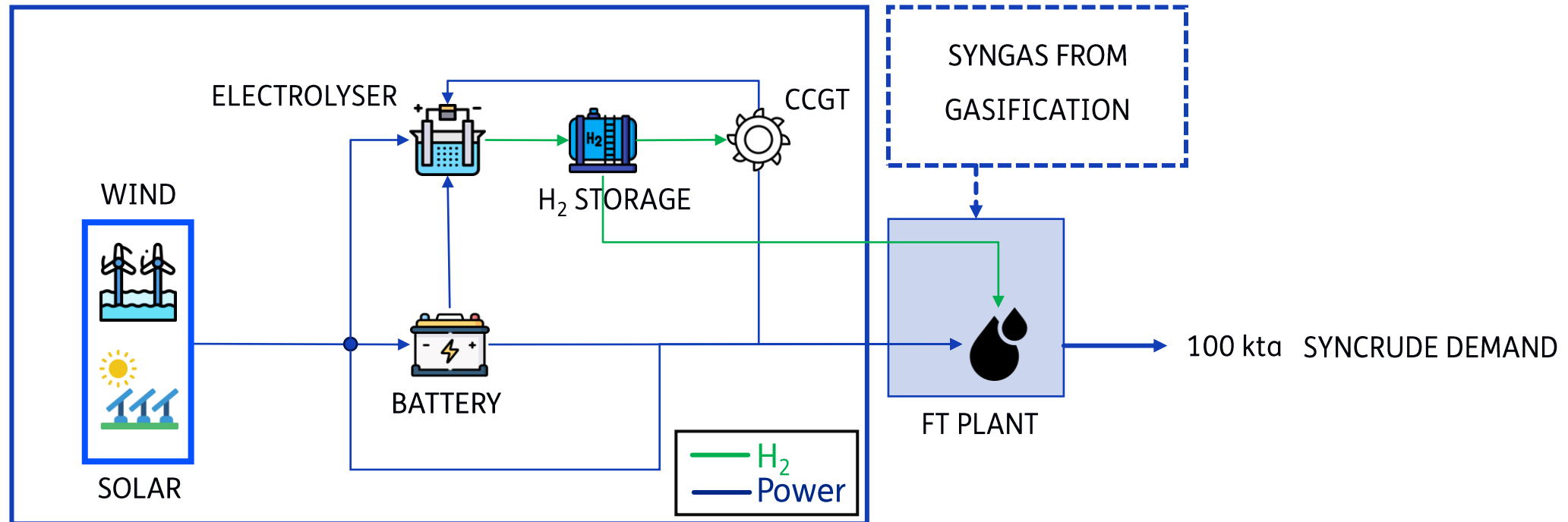
In this study, only the costs of the additional hydrogen and the electricity used by the Fischer-Tropsch process are optimized. The feedstock and energy for the gasification process, as well as all investments in the industrial processes are not modelled.

The FT plant is operated at a baseload hydrogen and electricity demand. The total annual input to the plant is 9.0 kt hydrogen and 24 GWh electricity, which together amounts to 324 GWh of energy input (around 37 MW) to produce 100 kt of syncrude. As mentioned, this excludes other input to the FT process, such as the syngas from the waste gasification.



Syncrude production

Below a schematic of the model scope is illustrated for the Fischer-Tropsch process:

