Supplementary Material

1 SUPPLEMENTARY DATA

1.1 Methods

As discussed in section 2, interviews were conducted to verify and complement information from literature. The questions and notes taken during the interviews are presented in the following.

1.1.1 Interview reference *a*

1. Does your company have greenhouse gas emission reduction targets?
   Yes, they do.
2. Can you estimate which part of the production process emit the most greenhouse gases?
   Mainly air separation, hence electricity.
3. Regarding the emissions originating from utilities, which measures is your company considering at this moment? And for emissions from the process?
   Green hydrogen, but that's mainly certificates that don't help anything because they just shift the emissions to elsewhere. CCS really helps, and if the responsible wouldn't have waited to deploy it while developing green hydrogen we could have stored a lot of CO2.
4. Is your company considering alternative feedstocks to replace fossil carbon feedstocks?
   No, but they are planning to sell the CO from their processes to others as alternative feedstock.
5. Does your company foresee problems that could arise from electrifying your processes?
   Efficiency goes down so much, that it is not reasonable to run an electrolyser flexibly. So rewards/incentives would need to be very high.

   With the increasing use of renewable energy sources for electricity production, prices for electricity will fluctuate, which might cause difficulties for the prediction of costs of production. In addition, peak prices are foreseen to increase. Literature suggests that flexible production processes could cope with intermittent electricity supply, but it may affect cost of production.
6. Would you consider running your process in a flexible way?
   No, they would not, because it is so inefficient.
7. What would you still need to know to assess the potential of flexible production and to understand the challenges that come with it?
   Electrolysers would need to be able to efficiently deal with seawater and ramping up and down/being shut on and off. There needs to be an economic level playing field, so difference between conventional and alternative has to become smaller, either via CO2 costs or incentives. Legislation needs to become clearer and more reliable.
8. Do you consider flexibility as a criterion in further investment decisions?
   Some plants are run according to electricity prices already today (using buffers), thus they are offering emergency capacity to the TSO already today, and it is very well paid. Step has been done in the past from steam driven processes to electricity driven processes. There has to be a balance because of dependence on electricity prices and flexibility.

9. Do you think it will be playing a main role after 2030?
   Generating and consuming parties need to find ways how to balance uncertainties that are increasing with increasing deployment of renewables. No, it won't play a main role in 2030, because for offering it to the TSO that is already being decided (by the TSO) now, and they require 15 minute data for 2030 being available today.
10. Do you see an opportunity to use this flexibility to provide grid stabilizing services to the grid operators?
    Very difficult.
11. Why not? What would be necessary to change it?
    Grid operators are not willing to be more flexible in their regulations, so there is no room for cooperation because they are not taking steps towards other parties. But they are also subject to political decision making, which is not clear and too slow.

1.1.2 Interview reference *b*

1. Is your company concerned about the intermittency of electricity generation from RES?
   Yes, definitely. Part of offshore tenders are requirements for system integration. Profiles have to be matched.
2. Do you see potential solutions to overcome this issue?
   Yes, they see all kinds of options. PtX (e.g., power to molecules) and storage (electrical storage in batteries, but also heat storage). They are also looking into demand response from customers, both, private costumers (smart EV charging, use of heat pumps and electrical boilers for warm water generation) and industrial consumers (heat storage in food industry).
3. Where do you see the potential(s) of hydrogen?
   Potential might by heavy duty mobility, or using the PoR as hub for export. They are also looking into blending hydrogen with natural gas for use in households (for warm water generation). They decided not to consider the application in light duty mobility, because batteries make more sense. But in the end, OEMs decide about application in mobility sector.
4. Is your company planning to produce hydrogen themselves?
   Yes, they are working on hydrogen production via water electrolysis with green electricity from, e.g., offshore wind parks. At the moment, green hydrogen production is not economically feasible and it gets even more difficult when intermittent production is considered.
5. Are you concerned about intermittency in electricity supply?
   Yes, definitely. Buffers are required, especially because the industry requires continuous hydrogen supply. Maybe hydrogen can be stored in salt caverns in the border region with Germany.
6. Until reaching full decarbonisation, is your company looking into strategies to deal with remaining CO2 emissions?
   They are not in favour of CCS, because that means just postponing problems to the future. So storing CO2 is not part of their strategy.
7. Do you think CCU, carbon capture and utilisation, is a potential solution?
   Yes, they see a real potential in CCU, because there will be a scarcity in the future. Many new applications are appearing that require additional CO2.
8. Where do you see the main benefits from CCU?
   In CCU for chemical processes to move towards a sustainable chemical industry.

