# Analysing the feasibility of industrial decarbonisation pathways through electrification and zero carbon fuel (ZCF) applications

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## Abstract

Industrial decarbonisation is one of the most significant hurdles as we move towards a global net-zero $CO_2$ emissions target. Processes requiring high temperatures and heavy-duty transport are major complications, with cost and feasibility of implementation of zero carbon methods often significant barriers, especially for medium sized or smaller businesses. This study shows that decarbonisation of business processes through electrification as well as on-site green ammonia generation, is possible and can be profitable for this scale of company. Mühlendorfer Kreidefabrik, used as a case study, is an Austrian chalk processing factory that emits approximately 4680 tonnes of $CO_2$ per year whilst spending EUR 664,000 on energy.

Different decarbonisation scenarios were investigated, based on the general concepts of electrification and zero-carbon fuel (ZCF) generation. The study leveraged simulation algorithms in conjunction with past usage data of the company in order to model supply and demand in future years. 4.7 MW of solar PV panels as well as one 3 MW wind turbine are required in a pure electrification scenario. Including the replacement cost of fossil-fuel by electrified equipment and an estimated lifetime of 20 years, this system is expected to cost ~EUR 512,000 annually. A larger electricity generating system of 13.7 MW solar PV panels and one 3 MW wind turbine is required in a ZCF scenario, along with a 3.9 MW alkaline electrolyser connected to an air separation unit and Haber-Bosch equipment. This system will produce ~1887 t of green ammonia per year, sufficient to replace both natural gas and Diesel currently used in the factory, requiring only adaptation of current plant and machinery instead of replacement. Costing ~EUR 714,000 annually, this option is more expensive, however has further advantages in minimising interference in factory operations. This pathway seems also preferable due to the uncertainty in availability of a pure electrified solution even with the extra costs.

## Introduction

As climate change and global warming are increasing threats to our planet, global leaders have made efforts to set sustainability goals, within frameworks such as the Paris Agreement[1], which aims at keeping the global average temperature rise below 2°C and pursuing efforts to limit this change to 1.5°C above pre-industrial levels in both cases. Within the context of this agreement, every participating country is meant to publish Nationally Determined Contributions (NDC), which outline the nation's goals and hence roadmap to net zero, every 5 years. Most of these NDC's include a full decarbonisation target within the next 30 to 40 years[2].

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[1] UNFCCC, "The Paris agreement," [Online], https://unfccc.int/documents/184656

[2] ECIU, "Net zero: why is it necessary?" [Online], https://eciu.net/analysis/briefings/net- zero/net-zero-why [20/6/2021].

In order for a country to reach such a target, it must decarbonise its energy system[3], a process often referred to as "energy transition", in which all energies supplied must become net carbon neutral. High heat and long-distance transport are often referred to as the most difficult areas to decarbonize. Hence, industrial decarbonization is frequently perceived as one of the most ambitious ones when it comes to decarbonization efforts. Much of the research in this area, when thinking about energy intensive heavy industries, considers large scale enterprises or facilities[4] and though key and strategic there are a large number of middle size and smaller companies that are still heavy industry or large consumers for whom some of the solutions proposed would be economically very difficult to utilise.

Nonetheless, policymakers have made attempts to cover this area, too. Within the EU, the commission has published its 2050 strategy that includes high level goals for industrial decarbonisation[5]. In Austria, specifically where the cases study that is described later is located, the government has also developed a 2050 strategy that includes industrial decarbonisation[6].

The main pathways mentioned in literature are electrification and fuel replacement. Key issues with these, however, are the need for wholesale replacement of consuming devices and alterations to key processes in the case of electrification and efficiency challenges in the case of zero carbon fuels. Green Hydrogen is often considered one of the key alternative ZCFs, even though there are specific challenges around the adaptation of infrastructure, complex storage conditions and leakage concerns that may be key impediments to a wider hydrogen economy roll out. Green hydrogen is created through the use of low or zero carbon electricity-powered electrolysis, to split water into hydrogen and oxygen[7]. Currently, only around 4% of the hydrogen produced world-wide uses electrolysis[8]. There are three common versions of electrolysis that are promising when looking towards a hydrogen economy: Alkaline water electrolysis, Polymer electrolyte membrane electrolysis (PEM), and solid oxide electrolyser cell (SOEC)[9]. From this production the $H_2$ is liquefied before storage, requiring temperatures of -253°C or pressure of 350-700 atm[10].

Ammonia has been found to be a suitable carrier for hydrogen storage, enabling energy to be stored for even longer periods of time, with less difficulty. Other advantages of ammonia, in comparison to hydrogen, include its lower Low Calorific Value (LCV) of 18.8 MJ/kg at 300 K and 100 kPa and therefore its ability to directly replace traditional fuels[11]. The production of ammonia requires hydrogen and nitrogen to catalytically react, in what is called the "Haber-Bosch" process. Hence, the "colour-code" ammonia gets depends on what type of hydrogen has been used in this process, as well as how the electricity required for the process itself was sourced. Large quantities of ammonia are usually stored at around -33°C or at compression to 10 atm. The energy density of the fuel reaches around 3 kWh/litre in this state, compared to just under 2.5 kWh/litre at room temperature. Fossil fuels, in comparison, range between around 6-10 kWh/litre[27].

Even though the energy storage question is often treated as a binary one between ZCFs and battery storage, a hybrid-model will likely be most effective within the future energy system, as argued, for example, by Hinds[22]. Use cases of Zero Carbon Fuels can be found in the sectors of Transportation, Industry and Power Generation. Green ammonia is expected to be either a carrier of hydrogen, from which hydrogen will be separated before conversion back into power, or as a fuel, used in ICEs or direct $NH_3$ fuel cells[12]. Due to its low LCV (Lower Calorific Value), ammonia can be fed directly where natural gas or petroleum used to be [13,14].

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[3] UCL, "Decarbonising energy and the energy transition," [Online], [20/6/2021].

[4] Nurdiawati A, Urban F. Towards Deep Decarbonisation of Energy-Intensive Industries: A Review of Current Status, Technologies and Policies. *Energies*. 2021; 14(9):2408. https://doi.org/10.3390/en14092408

[5] European Comission 2050 Strategy, https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en [Online]

[6] Austrian Strategy for 2050; https://unfccc.int/sites/default/files/resource/LTS1_Austria.pdf [Online]

[7] S. Atilhan, S. Park, M. M. El-Halwagi, M. Atilhan, M. Moore, and R. B. Nielsen, "Green hydrogen as an alternative fuel for the shipping industry," Current Opinion in Chemical Engineering, vol. 31, p. 100668, 2021. [Online].

[8] M. Petrova, "Green hydrogen is gaining traction, but still has massive hurdles to over- come," [Online], [25/6/2021].