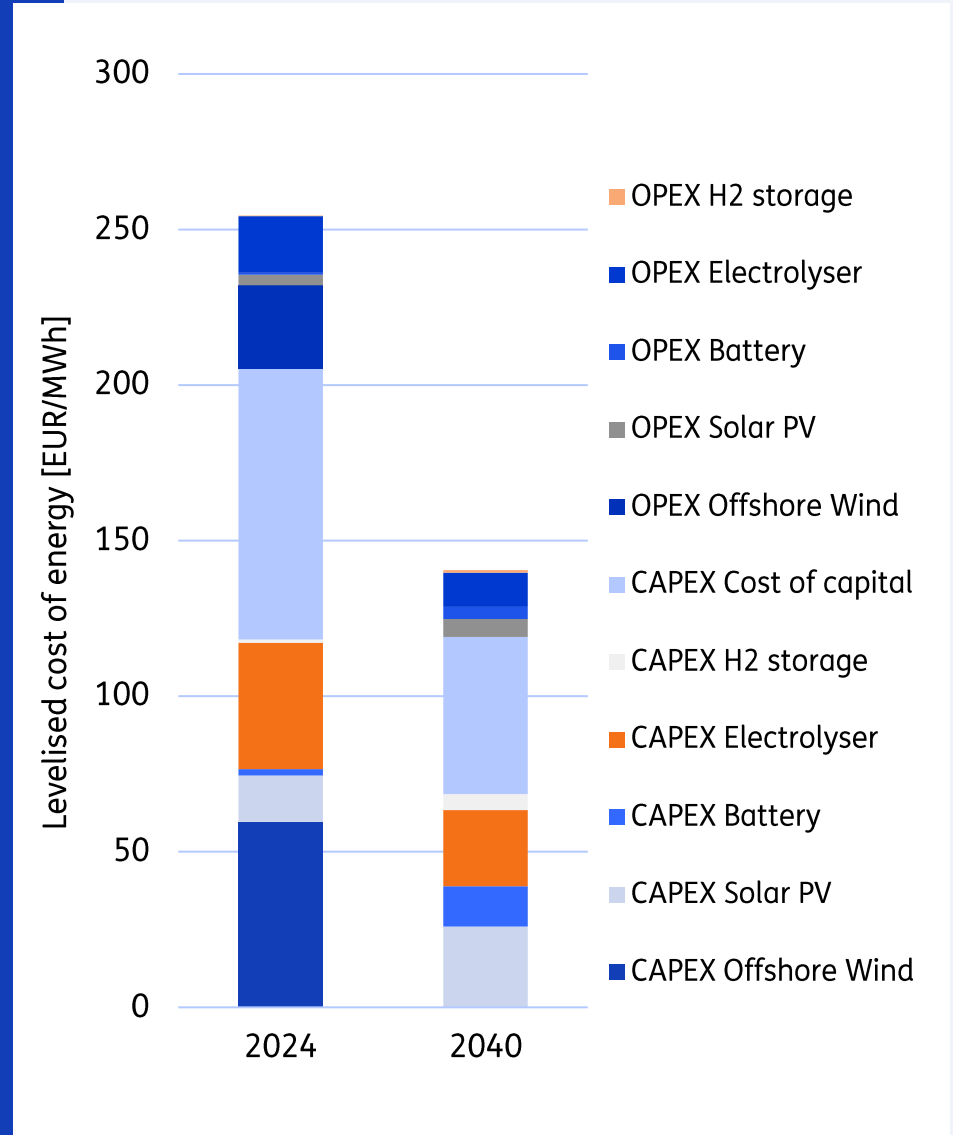


Renewable energy costs – NL

For The Netherlands, the costs of the supplied energy to the FT plant amount to 254 EUR/MWh. This requires an installed capacity for solar PV and offshore wind of 95 and 76 MW_e, resp. Additionally, a battery storage capacity of 39 MWh and 0.43 kt of hydrogen cavern storage is needed. All of the hydrogen that is produced by the 69 MW_e electrolyser is eventually used by the FT plant and none of it is converted by a CCGT. Wind supplies roughly twice the amount of energy compared to solar PV. Only 9% of the supplied electricity from solar and wind together is curtailed.

For 2040, the relatively high cost reductions that are projected for solar PV and battery storage result in a shift in the installed capacities. No wind capacity is installed, while both the capacity of solar PV and batteries increase to 374 MW_e and 967 MWh. Also the hydrogen storage increases to 2.05 kt (around 30% of an average cavern). Not surprisingly, the cost reductions result in lower cost of energy of 141 EUR/MWh. All of the energy is now produced by solar PV (613 GWh/yr) of which 16% is curtailed.

The influence of the discount rate of 7.2% is indicated by the “Cost of capital” category, as the discount rate varies typically among different regions.



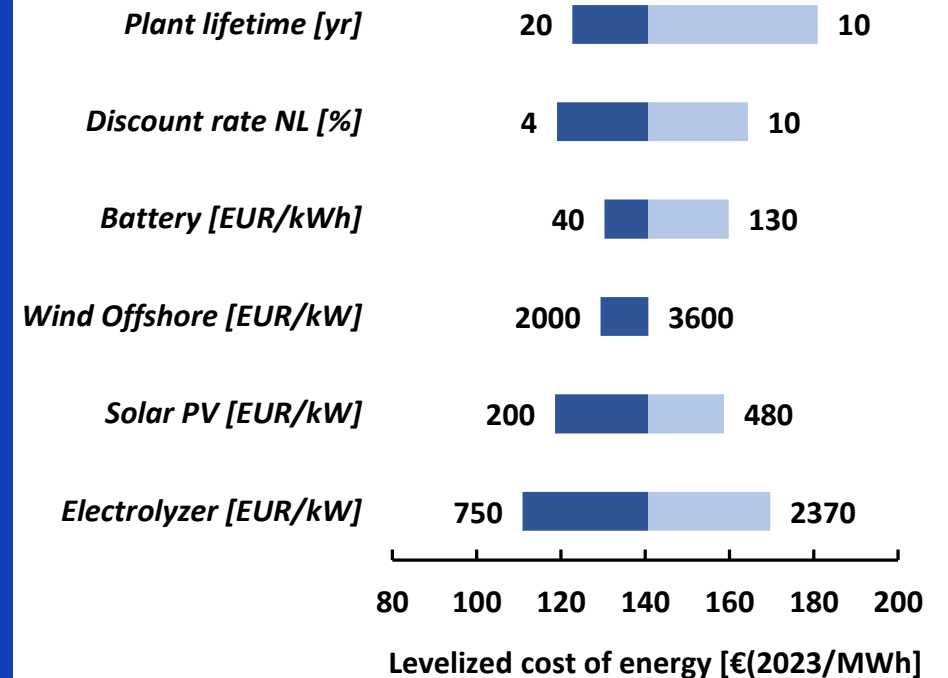
Sensitivity analysis for NL

How different parameters affect the costs is explored through sensitivity analysis in which the effect of changing a single parameter is indicated. Only the influence on the cost of energy is investigated for the 2040 projection.

The plant lifetime has a significant impact on the energy costs. The base case of 15 years is for simplicity reasons kept the same for all assets. Solar panels and wind turbines, for example, may last longer, which will reduce costs. Renewable energy is capital intensive and the discount rate has a substantial influence. A rate of 10% would increase the costs to 164 EUR/MWh, while a low rate of 4% leads to energy costs of 119 EUR/MWh.

A change in CAPEX of the battery demonstrates a substantial impact. If costs reduce less as projected, the energy costs go up to 160 EUR/MWh and installed battery capacity would go down from 967 MWh to 255 MWh and 57 MW_e of offshore wind is installed for compensation. If investment costs for offshore wind appear lower towards 2040, costs of energy may go down to 129 EUR/MWh (for offshore wind CAPEX of 2000 EUR/kW_e). This would also shift the installed capacity from 0 to 63 MW_e. Solar capacity would decline from 374 to 140 MW_e and battery capacity from 967 to 310 MWh. A different CAPEX for solar PV also clearly affects the energy costs. For solar PV CAPEX of 480 EUR/kW_e, the LCOE goes up to 159 EUR/MWh, mainly due to less solar PV and battery capacity and increased offshore wind capacity (35 MW_e). The electrolyser costs appear very influential and energy costs vary between 111 and 170 EUR/MWh for the explored CAPEX range. In the optimistic case, the battery capacity is lower and the electrolyser capacity increases from 78 to 120 MW_e.