9. Where do you see main challenges for the deployment of CCU?
   In the costs! The quality will also be an issue, but costs will be the main challenge. The technology is there.
10. In academia, PtX is regarded as potential grid stabilizing method, to balance out electricity demand and generation. Do you agree or disagree with this consideration? Why?
    That would be very complex. Rather use batteries or gas fired stations (fuelled with hydrogen). But it seems like an interesting idea to look into.
11. Do you see potential barriers for the use for grid balancing?
    Yes, because even though energy managers might be inclined to the idea, plant managers see their production schedule endangered and are strongly opposing the idea.

1.1.3 Interview reference *c*

1. Your company wants to be carbon neutral in 2040. Which measures is your company taking at this moment? And in the long term?
   For electricity-based processes: moving towards green electricity, for steam-based processes: getting rid of steam from gas. Short-term measures: steam from waste incineration, long-term options are heat pumps. Hence, moving towards electricity-based processes and the use of green electricity

   With the increasing use of renewable energy sources for electricity production, prices for electricity will fluctuate, which might cause difficulties for the prediction of costs of production. In addition, peak prices are foreseen to increase. Literature suggests that running production processes in a flexible way could help coping with these consequences of intermittent electricity supply, but that it may affect cost of production.
2. Would you consider running your processes in a flexible way? What are the main barriers, and where do you see the greatest potential?
   The potential or motivation is the incentive of reducing costs for electricity. At the first look, this seems rather easy, but there are challenges. Technical challenges are the response time of the installation, but also challenges related to IT: How can a connection be installed that ensures that no external party can interfere in the processes? Next to technical challenges, there are economic barriers. Investment costs might be high, and the payback time is uncertain because of the difficult prediction of the market and of electricity and gas prices.
3. Do you consider flexibility as a criterion in further investment decisions?
   No, flexibility alone is not a driver for investment. The demand for products has priority, so if the market price is good, processes won't be run flexibly. It might be an incentive to increase the capacity of existing installations, but not for new installations.
4. Do you think it will be playing a main role after 2030?
   It might change in the future, but that depends on the value of flexibility. However, chlor-alkali might not be the best product for flexibility provision, since chlorine is not stored easily. Water electrolysis might be a better candidate.
5. Do you consider the pilot as an example or inspiration for other chemical companies?
   The case has to be assessed for each industry separately. Especially for high-temperature processes it might be very difficult. The case for electricity driven processes is easier, and there's a big potential for heat pumps. Distillation columns can run more flexible, but that's a relatively new technology and there are no incentives to invest in these.

6. During your collaboration with the company from the power sector, were there any mayor points of misunderstanding? Have they been aware of the technical challenges that had to be solved?
   The 'language' they speak is indeed different. They wanted to move fast. The risk is not with them, so it's relatively more easy for them to set up the cooperation. [Remark: The interviewee mentioned that he was not involved in the communication much]
7. Do you see an opportunity to use your flexibility to provide grid stabilizing services directly to a grid operator, or offer it on the electricity market?
   Working with an aggregator, or someone that has a portfolio of options is advantageous, since the plant cannot always be online. If a costumer requires changes in the production, this request has to be fulfilled with priority.