[9] S. P. Badwal, S. Giddey, and C. Munnings, "Hydrogen production via solid electrolytic routes," WIREs Energy and Environment, vol. 2, no. 5, pp. 473–487, 2013. [Online].

[10] B. David, F. Armstrong, P. Bowen, D. Fowler, J. Irvine, and L. T. Murciano, "Ammonia: zero- carbon fertiliser, fuel and energy store," The Royal Society, 2020.

[11] A. Valera-Medina, H. Xiao, M. Owen-Jones, W. David, and P. Bowen, "Ammonia for power," Progress in Energy and Combustion Science, vol. 69, pp. 63–102, 2018. [Online]. 0

[12] J. Lewis, "Fuels without carbon," [Online], [27/6/2021].

[13] S. Giddey, S. P. S. Badwal, C. Munnings, and M. Dolan, "Ammonia as a renewable energy transportation media," ACS Sustainable Chemistry & Engineering, vol. 5, no. 11, pp. 10 231–10 239, 2017. [Online].

[14] W. L. Ahlgren, "The dual-fuel strategy: An energy transition plan," Proceedings of the IEEE, vol. 100, no. 11, pp. 3001–3052, 2012.

However, the generation of the fuels is limited by each step's efficiency. Therefore, whenever electricity can be used directly, it should, in order to minimise wasted energy. Only in cases, where storage or direct combustion is required, ZCF's become useful.

*Table 1,Comparison of Efficiency and cost between different conversion components in the ZCF supply and utilisation chain.*

| **Process** | **Efficiency** | | **Cost** | |
|---|---|---|---|---|
| | 2020 | 2050 | 2020 | 2050 |
| **Electrolyser** | *kWh/produced kgH$_2$* | | *EUR/kWh* | |
| Alkaline | 50-78 | <45 | 250 | <90 |
| PEM | 50-83 | <45 | 370 | <90 |
| SOEC | 45-55 | <40 | >1830 | <180 |
| **Haber-Bosch** | *kWh/produced kgNH$_3$* | | *EUR/t NH$_3$* | |
| | 1.2 | 0.7 | 530 | 230 |
| **Fuel Cell** | *%* | | *EUR/kW* | |
| Alkaline | 50-60% | 70% | 1650 | - |
| PEM | 40-48% | 70% | 1650 | - |
| SOEC | 50-55% | 70% | 1650 | - |
| **ICE** | 35-40% | - | 1280 | - |

Research on system for the generation of green ammonia are, however, still at a very early stage, which is why Siemens, the Universities of Cardiff & Oxford and the Science and Technology Facilities Council (STFC) joined forces to set up a Green Ammonia Demonstrator at the Rutherford Appleton Laboratory in Oxfordshire[15]. This demonstrator is the first small-scale system to utilise on-site generated renewable electricity (through solar panels and wind turbines), turn it into green hydrogen and further green ammonia, and subsequently convert it back into electricity. At current sizes, it is planned to produce 30kg of ammonia per day. Even though still in early stages, the demonstrator is set out to prove that the conversions work, as well as aiming to maximise conversion efficiencies.

In light of the early stage of development of parts of the process, this research paper focuses on a specific case study and attempts to define decarbonization scenarios for a small industrial business, analysing their feasibility. Key within this is the production of necessary heat for utilising in specific parts of the processing operation. The basis of a zero-carbon energy system is low or zero carbon electricity generation. Within this study, solar as well as wind-sourced electricity will be considered.

## Methodology

### Identification of a suitable case

As a first step towards modelling deep decarbonisation in industry, a suitable case study was chosen. Based on data availability, current $CO_2$ emissions and an eagerness to reduce these by company management as illustrated by the willingness to share data, the scenarios were applied to Mühlendorfer Kreidefabrik[16], a small chalk-processing business in the east of Austria. Data available included 15 minute resolution electricity consumption and hourly gas consumption for the entirety of 2019. This quality of data is rare in industry, especially in small, countryside businesses and was the biggest decision factor when choosing this site.

The Mühlendorfer Kreidefabrik ("chalk factory") in Burgenland, a federal state in the East of Austria, is holder of a 40-hectare chalk quarry on the Leithagebirge near Müllendorf. Being mined during dry weather only, the chalk is then processed in the factory 2.7 km away from the quarry. The material is used as a filler in multiple industries, such as the production and processing of plastics, tyres, or rubber, as well as in recycling plants. Hence, it is a

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[15] I. Wilkinson, "Green ammonia for energy storage and beyond," in NH3 Fuel Conference, 2016.

[16] **Müllendorfer Kreidefabrik - Margit Hoffmann - Ostenhof GmbH,** http://www.kreide.at/

component of, for example, cables, building materials, paper bags, paints. Specifically, after the quarrying of the chalk, first, it gets broken up into smaller chunks, in order to subsequently be dried in a natural-gas-fuelled tumble-drying drum. The natural gas is burnt in a hot gas generator that dries the chalk. After the humidity of the material is reduced to around 0.3%, the chalk is ground in a ball mill, and further classified in an elutriator, in an effort to reach chalk diameters requested by customers[17].

**Scenario definition (Business as Usual, Decarbonisation 1 & 2)**

Analysis of the different decarbonisation routes was facilitated through the use of three scenarios. First, a Business-As-Usual (BAU) scenario was identified to develop a baseline to compare scenarios for specific decarbonization pathways to. This scenario's main elements were historic energy consumption data, already established sustainability plans as well as $CO_2$ pricing. The annual cost of energy was derived using this framework.

There were two different decarbonization scenarios, for the first of which all industrial processes were electrified. This approach aimed to replace every fossil-fuel-powered machine (specifically, the hot gas generator and the diesel vehicles) with an electric one while generating all required electricity, in terms of total annual energy, on site, while keeping the factory's energy usage timings and hence business operations unchanged. As electricity is not necessarily generated at the same time it is needed, system balancing efforts through leveraging the national grid were added. Explicitly, this means feeding surplus electricity into the grid and drawing from the grid during periods of local electricity-deficiency.

The second decarbonization scenario is one of fuel substitution, replacing fossil fuels with ammonia as a zero Carbon Fuel (ZCF) by adapting and reusing existing machinery in the factory. The financial feasibility of local ammonia production through deployment of electrolysis and Haber-Bosch machines on site was examined. Running the ammonia generating equipment at constant maximum capacity, the electricity required is modelled to be fully produced on the factory site, with system balancing through the grid in place, similar to the electrification scenario described above.

**Data acquisition**

The decarbonization scenarios utilize 2019 ERA5 weather data at the location of Mühlendorfer Kreidefabrik and company-specific energy consumption data, both of 2019. Further, they leverage data from Solarmodul Sunpro 370 PV solar PV panels and Vestas V126 3 MW and WEC 900 kW wind turbines with the aim to reliably estimate electricity generation from these resources with realistic input weather data.