FT - Sensitivity NL

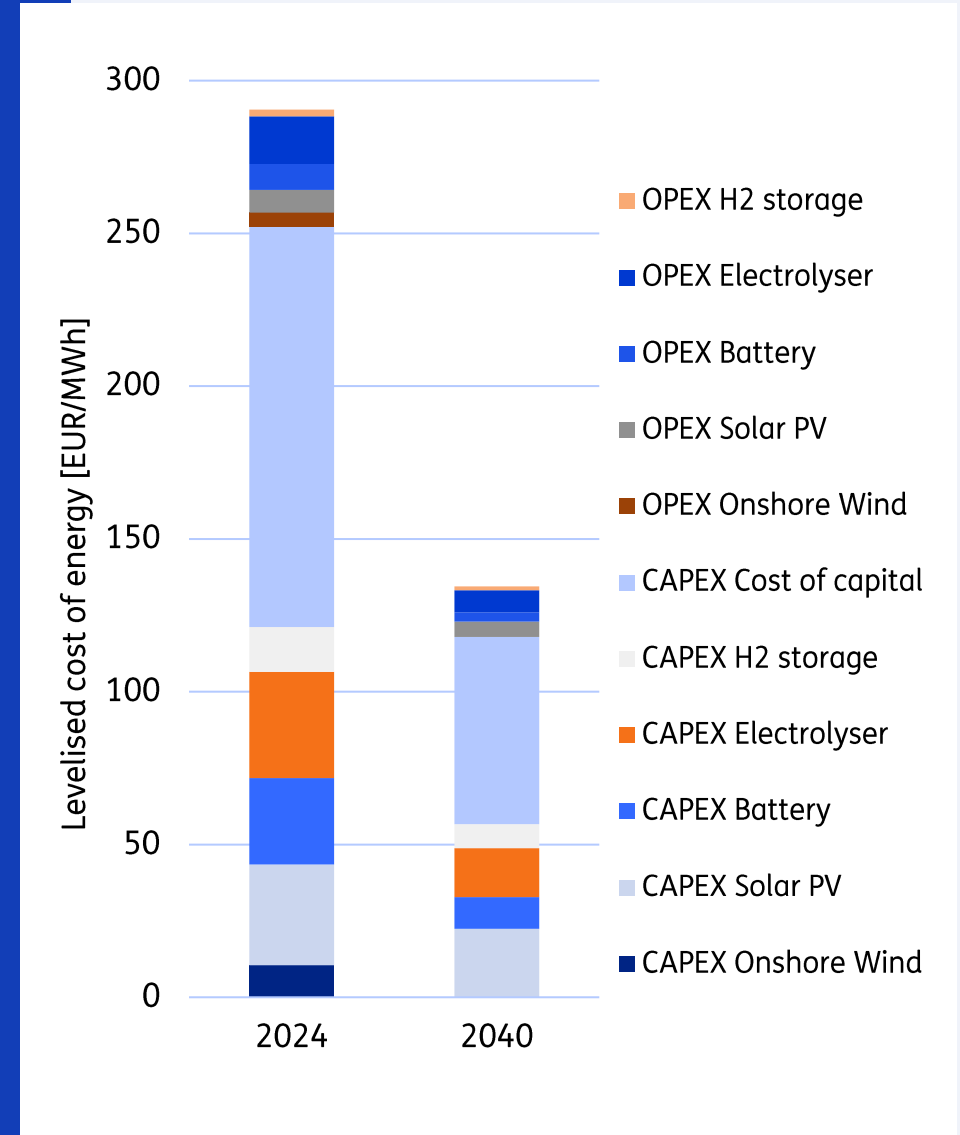


Renewable energy costs – SA

In Saudi Arabia, the base case costs of the supplied renewable energy to the FT plant amount to 291 EUR/MWh. This requires an installed capacity for solar PV and onshore wind of 211 and 45 MW_e, resp. Additionally, a battery storage capacity of 543 MWh and 48 ton of hydrogen tank storage is needed. All of the hydrogen that is produced by the 60 MW_e electrolyser is eventually used by the FT plant and none of it is converted by a CCGT. Around 87% of the produced energy comes from solar. 16% of the produced electricity from solar and wind together is curtailed.

For 2040, the relatively high cost reductions that are projected for solar PV and battery storage result in a shift in the installed capacities. No wind capacity is installed, while both the capacity of solar PV and batteries increase to 322 MW_e and 779 MWh. Slightly less hydrogen tank storage is required (26 ton). Not surprisingly, the cost reductions result in lower cost of energy of 135 EUR/MWh. All of the energy is now produced by solar PV (816 GWh/yr) of which 33% is curtailed.

The influence of the discount rate of 10.4% is indicated by the “Cost of capital” category, as the discount rate varies typically among different regions.



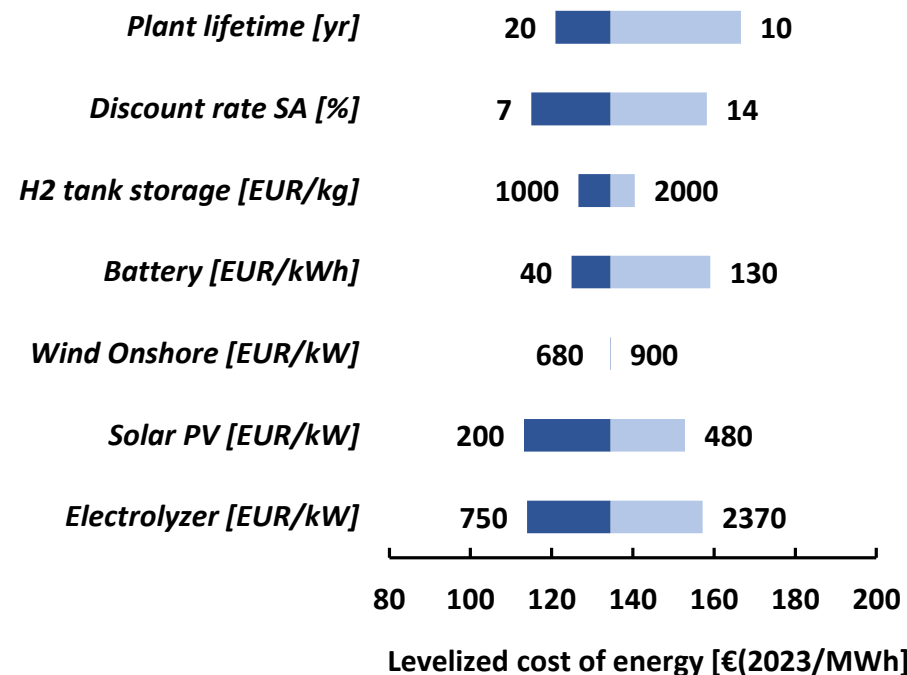
Sensitivity analysis for SA

Also for the syncrude case in Saudi Arabia a sensitivity analysis is performed to explore the influence of several parameters on the cost of energy in 2040. The plant lifetime has a significant impact on the energy costs. Variation between 10 and 20 years results in a range of the energy costs between 121 and 167 EUR/MWh. The discount rate has a substantial influence. When a discount rate similar to that in NL is applied, cost of energy reduce to 115 EUR/MWh, while a higher rate of 14% results in costs of 158 EUR/MWh.