1.1.4 Interview reference *d*

1. Can you estimate which parts of the production process emit the most greenhouse gases?
   For scope 1 it's in operations. Upstream is very little, bulk is refinery and chemicals production.
2. Scientific literature suggests that emissions come mainly from energy required for processes (generation of heat and electricity), and from the use phase of end products (from the use of fossil feedstock). Do you think the same sources for emissions apply for your company? Are any important sources missing?
   Scope 3 are higher than their own emissions, most emissions come from processes that require heat input at higher temperatures, like refining and steam cracking.
3. Regarding the emissions originating from utilities, which measures is your company considering at this moment? And for emissions from the process?
   Increasing the efficiency (has been going on for a while). Recently, they have started to replace cracking furnaces by high efficiency furnaces.
4. The suggestions we found in literature include a more efficient use of heat, but also the use of low carbon electricity and heat from, I.e., hydrogen or renewable energy sources. What do you think about these suggestions?
   In the long term, electrification of steam cracking with renewable power is an option. Hydrogen for heat production comes with a lower efficiency. It is easier to use direct electrification. Of course, hydrogen may offer advantages from a storage point of view.
5. Is your company considering alternative feedstocks to replace fossil carbon feedstocks?
   Yes, they are considering the use of recycled plastics via pyrolysis. A pilot project is running, the aim is to scale it up to 0.5 million ton/year by 2025.
6. Which options are most promising, in your opinion? Why not carbon from captured CO2?
   The aim is to degrade as little as possible, and with recycled plastics you directly get hydrocarbons. It is difficult to estimate if it can cover the full demand (supply chain problem). In the end, it will most likely be a mix of feedstocks and solutions, bio feedstocks might play a role too. They are investigating other options with lower TRL, such as direct ethylene production from CO2. This includes research focussed on the dynamics of this technology.
7. Does your company consider hydrogen a possible solution to reduce GHG emissions, and are you looking into the potential of power to X?
   Hydrogen is an enabler for sector coupling via PtX. They are investing in the use of hydrogen for mobility, for light-duty and heavy-duty vehicles, but maybe also for trains, and marine applications. Preferably, it should be green hydrogen, but as long as the market is not sufficiently developed it can

also be blue hydrogen. They are working on the supply chain, starting from the customer and working back into the supply chain.

8. Where do you see the greatest potential for PtX? What do you regard as the biggest challenge for PtX?
   The economics in the mobility sector are better than for other use cases of hydrogen. But the costs remain the biggest challenge. A major cost contribution is the price of renewable power. It is expected that by scaling up costs can be reduced. Also, dynamics can be a problem since renewable power is intermittent. Sector coupling has benefits, but also a serious downside. It requires large capital investment, so what if no low-cost renewable power is available? (large investment standing idle).
9. Earlier on, I mentioned the use of low carbon electricity. I would like to ask some further questions on this. Does your company foresee problems that could arise from electrifying your processes?
   Yes, the economics.

   With the increasing use of renewable energy sources for electricity production, prices for electricity will fluctuate, which might cause difficulties for the prediction of costs of production. In addition, peak prices are foreseen to increase. Literature suggests that flexible production processes could cope with intermittent electricity supply, but it may affect cost of production.
10. Would you consider running your process in a flexible way? *It would be difficult. You a) lose production and b) efficiencies go down, so you require more electricity, thus, you don't really get the benefit. Those losses are not going to be compensated. Plus, starting up processes takes too long. Flexibility should rather come from somewhere else. Also see* **?**. *It is worthwhile noting that in the overall supply chains only the production of fuels and base chemicals needs to be flexible. Methanol, ammonia, hydrocarbons etc., all liquids at ambient pressure and temperature can be stored in a cost-effective way for weeks even months.*
11. Do you consider flexibility as a criterion in further investment decisions? Do you think it will be playing a main role after 2030?
    Maybe, also see above, but there are also other options like storage and grid extension (using HVDC technology). Seasonal storage will still be required, storage of hydrogen has a potential, and other energy dense carriers such as ammonia, methane, methanol or other hydrocarbons (PtL).

1.1.5 Interview reference *e*

1. The national government has set greenhouse gas emission targets, to which most companies have responded with strategic roadmaps to align their emission reduction goals to the national target. Does your company consider hydrogen in their strategic roadmap?
   See **?**
2. Is your company concerned about maintaining grid stability with 100% deployment of RES?
   See slide 15 in **?**
3. Where do you see greater challenges: In short-term, or long-term balancing?
   Both! Volume for day-ahead market should increase, too.
4. Does your company think that industry plays a role as a provider for DR or other grid stabilizing services?
   Yes, consider **?**
5. How does the development of sector coupling with for example, the mobility sector, influence your answer to the previous question?