**Simulation model**

Modelling the decarbonised systems was based on three algorithms: a cost-optimising generation equipment capacity sizer, a system simulation and an ammonia-system sizer as an extension to the second algorithm. The equipment-sizing algorithm aims to find the least-cost combination of given electricity generation technology (solar panels at EUR 180 per 370 Wp module, a 900-kW wind turbine at EUR 1.45M and a 3 MW wind turbine at EUR 3.5M). Together with the hourly weather data of 2019, all possible combinations of these technologies that would generate the amount of electricity required – on an annual basis – are probed by the algorithm, and the one with the least cost attached to it given as a result.

In a second step, the resultant system is pushed through the actual simulation, outputting the electricity generation profile of the generation technology mix if it was at the Mühlendorfer Kreidefabrik location in 2019, on an hourly basis. Algorithm inputs were calibrated by cross-checking results with the pre-existing solar modelling, in order to maximise output reliability. The algorithm subsequently compares this profile with the energy demand profile and identifies how much electricity has to be bought from and fed to the grid. The balance of electricity procured from the grid against the excess sold to the grid is also recorded.

For the ZCF scenario, a further step is needed: based on the electricity output, the ammonia system is probed. The electricity output is sent through the ammonia generating equipment, and, assuming the machinery is meant to work at constant maximum capacity, demand and supply discrepancies are measured and required grid interaction calculated.

**Simulation results analysis (economics analysis)**

Finally, the study compares the scenarios that were created. In order to draw conclusions from the output data, final cost, spread over an equipment lifetime of 20 years, was calculated for both scenarios and compared with the BAU scenario.

# Results

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[17] ORF, "Kreide aus Müllendorf," [Online], https://burgenland.orf.at/stories/3057830/ [2/8/2021].

**Identified case study**

The factory uses three different energy vectors in the process of transforming the raw chalk from the quarry into the saleable product;

- diesel during the transport from the quarry to the factory,
- natural gas predominantly in the chalk drying process,
- electricity for all other energy services.

Figure 1 illustrates the overall set of processing steps the chalk has to go through in order to become the fine powder that customers require. This is similar to other chalk processing businesses. During the mining and transportation process, six Diesel-powered vehicles are used. In total, the company consumes approximately 71,000 litres of Diesel annually, which converts to approximately 774 MWh of energy, using a Gross Calorific Value (GCV) of 10.9 kWh/litre[18]).

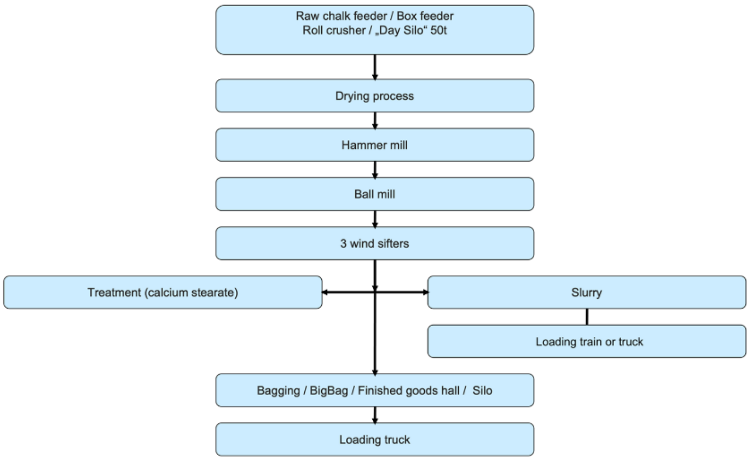

*Figure 1, The processing steps after quarrying for chalk from raw material to saleable product within Mühlendorfer Kreidefabrik.*

The other fossil fuel that the company consumes is natural gas, mainly for the drying process of the chalk. Specifically, the machines that run on natural gas are the 2.2MW hot gas generator required for the tumble dryer, and an 80-kW space heater that is only turned on in cold months and is necessary to avoid machines freezing. With a demand of approximately 10.2 GWh of natural gas throughout around 8000 operating hours (around 91% of time) in 2019, fluctuating as can be seen in Figure 2 (top), this is the largest source of energy used within the business. The natural gas load, however, varies extensively, depending on multiple different factors.

- The chalk production volume is not constant with gas consumption varying with product demand.
- The water content of the mined, raw chalk also influences the amount of gas needed to dry the material.
- Maintenance or other disruptions pause production at times, which obviously reduces the gas demand to zero during those hours.

Heating in the office building, as well as all other energy services within the company not explicitly mentioned, are powered by electricity. With an approximate load of around 700-800kW and a yearly consumption of 5.7 GWh, the energy demand through this vector is much lower than the energy demand through gas. The annual electricity profile, as shown in Figure 2 (bottom), also shows fewer fluctuations than the gas consumption, albeit there are recognisable dips, which can likely be attributed to production pauses, as mentioned above, as timings of these troughs correlate with the ones in the gas consumption.

Overall, the current energy consumption of the company emits around 2077.2 tonnes of $CO_2$ per year, estimating emissions of 0.202 kg$CO_2$/kWh for natural gas, 0.130 kg$CO_2$/kWh for the grid electricity and 2680 kg$CO_2$/litre of Diesel[19,20].

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[18] IRENA, “Green hydrogen cost reduction,” [Online], 2020, [15/7/2021].

[19] electricityMap, “Average carbon intensity,” [Online], 2021, https://www.electricitymap.org/zone/AT [27/8/2021].

[20] Umweltbundesamt, [Online], 2021, https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0761.pdf [3/3/2022].