A change in CAPEX of the H₂ tank storage indicates a modest impact but this is mainly because this type of storage remains costly and installed capacities remain limited (up to 38 ton). Energy is dominantly stored in the battery and a change in battery CAPEX results in an observed range of energy costs between 125 and 159 EUR/MWh. The effect on the installed capacities is limited. A different CAPEX for onshore wind has no effect as its capacity remains zero. As solar PV dominates the energy production, its CAPEX has a substantial impact on the energy costs. The installed capacity especially changes when the CAPEX of solar PV is higher as the base case. For a CAPEX of 480 EUR/kW_e, the solar PV capacity declines from 322 to 265 MW_e and more hydrogen tank storage is used (from 26 to 38 ton).

The electrolyser costs demonstrate a severe impact on the energy costs, which vary between 114 and 157 EUR/MWh for the explored CAPEX range. Interestingly, the installed capacities do hardly differ between the upper and lower side of the range.

FT - Sensitivity SA



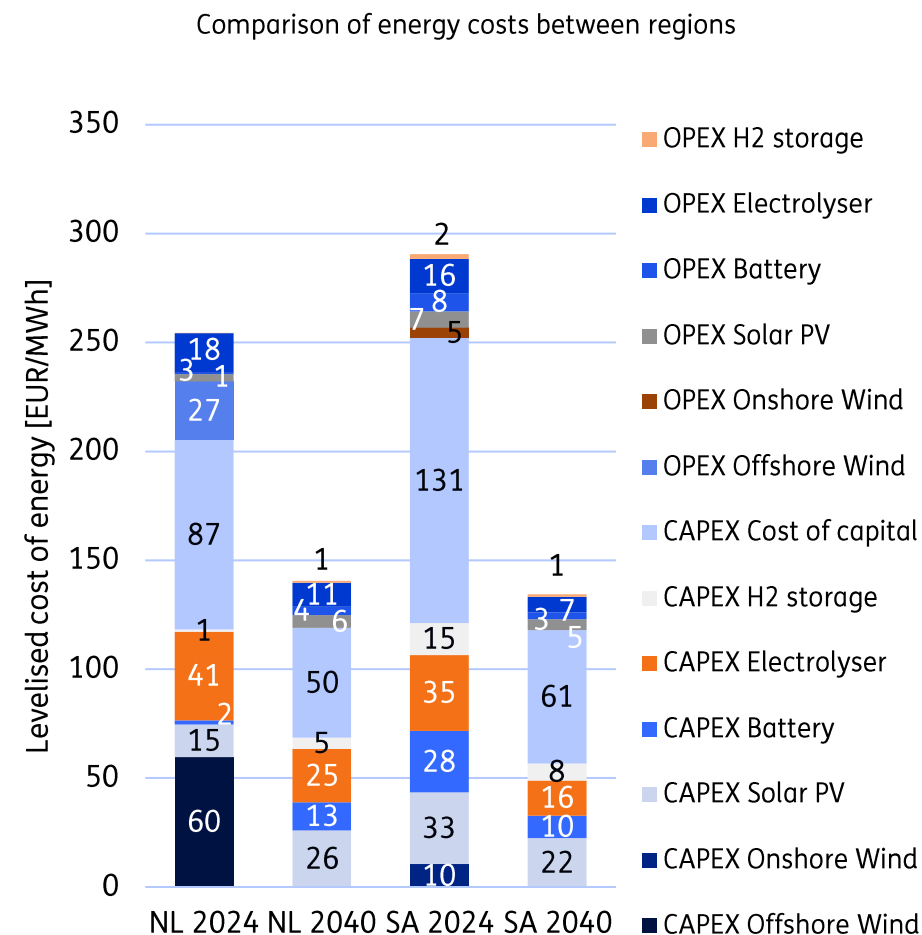
Comparison of regions

One of the main tasks of this study is to understand the difference in energy costs for industrial processes between regions. For the syncrude case, the results of the base case for 2024 indicate that the energy costs are very similar between NL and SA, namely 254 and 291 EUR/MWh.

Thanks to cost reductions for many of the technologies involved, projected energy costs reduce for both regions to 141 EUR/MWh in NL and 134 EUR/MWh in SA. This indicates that for the base scenario the energy costs are around 5% lower in SA compared to NL. This difference is very limited, especially when considering all uncertainty in the analysis.

These costs are substantially higher as often reported for only renewable electricity production (see also page 9). The main reason is the necessity to supply this energy continuously to the FT plant. All costs for flexibility and storage are included and these can be high. In the NL case, hydrogen cavern storage allows for more than 2 kt of hydrogen storage, while in SA only 26 ton of hydrogen tank storage is installed, but the latter at a higher cost. Modelling indicates (results not shown) that without cavern storage the cost of energy increases by around 50% for the NL.

Remarkably, the cost optimal result indicates for both regions in 2040 a nearly identical combination of installed assets, i.e. mainly solar PV combined with battery and hydrogen storage without any wind capacity.



Comparison of regions

Not only energy costs contribute to the production costs of the industrial process. Despite that energy costs may become slightly lower towards 2040 in SA than in NL, the syncrude production costs also depend heavily on other factors. The investment costs in the conversion facility, both for the gasification and FT processes, will contribute as well and are impacted by the discount rate. Also, the costs and availability of feedstock, such as municipal solid waste, are likely important other parameters. The total syncrude production costs are not investigated in this study.¹



¹ More details are provided in the report from RB “Study Energy Intensive Industries”, 2025.