Can't say exactly. EVs hold a very interesting and large potential for mitigating day/night fluctuations, but I can't say how fast bidirectional/smart charging will take off, although work is in progress.

6. Has your company investigated the future development of electricity demand from the chemical industry?
   We have not investigated future electricity demand from the chemical industry. We have looked into the potential contribution to demand response though (see **?***). We'd expect an increase rather than a decrease of electricity demand, since electrification is an important decarbonization route in most Cluster Energy Strategies (see* **??***).*
7. Has your company investigated a potential cooperation with the chemical industry for grid balancing services?
   There is a list of Balancing Service Providers – parties that we contracted for providing grid services. The list includes aggregators, such as Next Kraftwerke, that actively seek and aggregate demand response potential from multiple endusers, including industry.
8. Beside the technical conditions, are there other, non-technical, conditions for a successful collaboration?
   We haven't spoken much to chemical industry yet.
9. Have you identified barriers for the deployment of the chemical sector for DR?
   Uncertainty about availability of grid capacity required for electrification, grid tariff structure, additional layer of complexity, and for balancing services: product specifications

1.1.6 Interview reference *f*

1. Your company has announced greenhouse gas emission reduction targets, could you name the main pillars of your decarbonisation strategy
   Coal Phase-out and increasing deployment of renewable energy sources, transformation of gas assets: increasing replacement of gas by hydrogen, oil (very few operational hours): to be replaced with bio oil (expensive, but required volumes are low).
2. As an energy generator, is your company concerned about the intermittency of electricity generation from RES?
   They are aware of the requirement for storage, both for short-term and seasonal duration.
3. Do you see potential solutions to overcome this issue?
   CO2 based energy carriers for seasonal storage are technically feasible, but not economically. The 'ideal' solution remains the big question as of today.
4. Is your company considering using hydrogen for your products/processes?
   Yes, mostly for the replacement of gas assets. Production could be used to consume peaks in generation, but is not economically feasible.
5. Is your company planning to produce hydrogen themselves?
   Yes, there are projects aiming for plants at 100 MW scale. They would like to increase production, but it is too expensive as of today.
6. What process(es) are you considering for hydrogen production and why?
   Both blue hydrogen (SMR with carbon capture) and green hydrogen via water electrolysis (both PEM and alkaline have been tested).
7. Are you concerned about intermittency in electricity supply?
   PEM should be technically feasible for running flexibly, but there are no final studies or answers yet.

8. Is your company looking into strategies to deal with remaining CO2 emissions?
   Yes, they are considering CCS and CCU in their innovation departments. They are conducting feasibility studies alone and with partners, kerosene and methanol are in strong focus, while methanol could be used as platform chemical and as maritime fuels.
9. Where do you see the main benefits from CCU?
   There could be business cases for commodity trading, but it is not clear yet where the future position of the company will be and what the main interests are from customers. CCU is interesting for the 'clean' production of several end products that could become the new main energy carriers, however that potential depends on the classification of the companys' CO2 sources. Another potential is to offer decarbonisation for industrial customers (small to middle scale companies) as in use of CO2 emissions they can't avoid, alongside electrification.
10. Where do you see main challenges for the deployment of CCU?
    Regulations are not in place on European level, which hinders the economic feasibility. The willingness among industry is there. The main problem are the costs and the lack of clear regulations and rewards.
11. In academia, PtX is regarded as potential grid stabilizing method, to balance out electricity demand and generation. Do you agree or disagree with this consideration? Why?
    There are processes that require large amounts of electricity, so there is potential. Technically it has to be assessed carefully for different processes (CAE seems to suitable), but it doesn't seem to be impossible. Buffers could help to run flexible process units according to electricity production and units that require constant operation together.
12. Do you see potential barriers for the use for grid balancing?
    The main problem will be economical feasibility. Losses in revenues from production would need to be balanced by revenues from the grid operators. Another issue will be the planning of innovation or replacement of technologies. Existing assets will be running until the end of their lifetime. Patience will be required, and bridging solutions have to be found that are economically feasible even for a short operational period.