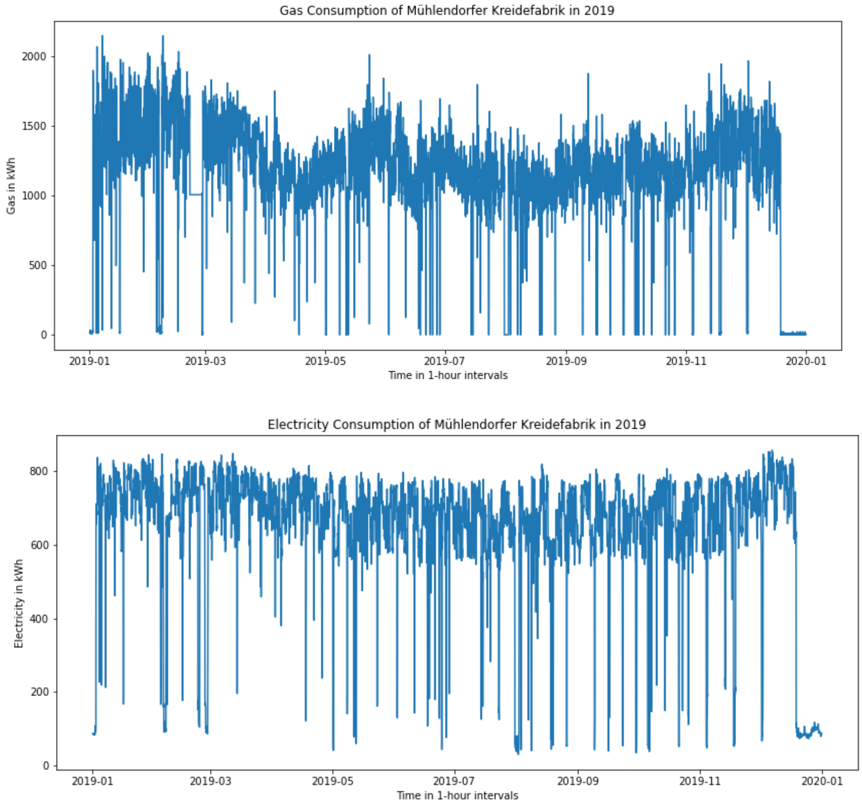

*Figure 2, Hourly gas (top) and electricity (bottom) consumption of Mühlendorfer Kreidefabrik (2019).*

### Sustainability of Mühlendorfer Kreidefabrik

Mühlendorfer Kreidefabrik is quarter owned by the global company Omya and has been identified as a good site for renewable energy generation by its parent company. Specific solar panels as well as wind turbines (Solarmodul Sunpro 370 PV panels, as well as Vestas V126 3M and WEC 900 kW wind turbines) have been investigated and their output profiles simulated by professional energy consultancies.[21] It has been found that on the factory site 207.2 kWp of solar panels can be built on the buildings' roofs and following local government approval this is under construction. Therefore, inverters and other equipment required to run an on-site solar farm will be assumed to be already in place, having the available capacity to allow the addition of further on-site PV systems and, are therefore not replicated in the proposed scenarios later. This additional on-site PV is space limited, and it is calculated that a further 600 kWp of solar panels may be added in the area around those buildings. Additionally, even though the location is very advantageous in terms of prevailing wind power densities, wind turbines if installed on the factory site are likely to be opposed, with "Negative visual impact on the landscape" the predominant complaint by neighbours described as the main hurdle in a report created by Omya.[22] To mitigate this opposition, it is proposed that wind turbines are installed instead at the quarry site.

## Scenario Definition

### Business As Usual (BAU)

The 2019 energy consumption using current busines practices and industrial processes of 5.7 GWh electricity, 10.2 GWh of natural gas, 774 MWh of diesel emits an estimated 2077.2 tonnes of $CO_2$ annually. Current plans of installing 207.2 kWp would generate around 300 MWh annually of low-carbon, solar electricity, which would reduce annual $CO_2$ emissions unnoticeably, to around 2077.0 tonnes of $CO_2$ per year.

*Electrification*

The first method of generating heat without emitting carbon dioxide is electrification. A prerequisite to this objective is decarbonised electricity provision, as well as investment in new machinery and technology. In this scenario, all energy demand will eventually be provided through electricity, meaning that natural gas as well as

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[21] Consulting report 10hoch4, 2020, 10hoch4.

[22] Wind energy viability check, 2020, Omya.

diesel using equipment will have to be replaced. Through the leverage of trading electricity with the national grid, this scenario suggests the creation of a virtual private network to optimize internal consumption and availability.

Electrifying the energy demand of the company through self-generated electricity that will either be directly used or fed into the national grid, depending on the demand-supply balance of each point in time, is a common methodology for decarbonisation. In order to design this system, the total electricity demand was first estimated at 15.5 GWh. The demand value was found by adding the current (2019) electricity consumption and estimated future electricity consumption when fossil fuels will be replaced. By assuming a current efficiency of the natural-gas-fueled dryer of 99%, based on the hot gas generator's efficiency[23], and the efficiency of electric drying of 99%,[24] an electricity demand of 9.1 GWh was assumed for the 10.2 GWh of energy that are currently provided through natural gas. Further, the vehicles' current energy consumption of 71,000 l of Diesel was assumed to be replaceable through 650 MWh of electricity, annually. This value was derived through research into tank-to-wheel (TTW) efficiency of both Diesel vehicles, as well as electric vehicles (EVs)[25]. The fossil-fuel-powered vehicle's efficiency was found as 28-42%, whereas EVs are estimated to have a TTW efficiency of 50-80%. As 71,000 l of Diesel have a primary energy of 774 MWh, always utilising the "worst" efficiencies in order to avoid under-estimating electricity demand, the final electricity consumption was projected for the transportation demand within the company.

With this information, an algorithm was implemented in Python with the aim of cost-optimizing the generation needed to provide for the electricity demand. Looking at solar panels, as well as two different models of wind turbines, the least-cost combination of these technologies was established. The three technologies were picked as specifically those that have already been considered for energy generation on the company site. Additionally, spatial constraints were considered: it is not permitted or possible to install a wind turbine as well as more than 807.2 kWp of solar capacity on the factory site, as established by the Austrian PV company 10hoch4 Energiesysteme[26]. Everything else will hence be placed at the quarry, around 2.7 km away from the factory, and interconnected with the local electricity grid.

*ZCF*

The second decarbonisation path focuses on replacing fossil fuels with Zero Carbon Fuels, in this case green ammonia. Specifically, green ammonia will be considered for the direct replacement of natural gas, as its relatively low LCV leads to the assumption that equipment can be adapted through retrofitting, rather than replaced. Therefore, a local electrolyser and Haber-Bosch plant will be required for the production of ammonia. As the generation of these fuels requires a significant quantity of electricity, the setups that were found in the electrification scenario will be utilised here, too, albeit capacities will have to be even higher due to efficiency losses incurred when converting electricity into fuels.

At first, the prospective green ammonia demand was derived from 2019's gas demand. Comparing their LCVs, the annual ammonia demand, in units of mass, was estimated to be around 5.2 times as high as the gas demand, and therefore 1.870 kt[28]. Using the same method to estimate the amount of ammonia needed in the Diesel vehicles, the LCV of 43.5 MJ/kg and the density of 0.85 kg/L for Diesel resulted in an estimate of 13.9 t annually, and therefore a total of around 1.884 kt[27].

The on-site system that feeds electricity through electrolysers, an air separation unit and a Haber-Bosch process, can produce this amount of ammonia with around 20 GWh of electricity, of which around 71% are used in the electrolysis process.[28] This value was derived assuming an electricity demand of 10.6 kWh per kg of ammonia, which was found through the efficiencies in the above table. Adding the company's power demand to this value, a total of 25.7 GWh of green electricity can be expected to be required, annually.

In order to size the equipment required, the ammonia production will be assumed at a constant, maximum capacity, with the fuel being stored consequently in order to be used whenever needed. This way, the chalk production processes barely have to be adapted, as the old machinery can still be used with the alternative fuel.