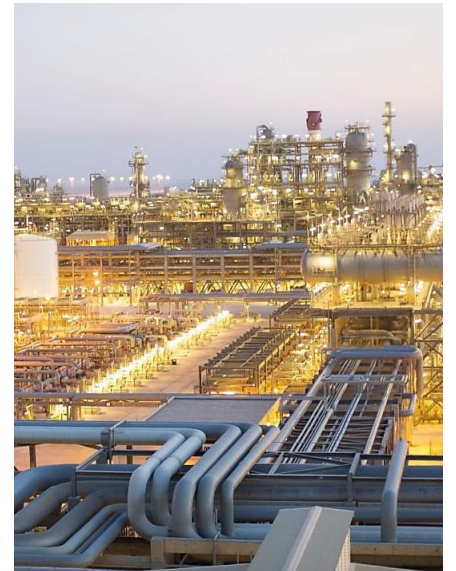
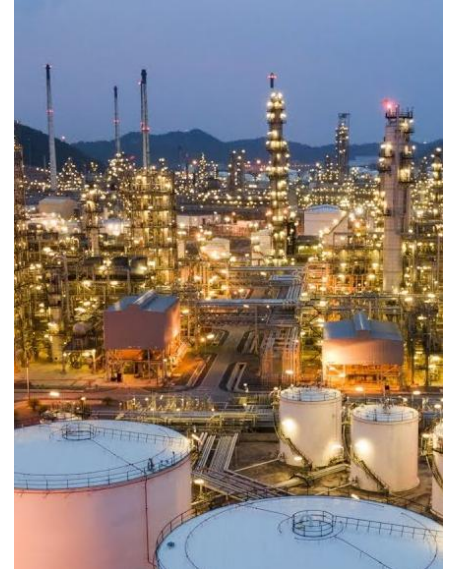
Conclusions and recommendations

The modelling approach allows to explore the cost of energy for different industrial processes, locations, and energy profiles, and the impact of those energy costs on the total product costs. The impact of running base load or allowing for some level of flexible operation can be investigated. The results from this study already indicate that **the type of process and level of flexibility can strongly influence the costs**. To acquire a better understanding of energy costs for industry, it seems worthwhile to analyse more value chains, with different modes of flexibility.

The model provides a **cost-optimal solution based on the energy input of the industrial process**. It excludes several other factors, such as operational risks, other costs for feedstocks and transport, and taxes. As the scope is currently limited to an “island” system, the impact of external connections is not investigated. An integrated system may provide a higher level of energy security and possibly offers more flexibility options that may appear cheaper than battery or hydrogen storage. Additionally, availability and use of existing assets and infrastructure are likely to have a substantial influence on the costs as well and are not investigated in this study. The only assumption around infrastructure is the supposed availability of a hydrogen network including cavern storage in The Netherlands.

Sensitivity analysis has already indicated the implications of other assumptions around the costs of different assets or parameters that affect project costs. Combinations of multiple changes in assumptions are not explored. Also, some inputs, such as the **weather profiles, are not varied and can have a substantial effect on the outcome**. Spatial limitations or social/political resistance can vary between regions and may limit the allowable installed capacities, e.g. for solar PV or onshore wind. Such constraints may lead to higher costs. It is recommendable to investigate these aspects in more detail.

The **learning curves of the different technologies impose a clear effect on the cost optimization**. Different learning rates and future deployment scenarios do directly impact the projected costs. Validation and impact analysis of the underlying assumptions is key to explore a proper solution space.

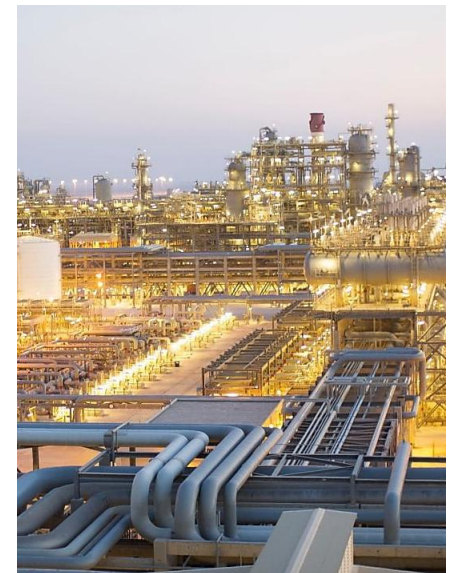
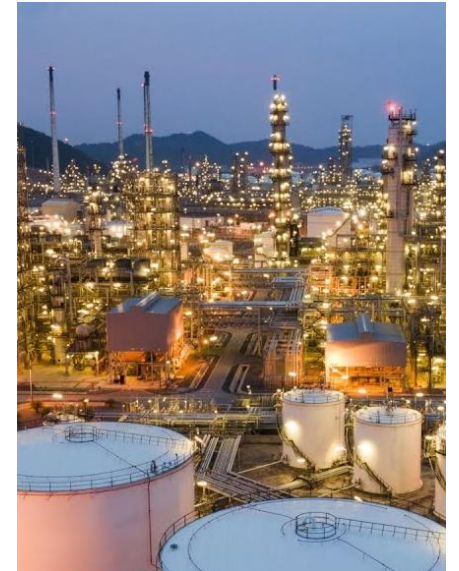


Conclusions and recommendations

Chlorine production chain. The first industrial value chain that is analysed is chlor-alkali production. In this analysis, this process only consumes electricity as energy source. The process is relatively flexible in that it can vary its operation between 40 and 100% and includes a chlorine storage facility, which can function as a buffer to secure a fixed and stable demand. The hydrogen that is produced as a byproduct can be stored and converted to provide electricity at times when no renewable supply is available. All together this results in projected energy costs in 2040 that are relatively low and amount to 73 EUR/MWh in NL and 43 EUR/MWh in SA. Energy costs are around 40% lower in SA compared to NL, but **the difference in chlorine production costs is only 8%**. To arrive at such costs in 2040, energy is in the NL case mainly supplied by solar PV but still around one third comes from offshore wind. In the SA case, all energy comes from solar PV in 2040. In NL, all hydrogen is converted into electricity by a CCGT, while in SA the CCGT capacity is typically one third of the capacity in NL and converts about 40% of the produced hydrogen.

Syncrude production chain. The second value chain, the syncrude production process, consumes both hydrogen and electricity and is assumed to operate without any flexibility. As the process requires hydrogen, an electrolyser plant is required as well. This results in **substantially higher projected energy costs in 2040** of 141 EUR/MWh in NL and 134 EUR/MWh in SA. The total syncrude production costs are not investigated. In contrast to the CA process in NL, in both regions energy in 2040 is solely supplied by solar PV. The demand for both hydrogen and electricity of the FT process also avoids the conversion of hydrogen in electricity by a CCGT.

This analysis of energy system costs, including storage, provides important insights in the future costs of energy for industrial processes. The results illustrate that **the type of value chain and the level of flexible operation has a significant impact on the costs of energy** and, also, on the observed difference between regions.



Appendix A – Data and modelling

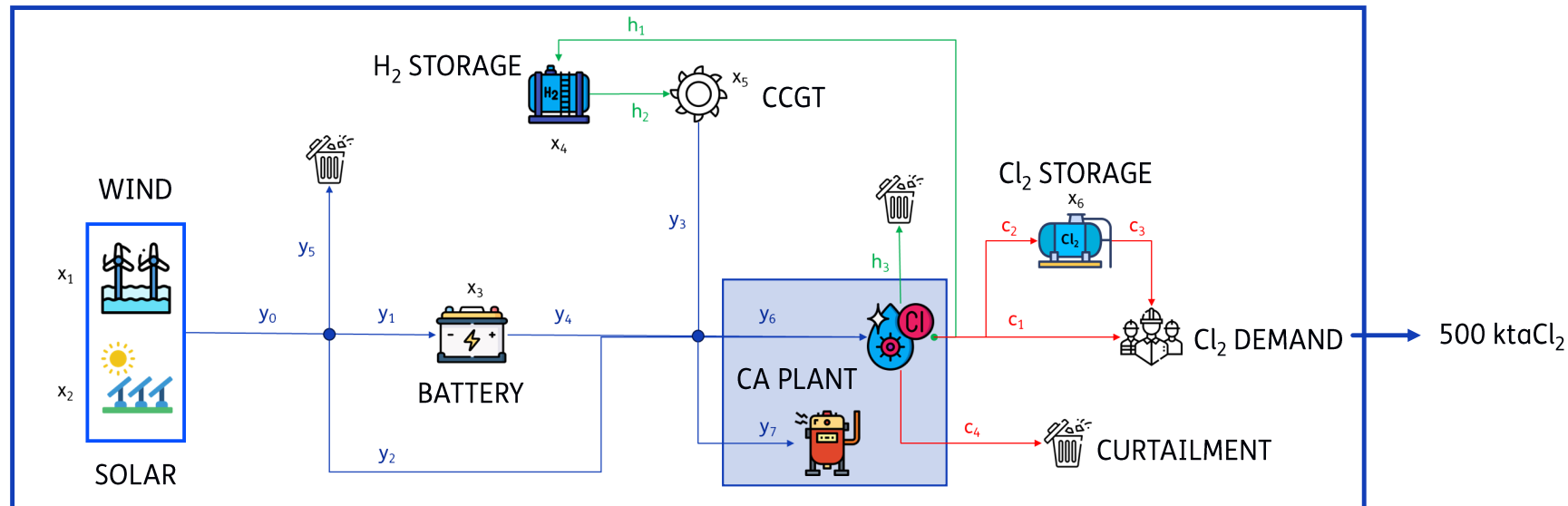
The costs for all assets and infrastructure, which are required to construct the “island” system, are determined for 2024 and projected for 2040.

- Costs for wind and solar energy supply, batteries and electrolyzers are projected based on their respective technology learning curves, typically by extrapolation of the observed costs reductions of the last decade
- Costs for hydrogen storage, infrastructure costs, and CCGT are based on current estimates and (almost) no cost reductions are implemented

The costs and operational parameters of various assets are determined and used in an “island-type” model of an industrial production process. The “island” approach is followed to avoid interaction with costs of systems that are influenced by (fossil-based) prices and tariffs, which may also depend on specific regulations and policies. For instance, coupling the island to an electricity grid would also require accurate forecasts of hourly prices in the specific region in 2040, which is barely impossible to do. By following this “island” approach the different value chains can be compared as cleanly as possible while it still allows to investigate several selected differences that apply for the specific regions. The system is solely dedicated to provide energy for the analysed industrial process. This also means that the analysed energy system is relatively small and that the influence of other energy supply options and energy demand from other sectors is not investigated.

Appendix A – Data and modelling

The model is mainly set up to find the optimal cost of energy that is supplied to the industrial process using renewable energy profiles on an hourly basis. The system for chlorine production is illustrated below. The analysis approach should enable to study the implications of operating a chemical process flexibly, at least to some extent. To do so, an optimization model has been setup based on linear programming. This approach allows full flexibility to the variables being optimized, as long as a set of hard constraints are satisfied. The capacities of several assets, such as the wind farm, solar PV, battery and hydrogen storage, CCGT, and (if applicable) an electrolyser plant, are optimized over the entire lifetime of the industrial plant (with perfect foresight) in the linear programming modelling to generate the lowest costs of energy.



Appendix A – Data and modelling

Assumptions and boundary conditions for the analysis:

- From the renewable energy that is produced 5% is lost due to conversion and distribution
- The battery operates at a round-trip efficiency of 90%
- All storages are initially filled by 50% and should be filled by 50% at the end of the run
- The efficiency of the CCGT is 50%, based on the hydrogen LHV
- The electrolyser plant has an efficiency of 70%, based on the hydrogen LHV

Appendix A – Data and modelling

The following cost data are used for the optimisation:

Component	CAPEX 2024	CAPEX 2040	OPEX	Sources
Onshore Wind Farm	1069 EUR/kW	712 EUR/kW	3% of CAPEX	IRENA + learning curve
Infra Onshore Wind	75 EUR/kW	75 EUR/kW	3% of CAPEX	NSWPH Pathway Study 2.0 (for 15 km land)
Offshore Wind Farm	3220 EUR/kW	2282 EUR/kW	3% of CAPEX	IRENA + learning curve
Infra Offshore Wind	567 EUR/kW	567 EUR/kW	3% of CAPEX	NSWPH Pathway Study 2.0 (for 50 km sea + 10 km land)
Solar PV	702 EUR/kW	278 EUR/kW	1.5% of CAPEX	IRENA + learning curve (average)
Infra Solar PV	60 EUR/kW	60 EUR/kW	1.5% of CAPEX	NSWPH Pathway Study 2.0 (for 15 km land)
Gas Turbine	963 EUR/kW	928 EUR/kW	3.5% of CAPEX	NSWPH Pathway Study 2.0
Battery Electric Storage	253 EUR/kWh	65 EUR/kWh	2% of CAPEX	IRENA + learning curve
H ₂ Tank Storage	1478 EUR/kg	1478 EUR/kg	1% of CAPEX	DOE Energy storage analysis 2019
H ₂ Cavern Storage	12.2 EUR/kg	12.2 EUR/kg	1% of CAPEX	EWI, HyWay27 (incl 0.22 EUR/kg for infra)
Cl ₂ Tank Storage	0.15 MEUR/kt _{Cl2}	0.15 MEUR/kt _{Cl2}	3% of CAPEX	Estimate provided by Nobian
Chlor-Alkali Plant	1.7 MEUR/kt _{Cl2}	1.7 MEUR/kt _{Cl2}	6% of CAPEX	Estimate provided by Nobian
Electrolyser Plant	2843 EUR/kW	1520 EUR/kW	3% of CAPEX	Eblé & Weeda, 2024, Detz & Weeda, 2022

Sources: IRENA Renewable power generation costs in 2023 ([Renewable Power Generation Costs in 2023](#)); IEA World Energy Outlook 2024 ([World Energy Outlook 2024 – Analysis – IEA](#)); North Sea Wind Power Hub Programme, [Pathway 2.0 Study](#), 2024; DOE Hydrogen and Fuel Cells Program, [Energy Storage Analysis](#), 2019; EWI, [Die Bedeutung von Wasserstoffspeichern – Eine Analyse der Bedarfe, Potenziale und Kosten](#), 2024; HyWay27, [HyWay 27: hydrogen transmission using the existing natural gas grid?](#), 2021; Eblé, L. F. J., Weeda, M. (2024). ([TNO 2024 R10766](#)); Detz, R., Weeda, M. (2022). ([TNO 2022 P10111](#));

Appendix B – Cost of energy

The **levelized cost of energy (LCOE)**, which is optimised in the modelling, is defined as:

$$LCOE = \frac{NPV_{costs}}{NPV_{Energy}}, \text{ where: } NPV_{costs} = -CAPEX + \sum_{i=1}^{operation\ years} \frac{-OPEX}{(1 + discount\ rate)^i}$$

$$NPV_{Energy} = \sum_{i=1}^{operation\ years} \frac{Energy_{total\ yearly\ input\ to\ plant}}{(1 + discount\ rate)^i}$$

with CAPEX representing all investments required into the assets in the system (all spend in year 0), operation years referring to the plant lifetime minus the year of construction, OPEX covering all fixed operational & maintenance costs for the assets in the system, and the discount rate describing the weighted average cost of capital (WACC) in a region

- The cost for the industrial process are not considered in the energy cost's calculation
- The energy to produce steam is included in the *NPV*
- If applicable, the energy content of hydrogen input to the plant is calculated via the lower heating value (LHV = 120 MJ/kg)

Definition of the LCOE in this study

The levelized cost of energy (LCOE) represents the average discounted cost of energy provision for a system over a specified lifetime.

The value of the energy provided can change depending on the [perspective](#).

- The first perspective is the amount of energy (most often electricity) generated by the renewable energy generation system. This does not consider curtailment and intermediate conversion losses.
- The second perspective is the amount of energy consumed by the system. Here all the curtailment and intermediate conversion losses are not counted as energy provision. As a result, the levelised cost of energy are higher.

In this analysis, the second perspective is consistently used. Considering the focus on overcoming the intermittency of renewables to provide energy for an inflexible process, it is important to take into account all of the energy losses resulting from these dynamics. In these costs are the additional cost of energy to drive an industrial process continuously incorporated.

Appendix C

Data chlor-alkali production in The Netherlands

CA-NL		Base case	Sensitivity 2040														
		2024	2040	Chlorine storage	Solar PV		Wind Offshore	Battery		CCGT		Discount rate		Plant lifetime			
parameter			opt	con	opt	con	opt	con	opt	con	opt	con	opt	con	opt	con	
Wind [MW]		201	118	137	110	102	152	191	108	115	181	118	117	117	118	117	118
Solar [MW]		283	588	487	650	762	410	298	662	569	366	580	596	598	583	590	580
Battery [MWh]		267	1366	1122	1435	1366	1001	421	1433	1562	432	1368	1344	1361	1356	1368	1368
Cl ₂ Storage [Ton]		2000	2000	4000	1000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
H ₂ Storage [Ton]		2680	6481	5610	6749	6860	5089	3090	6794	6721	3435	6463	6459	6494	6451	6490	6463
CCGT [MW]		81	74	58	91	74	78	80	73	74	80	74	74	74	74	74	74
LCOE [EUR/MWh]		113	73	72	75	65	80	61	81	70	79	71	75	62	85	64	94
LCOC [EUR/kg]		0.75	0.63	0.63	0.64	0.61	0.65	0.59	0.66	0.62	0.65	0.62	0.64	0.56	0.71	0.58	0.76
Cl ₂ To Demand [kTon]		500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Cl ₂ Curtailed [kTon]		0	3	0	5	4	0	0	4	5	0	3	3	3	3	3	3
Cl ₂ Produced [kTon]		500	503	500	505	504	500	500	504	505	500	503	503	503	503	503	503
Total Energy Input Plant [GWh/year]		1453	1462	1453	1468	1465	1453	1453	1465	1466	1453	1461	1461	1462	1461	1462	1461
Total Energy Produced Solar [GWh/year]		464	964	797	1064	1249	671	488	1084	931	599	949	976	979	955	967	949
Total Energy Produced Wind [GWh/year]		900	526	615	491	456	683	857	484	516	812	531	525	522	530	525	531
Total Energy Curtailed [GWh/year]		123	184	129	237	382	84	97	251	136	159	174	196	196	181	187	175
Total Energy Curtailed Solar [GWh/year]		70	162	107	213	352	63	59	227	117	113	152	173	173	158	165	152
Total Energy Curtailed Wind [GWh/year]		53	23	22	24	30	21	38	24	19	46	22	23	23	23	23	22
H ₂ produced used for CCGT [%]		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Appendix D