Using the numbers from above, an average ammonia consumption of 215 kg per hour can be expected, which would relate to a 1.9 MW Alkaline electrolyser as well as equipment that enables the storage of ammonia. The sizing of storage was facilitated through the examination of local extrema of the difference between generation

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[23] B. Böhler, "Heißluft- und Heißgaserzeuger," [Online], 2018, http://docplayer.org/75676414-Heissluft-und-heissgaserzeuger.html [15/7/2021].

[24] Energy.gov, "Electric resistance heating," [Online], 2021, [15/7/2021].

[25] A. Albatayneh, M. Assaf, D. Alterman, and M. Jaradat, "Comparison of the overall energy efficiency for internal combustion engine vehicles and electric vehicles," Environmental and Climate Technologies, vol. 24, pp. 669–680, 10 2020.

[26] https://www.10hoch4.at/

[27] D. Erdemir and I. Dincer, "A perspective on the use of ammonia as a clean fuel: Challenges and solutions," International Journal of Energy Research, vol. 45, no. 4, pp. 4827–4834, 2021. [Online].

[28] Richard Nayak-Luke et al, "Green" Ammonia: Impact of Renewable Energy Intermittency on Plant Sizing and Levelized Cost of Ammonia", *Industrial & Engineering Chemistry Research,* 2018, *57* (43), 14607-14616.

and consumption. The maximum jump between local maximum and local minimum was then investigated, giving the maximum required storage[29].

Through this method, it was found that a minimum of 355 kg of ammonia storage is required at site to account for fluctuations in demand. However, it has been found that ammonia storage costs between around EUR 0.04/kg and EUR 0.255/kg[30]. This information leads to the assumption that storage in this small scale will just be facilitated through standard tanks, which are available within the industrial company in question. Hence, the cost for ammonia storage will be neglected in such small quantities.

## Scenario results

**Electrification**

Having programmed a simulation for solar generation, and utilising wind-generation simulation data from the renewables.ninja database , the amount of energy generated per unit of equipment, specific to the area, was found.

The equipment considered were 370 Wp solar panels, a 900 kW ("small") wind turbine, and a 3 MW ("large") wind turbine. With this information, as well as financial data of the equipment, an algorithm was created that would simulate the generation of any mix of capacities and output the minimum-cost combination of 4749 kW of solar capacity in total and 1 large wind turbine, with 807.2 kWp of solar panels on the factory site and the rest on the quarry. This set-up is estimated at a capital cost of EUR 5.8m, based on the equipment chosen, and is a very slight oversizing (0.004%) of capacity, compared to the estimated consumption. These technologies together emit around 36 tonnes of $CO_2$ annually, saving a considerable amount of emissions in comparison to the BAU scenario.

In this system, all electricity produced on the quarry is fed into the grid, while the electricity produced on the factory site was modeled against current (2019) usage data in order to precisely evaluate profile discrepancies. As they do not overlap perfectly at every point in time, electricity will have to be exported as well as imported to and from the grid. Feed in Tariffs (FiTs) in Austria are different depending on whether the fed-in electricity comes from solar or wind sources: around EUR 0.0399/kWh and EUR 0.0812/kWh, respectively. The capacity on the quarry, 10 GWh of electricity generated through the wind turbine, and 4.5 GWh generated through solar, will be fed into the grid. This results in an annual income of EUR 993,000, according to tariffs from above.

The solar capacity of 807.2 kWp on the factory site generates 928 MWh annually of which, on an hourly comparison level, a total of 23 MWh is above the load and therefore would be fed into the grid. Through FiTs, this would generate an income of around EUR 909 yearly.

In order to balance for the electricity fed into the grid when not needed, the company will still have to buy 14.6 GWh electricity from the grid. At 2019 electricity prices of EUR 0.068/kWh, this would amount to EUR 976,000 annual electricity expenditure.

In addition to the costs mentioned above, electrification requires the replacement of all equipment currently fuelled through other vectors. As industrial equipment is often customised rather than one-size-fits-all, it was not possible at this point to present an exact result of the expected cost. However, the literature has been searched to find estimates and ranges which will be used here.

For electric drying, multiple sources have been consulted. At first, it was stated that microwave drying would cost around EUR 85/kW, which translates to around EUR 190,000 for the required capacity of 2.2 MW. A source for electric boilers, which is here used as a proxy, states a similar capital cost of EUR 0.12m/MW, so EUR 120/kW, translating to EUR 270,000 for the relevant system. An average of EUR 230,000 will be assumed for this case. The second area where electrification comes with extra investment are the currently Diesel consuming vehicles. One forklift, one pick-up, two-wheel loaders, one crawler excavator and one truck are required for processes such as excavating the chalk and transporting it to the factory. Price estimations of electric versions of all these vehicles have been found in various sources. An electric forklift costs around EUR 30,000, a pick-up around EUR 35,000-40,000, and electric wheel loaders, trucks as well as an electric version of the crawler excavator EUR 130,000.

In total, the swapping of equipment is expected to induce a CAPEX of around EUR 815,000 in the above scenario. Additional costs that might be incurred through the disposal of old machines as well as potential installation costs have not been included. Operating costs of the system will have to be added to all initial investment costs that have been mentioned so far. Annual costs such as electricity from the grid, but also maintenance and other regular costs such as insurance are part of this.

Specifically, wind turbines require an operating expenditure of around EUR 9.3/MWh produced or EUR 65/kW installed, and solar farms have been estimated to generate an annual cost of 1.5-3% of the initial CAPEX. The

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[29] P. Larsson and P. Börjesson, Cost models for battery energy storage systems, 2018. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:1254196/FULLTEXT01.pdf [15/8/2021].

[30] J. P. Vrijenhoef, "Opportunities for small scale ammonia production." International Fertiliser Society, vol. 69, 2017. [Online].

solar panels therefore can be estimated at an additional cost of EUR 35,000 - 70,000 per year and the wind turbine EUR 93,000 - 195,000. On average, therefore, this part of the system generates an extra annual cost of EUR 196,000. Additionally, similar to the current gas-fueled dryer, the electric drying equipment will also require maintenance, which was estimated to cost around EUR 2920 per year (EUR 1100 basic annual cost plus EUR 0.2/MWh). Therefore, an annual operation cost of EUR 200,000 has been assumed for the system. In total, over an estimated average lifetime of 20 years for the described system, annual cost amounts to EUR 512,000.