Data chlor-alkali production in Saudi Arabia

CA-SA	Base case		Sensitivity 2040															
	2024	2040	Chlorine storage	Solar PV	Wind Onshore		Battery		CCGT		H2 tank storage		Discount rate		Plant lifetime			
parameter		opt	con	opt	con	opt	con	opt	con	opt	con	opt	con	opt	con	opt	con	
Wind [MW]	23	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0
Solar [MW]	713	717	590	918	722	716	717	717	718	711	718	717	716	721	717	717	717	717
Battery [MWh]	1576	2058	2117	2581	2061	2056	2058	2058	2091	1685	2047	2089	2056	2068	2058	2058	2058	2058
Cl2 Storage [Ton]	2000	2000	4000	1000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
H2 Storage [Ton]	18	2	1	4	1	2	2	2	2	13	2	3	2	1	2	2	2	2
CCGT [MW]	47	25	28	21	25	26	25	25	23	40	26	23	26	25	25	25	25	25
LCOE [EUR/MWh]	112	43	39	53	33	54	43	43	38	57	42	44	43	43	37	51	39	54
LCOC [EUR/kg]	0.78	0.58	0.57	0.61	0.55	0.61	0.58	0.58	0.57	0.62	0.58	0.59	0.58	0.58	0.53	0.65	0.54	0.68
Cl2 To Demand [kTon]	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Cl2 Curtailed [kTon]	0	0	2	11	2	1	0	0	1	0	1	0	0	2	1	1	1	1
Cl2 Produced [kTon]	500	500	502	511	502	501	500	500	501	500	501	500	500	502	501	501	501	501
Total Energy Input Plant [GWh/year]	1452	1454	1458	1484	1458	1455	1454	1454	1455	1453	1455	1453	1453	1458	1455	1456	1454	1455
Total Energy Produced Solar [GWh/year]	1805	1816	1494	2325	1830	1814	1816	1816	1818	1802	1819	1815	1814	1826	1816	1816	1816	1816
Total Energy Produced Wind [GWh/year]	43	0	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0
Total Energy Curtailed [GWh/year]	437	286	40	667	305	283	286	286	272	389	290	272	280	300	284	285	284	285
Total Energy Curtailed Solar [GWh/year]	430	286	40	667	305	283	286	286	272	382	290	272	280	300	284	285	284	285
Total Energy Curtailed Wind [GWh/year]	7	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0
H2 produced used for CCGT [%]	81	41	70	22	46	41	41	41	37	68	43	37	40	46	42	42	41	42

Appendix E

Data syncrude production in The Netherlands

FT-NL	Base case		Sensitivity 2040											
		Electrolyser		Solar PV		Wind Offshore		Battery		Discount rate		Plant lifetime		
parameter	2024	2040opt	con	opt	con	opt	Con	opt	con	opt	con	opt	con	
Wind [MW]	76	0	0	9	0	35	63	0	0	57	0	0	0	0
Solar [MW]	95	374	335	364	425	224	140	374	371	164	375	374	375	374
Battery [MWh]	39	967	537	903	914	652	310	967	1000	255	967	965	967	963
Electrolyser [MW]	69	78	120	71	74	69	62	78	78	70	78	79	78	79
H2 Storage [Ton]	430	2050	2169	1720	1888	1120	534	2050	2063	684	2047	2051	2047	2052
CCGT [MW]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LCOE [EUR/MWh]	255	141	111	170	119	159	129	141	130	160	119	164	123	181
H2 To FT [kTon]	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
H2 Curtailed [kTon]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Electricity Input Plant [GWh/year]	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Total Energy Produced Solar [GWh/year]	156	613	548	597	696	367	230	613	607	269	615	613	615	612
Total Energy Produced Wind [GWh/year]	342	0	0	40	0	157	282	0	0	254	0	0	0	0
Total Energy Curtailed [GWh/year]	43	99	62	122	177	33	33	99	93	44	100	98	100	98
Total Energy Curtailed Solar [GWh/year]	23	99	62	120	177	28	23	99	93	35	100	98	100	98
Total Energy Curtailed Wind [GWh/year]	20	0	0	2	0	4	11	0	0	9	0	0	0	0
H2 produced used for FT [%]	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total Energy Input Plant [GWh/year]	324	324	324	324	324	324	324	324	324	324	324	324	324	324

Appendix F

Data syncrude production in Saudi Arabia

FT-SA	base case	Sensitivity 2040															
	2024	2040Electrolyser		Solar PV		Wind Onshore		Battery		H2 tank storage		Discount rate		Plant lifetime			
parameter		opt	con	opt	con	opt	con	opt	con	opt	con	opt	con	opt	con		
Wind [MW]	45	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
Solar [MW]	211	322	312	327	336	265	322	322	328	309	265	329	322	322	322	322	322
Battery [MWh]	543	779	778	800	779	791	779	779	805	730	791	808	779	779	779	779	779
Electrolyser [MW]	60	51	52	51	51	52	51	51	51	51	52	51	51	51	51	51	51
H2 Storage [Ton]	48	26	28	24	24	38	26	26	24	29	38	24	26	26	26	26	26
CCGT [MW]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LCOE [EUR/MWh]	291	135	114	157	113	153	135	135	125	159	127	140	115	158	121	167	167
H2 To FT [kTon]	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
H2 Curtailed [kTon]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Electricity Input Plant [GWh/year]	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Total Energy Produced Solar [GWh/year]	533	816	790	829	851	672	816	816	832	782	672	833	816	816	816	816	816
Total Energy Produced Wind [GWh/year]	82	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
Total Energy Curtailed [GWh/year]	99	270	245	283	304	134	271	271	286	251	139	288	271	270	272	271	271
Total Energy Curtailed Solar [GWh/year]	89	270	245	283	304	134	271	271	286	249	139	288	271	270	272	271	271
Total Energy Curtailed Wind [GWh/year]	11	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
H2 produced used for FT [%]	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total Energy Input Plant [GWh/year]	324	324	324	324	324	324	324	324	324	324	324	324	324	324	324	324	324