*Table 2 Summary of costs for electrification scenario*

| **Component** | **CAPEX** | **Annual OPEX** | **Income** | **Lifetime/annual cost** |
|---|---|---|---|---|
| **PV and wind generation** | 5,800,000 | 976,000<br>196,000 (O&M) | 994,000 | 20 years |
| **Electrified vehicles and dryer** | 815,000 | 2,920 (O&M) | - | 20 years |
| **Total** | 6,615,000 | 1,175,000 | 994,000 | 512,000/year |

### ZCF

The annual electricity demand was also estimated to be around 25.7 GWh, and electricity generation is provided via a set of 370 Wp solar panels, a small 900 kW wind turbine and/or a large 3 MW wind turbine. Through the same least-capital-cost algorithm as before, it was found that 25.7 GWh can be produced best via 13.7 MW of solar capacity and one large wind turbine. However, despite being the cheapest option, this would cost around EUR 10.2m for a generation capacity of 25.8 GWh of electricity.

The electricity generated through this capacity, situated on the quarry, will power an electrolyser coupled with a Haber-Bosch process. This system will be sized, minimising the required capacity by assuming constant production at maximum potential. Through interaction with the national grid, the system will cover all of the company's energy demand, eliminating the use of fossil fuels.

The reason why the national grid will have to be a part of this solution is that electrolysers have lower and upper boundaries of how much energy can be fed into them. Within this section, one of Nell Hydrogen's A300 electrolysers will be used as a reference in order to compare electricity generation with demand.

The current electricity demand of 5.7 GWh, which is consumed on the factory site, will have to be drawn from the grid. This power will cost around EUR 0.068/kWh and therefore will amount to approximately EUR 387,600. From the rest of the annual generation of 20 GWh, 71% are planned to go into electrolysis and the rest into Haber-Bosch and air separation, which together are expected to consume 5.8 GWh.

Figure 3 shows the generation of the simulated system - excluding the 5.8 GWh reserved for Haber- Bosch and air-separation -, and two horizontal lines which represent the maximum and minimum load levels that the electrolysers can work within. Making sure that the system constantly runs at maximum capacity, electricity has to be bought for all times where generation is below the maximum line and sold whenever it is above. Even though, compared to the fluctuations in the generation profile, the interval between the maximum and the minimum seems small, the average of the electrolyser-dedicated generation output is about the same as what would be required for constant production at maximum electrolyser capacity, i.e., around 1.6 MW. The surplus seen in Figure 3 amounts

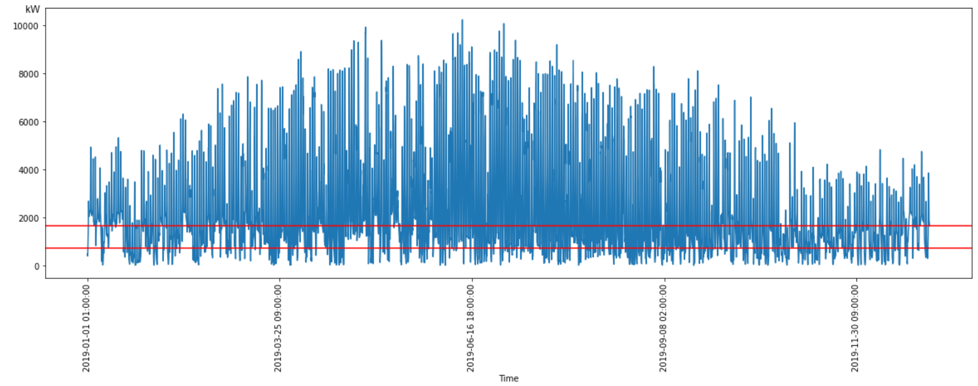

*Figure 3, The generation pattern with the solar and wind capacities defined fluctuates heavily. In comparison, the two lines at 729 kW and 1640 kW show the interval within which the electrolyser works. The total generation is the same as constant production at maximum electrolyser capacity.*

to 9.4 GWh annually, which will be fed into the grid. Electrolyser, air-separation unit and Haber-Bosch process together emit around 139 tonnes of $CO_2$ per year.

Through the Feed-in-Tariffs, an annual total income of EUR 519,000 can be expected in this scenario. Purchasing 3.8 GWh in order to keep production at maximum capacity costs additional EUR 261,000 yearly, bought at the smallest rate of EUR 0.068/kWh, as mentioned earlier.

In order to simplify the next step of evaluating how much of the 5.8 GWh that are required for the rest of the ZCF producing process (i.e., Air separation unit and Haber-Bosch) are sold or bought, the same ratio of sold to bought electricity, as was established above will be applied here. Therefore, 2.7 GWh, i.e., around 47%, more will be expected to be fed into the grid at an annual income of EUR 149,000, and 1.1 GWh will have to be purchased at EUR 75,000.

The Zero Carbon Fuel scenario generates green ammonia on site and therefore requires investment in an electrolyser, an air separation unit and a Haber-Bosch unit. An electrolyser with generation capacity of 3.4 MW is expected to cost around EUR 918,000 in 2020 and as little as EUR 340,000 by 2050. The cost of the Haber-Bosch process is harder to obtain, especially as research on green ammonia generation is a new area. Different sources have led to the assumption that the capital cost of the ammonia generation equipment for an annual production of around 1884 t will be between EUR 1m-1.1m[31]. Hence, an average cost of EUR 1.68m will be added.

In addition to the initial cost of the system, annual maintenance and reparation costs have to be considered, as well. Electrolysers are estimated to have a maintenance cost of around EUR 0.07/kg H2 attached to them[32]. For the set for ammonia production, an annual cost of around EUR 34/t has to be added, which totals to around EUR 64,000 per year[33]. In total, over an estimated average lifetime of 20 years for the described system, annual cost amounts to EUR 714,000.

*Table 3 Summary of costs for ZCF scenarios*

| Component | CAPEX | Annual OPEX | Income | Lifetime/annual cost |
|---|---|---|---|---|
| **PV and wind generation** | 10,200,200 | 723,000 | 668,000 | 20 years |
| **Electrolyser and Haber Bosch** | 1,680,000 | 64,000 (O&M) | - | 20 years |
| **Total** | 11,880,000 | 787,000 | 668,000 | 714,000/year |

## Economic simulation result analysis

In order to assess the company's financial state, this section summarises key economic values, before later sections delve into investment plans of the energy transition.

The chalk sales, i.e., 65 kt in 2019, yielded a gross revenue of EUR 6.2m. After costs, the net income was EUR 0.42m. In the past 6 years, the gross revenue has not varied significantly, fluctuating between EUR 5.6m in 2020 and EUR 6.5m in 2015. Net income, however, varied more intensely, due to different extents of expenditure.

Highest expenditures of the company are raw material cost, salaries, as well as what has been categorised as "others", which includes miscellaneous costs such as shipping, tolls, and customs. Energy expenditures also largely contribute to the firm's balance sheet, making up around 20% of the company’s expenditure. In 2019, around EUR 386,000 were spent on electricity consumption, EUR 78,000 on petrol, and EUR 200,000 on natural gas. In total, over the past 6 years, between EUR 664,000 in 2019 and EUR 839,000 in 2015 have been spent on energy annually.

Based on these values, an electricity price of EUR 0.068/kWh, including fees, was spent. Mühlendorfer Kreidefabrik further spends below EUR 0.02/kWh for natural gas, and an average of EUR 1.10/litre for Diesel. Electricity and natural gas are both purchased in bulk through the mother company Omya.

As can be observed in the current balance sheets of Mühlendorfer Kreidefabrik, the energy expenditure of 2019 is higher than the annual cost of both proposed scenarios when considering a lifetime of 20 years.

Without operational adaptation, however, the annual energy expenditure is expected to increase steeply. Since the company currently emits around 2077 tonnes of $CO_2$ per year, priced at a minimum of EUR 62/t$CO_2$, these

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[31] T. Brown, “Industry report sees multi-billion ton market for green ammonia,” [Online], 2020, https://www.ammoniaenergy.org/articles/industry-report-sees-multi-billion-ton-market-for- green-ammonia/ [22/8/2021].

[32] A. Christensen, \Assessment of hydrogen production costs from electrolysis: United states and europe," [Online], 2020, https://theicct.org/publication/assessment-of-hydrogen-production-costs-from-electrolysis-united-states-and-europe/ [2/3/2022].

[33] T. Maung, D. Ripplinger, G. McKee, and D. Saxowsky, “Economics of using flared vs. conventional natural gas to produce nitrogen fertilizer: A feasibility analysis,” Agribusiness Applied Economics, 12/2012, [20/8/2021].

operating costs would increase by around EUR 130,000 per year. In total, energy costs would therefore amount to around EUR 793,000 annually in a Business As Usual (BAU) scenario.

Hence, with assumption of constant $CO_2$ and electricity prices over the next 20 years, Scenario 1 would have a payback period (i.e. the point at which the CAPEX + OPEX of the particular scenario is equal to the continued OPEX to which it is being compared) of under 13 years considering a comparison with the BAU scenario. For Scenario 2, the payback period is 19 years, which is much higher, but with an average lifetime of 20 years of the equipment, the investment still proves profitable. For simplicity both energy and $CO_2$ prices are assumed constant as their projected changes are only positive to the viability of the solutions presented.

**Margin of error**

In the electrification scenario, the main cost drivers are annual expenditures on electricity, in order to balance consumption and generation, whereas the ZCF scenario cost is led by the initial CAPEX, as much more electricity is produced on site in this scenario.

The research was solely based on values from 2019, as they were available and permitted the creation of an entire simulated system. Nonetheless, more superficial data such as annual energy consumption in the past 10 years shows the fluctuations that this value can have. Analysis of these variations can provide insights into the necessary error margins for predictions of demand and supply for energy in the future.

An average of 5.3 GWh of electricity used annually between 2009 and 2020 has been found to fluctuate by around ±11%. Hence, this error margin should be adopted and a surplus of 11% should be added to the expected expenditure from the scenarios, accounting for a larger capacity and more supply in order to match potentially higher demand. The resulting expenditures are therefore around EUR 880,000 for the BAU scenario, EUR 570,000 for Scenario 1 and EUR 793,000 for Scenario 2 per year. This added error margin ensures improved energy security of the company and still proves as profitable assuming a lifetime of 20 years, compared to paying utility energy prices and carbon fees.

## Discussion

Comparing the scenarios in order to create a suggestion depends on the factors considered, as well as how much weighting will be put on each of them. Within this section, financial, environmental, as well as implementation and energy security arguments will be considered.

In terms of financial aspects, both scenarios are cheaper in total than the BAU scenario. As the case study's subject is an industrial company, financial aspects will be weighted most strongly in this comparison. In this regard, both scenarios save the company money and are hence advantageous, even if all other things were equal. In addition, the state Austria is investing increasingly in renewable energy projects and proposed a new fund of annual EUR 1bn of subsidies going towards renewable energy projects. Hence, there is financial support that Mühlendorfer Kreidefabrik will be able to fall back onto, which will make the plan even more cost-effective[34]. Further, it can also be expected that the cost of implementation will become gradually cheaper in the coming years, as technologies such as electrolysers (as mentioned above) are falling in price. What becomes complicated in this regard is the correct timing of decarbonisation ventures. Minimising investment while making sure that the product will not become undesirable, as clients increasingly demand sustainability and circularity, requires thorough analysis of not only cost developments but also customers.

The parent company of Mühlendorfer Kreidefabrik, Omya, carries the biggest burden here. Switching to net-zero before customers desire, and therefore potentially raising the cost of the chalk, could be detrimental for the company's profit. Keeping a carbon-intensive product for too long will also scare off customers. Therefore, a slow implementation of the suggested equipment will be suggested, starting with some purchases now and increasing capacities as well as the stock of environmentally friendly equipment year by year.

In terms of environmental effects, however, both scenarios aim at turning the energy consumption of Mühlendorfer Kreidefabrik into net-zero. As established above, scenario 1 emits around 36 tonnes of $CO_2$ annually, and scenario 2 around 139 tonnes of $CO_2$ per year. In comparison, the national grid of Austria has an average of 130g $CO_2$ emissions/kWh,[35] which would amount to annual emissions of around 2000 tonnes per year if everything was electrified. On top of the saving of expenditures, therefore, both scenarios are highly advantageous when it comes to environmental impact.

In terms of facility to implement each of the scenarios, based on how much equipment will have to be installed, removed or replaced, the scenarios differ from each other. Here, the green ammonia scenario has an advantage as fossil-fuel powered vehicles as well as the dryer are expected to be able to function with ammonia, too. This reduces waste and therefore the emissions that are caused by disposing of old equipment.

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[34] APA, "Wirtschaftsausschuss gibt grünes Licht für erneuerbaren-Ausbaugesetz (eag)," [Online], 2021, https://www.ots.at/presseaussendung/OTS 20210629 OTS0229/wirtschaftsausschuss- gibt-gruenes-licht-fuer-erneuerbaren-ausbau-gesetz-eag [15/8/2021].

[35] electricityMap, "Average carbon intensity," [Online], 2021, https://www.electricitymap.org/zone/AT [27/8/2021].

In terms of energy security, the deciding factor in this comparison will be the reliance on the grid as well as on changes in weather. The electrification scenario relies on the grid insofar, as it expects to feed over 14.5 GWh into it annually, as well as buying the same amount per year, in periods of "bad" weather. This expectation relies on the approximation that the national grid of Austria has infinite capacity in terms of accepting or providing electricity.

The ZCF scenario also feeds to and buys from the grid. Specifically, 12.1 GWh are expected to be traded annually. This value proves not only lower than the one in the electrification scenario but, in addition, ammonia production has as great advantage its ease to be stored. Hence, potential over-production during sunny or windy times can offer increased security. Therefore, the two scenarios both seem to have their advantages and disadvantages, but can both be considered feasible in the context of a small industrial company.

## Limitations of the study

The scenarios above plan the decarbonisation of Mühlendorfer Kreidefabrik by creating an outline of adaptions required. Naturally, there are some limitations of the plans, as not all factors could have been included in full detail. Feed-in-Tariffs in Austria, that the scenarios rely on heavily, are currently only outlined for rooftop solar PV plants. Here, the same policies and pricing have been assumed for solar farms on the ground. Additionally, this policy mechanism has been assumed as constant throughout the next years. The same holds true for weather and energy consumption values, that have continually been taken from 2019 values, in order to create a coherent model. However, it has to be acknowledged that an error margin for all values considered will have to be added before installing a system.

Further, the cost of generation technology is expected to be decreasing in the future. This fact has not been taken into account in order to retain simplicity, however, will only have a positive effect on the pricing, especially when the electrification projects would be delayed slightly, or investments would be made in steps. However, the disposal costs of current vehicles and machines has not been included in these calculations. Further, the error margin on capital costs of electric machines is comparably large, as this equipment is not fully on the market, yet.

In the ZCF scenario, some limitations have to be taken into account, as well. Due to lack of data on direct conversion from electricity to ammonia and the early state of research in this area, it was difficult to find estimations on this time interval. Hence, the transformation from electricity to ammonia was assumed as instantaneous, comparing the weather data of one hour with the 2019 demand data of the same hour. Further research might include adding this time shift into the calculations, however, as has been detailed before in this paper, ammonia storage is cheap and easy, and might be a way of bridging these time shifts. Another option could be adapting the operation of the factory according to the ammonia production times.

## Conclusion

This study aimed the feasibility validation of on-site green ammonia generation for a small industrial company. Specifically, Mühlendorfer Kreidefabrik is a chalk quarrying and processing company and factory in Burgenland, in the East of Austria. Its current energy use consists of around 10 GWh of natural gas, mainly used for drying the product in a 2.2 MW hot gas generator coupled with a dryer, 5.7 GWh electricity, and 71,000 l Diesel. Through this energy consumption, it causes around 4680 tonnes of carbon dioxide emissions, annually. With the aim of decarbonising the energy use of the company, several pathways were compared against each other, based on financial, environmental, energy security, and implementation ease factors.

The two main categories that were explored in this context were electrification of the entire energy consumption, or a fuel-switching to zero carbon fuels, specifically green ammonia. The report concludes that both the electrification and the on-site generation of ammonia are economically feasible energy systems in this context, saving the company money in the long term. Due to Mühlendorfer Kreidefabrik's current energy expenditure of EUR 664,000, and future carbon pricing of EUR 62/t $CO_2$ emitted, it was shown that with payback periods lower than the equipment's lifetimes, the consumption can be decarbonized as well as energy security raised by increased independency from the grid.

Specifically, in the electrification scenario, a virtual private network was found the most profitable solution. Placing the majority of the electricity generation on the quarry and making use of the national grid, creating a virtual private network, would cost the company around EUR 512,000 annually, considering a lifetime of all the equipment of 20 years. This cost was derived by analysing the depreciation of capital investment required, as well as operating expenditure such as electricity fees. Included in this are the provision of energy generating technology, in particular 4749 kW of solar panels and one 3 MW wind turbine, as well as outgoing and incoming cashflow through the grid interactions. A second option suggests decarbonising the energy usage via production of zero carbon fuels. In this scenario, electricity generation capacity of 13.7 MW solar PV panels, and one 3 MW wind turbine are planned to be placed on the quarry, along with a 3.9 MW alkaline electrolyser, connected to an air-separation unit and Haber-Bosch equipment. Here, the interaction with the grid is just as crucial, as keeping hydrogen generation through the electrolyser at a constant maximum is a main part of economic fuel generation. Through calculations using LCVs of different fuels, a projected ammonia demand of 1887 t for a year similar to 2019 was assumed, requiring a hydrogen stock of 334 t.

In a broader context, the findings of this study prove that industrial decarbonization is not only feasible but also profitable. Further, it was found that annual $CO_2$ emissions of the proposed systems are around 36-139 tonnes per year. Hence, investment in carbon offsetting projects, such as suggested by Climate Austria, is recommended.[36]

*Outlook*

In general, demand side management in terms of shifting or changing operation of the dryer or other machines within the factory has not been considered within this research project. Especially within old, industrial companies, demand side management is an understated practice. Mühlendorfer Kreidefabrik decides the amount of gas required to dry the chalk by the waste heat temperature at the exit of the gas dryer. Independently of how wet the chalk is in the first place, the amount of gas used is likely overestimated. In addition, the 40-year-old dryer has no recovery mechanism for the constantly wasted heat of around 100 degrees C.

Minimising the input gas as well as renovating equipment promises significant savings in this energy vector. Before replacing it with ammonia, it will be crucial to find a value that ensures minimum waste. This effort will also decrease the required capacity of ammonia-generated equipment drastically[37]. In addition to reducing the amount of energy required for heat, another demand side management practice that would be beneficial in this situation is demand shifting. The adaptation of chalk production would enable the usage of the final product as energy storage. Two options here are either producing chalk according to the weather, and hence ammonia availability, or keeping chalk drying and processing at a constant level, relating to the ammonia output when machines are run at maximum capacity. By increasing chalk storage capability, this could increase the efficiency of the system by optimising the time-relationship between electricity/ammonia generation and chalk production.

The security of constant energy provision can be limited by multiple factors. Currently, Omya's energy department arranged agreements with national grids in Austria and Germany, that all affiliated companies are cut off the grid in case demand gets too high, a practice also known as "load shedding". Through this arrangement, the energy security is limited and dependency on the national grid functionality is high.

Increased independence through some off-grid energy provision assures higher security, as there will be no unwanted energy cut-offs in this system. On the other side, the proposed solutions rely on the grid in other ways, such as providing electricity during low-sun, low-wind periods and buying electricity when on-site supply is too high. A problem that is raised by this reliance is that there is no guarantee that the national grid will be able to balance out the on-site provision perfectly. When there is no wind, the grid might also have a lack of supply, especially as Austria is moving towards 20% of its electricity being produced through wind energy. Vice versa, when there is a lot of wind, the national grid might not be interested in buying the surplus electricity, as it itself will have plenty during those times, and demand might not be high enough.

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[36] ClimateAustria, $CO_2$ offsetting," [Online], 2021, https://www.climateaustria.at/eng/co2offsetting.html [1/9/2021].

[37] E. Masanet, P. Therkelsen, and E. Worrell, "Energy efficiency improvement and cost saving op- portunities for the baking industry," [Online], 2012, https://www.osti.gov/servlets/purl/1172002 [3/9/2021].