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The economics of nitrogen fertilizer in the green transition

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Abstract

Global food production today is critically dependent on synthetic nitrogen fertilizer, the production of which has a significant climate impact. For the fertilizer industry to become part of the ongoing transition to a zero emissions economy, production needs to shift to one of two alternative methods: conventional, natural gas based production with added carbon capture and storage ("blue ammonia"), or replacing natural gas with electrolysis of water based on renewable electricity ("green ammonia").

These options each come with their own set of benefits in the short and long term, and policy mechanisms that may drive the technological transitions along each of the two paths are likely to differ. The aim of this thesis is therefore to combine economic theory with technological insight to better understand what strategies may promote or hinder a desired development.

It is useful to view green ammonia as what in the environmental economics literature is often referred to as a "breakthrough technology": a new technology that starts out as more costly than the current, conventional alternative, but that may provide the best societal outcome over time. Market mechanisms will typically direct investments toward the more mature technology, resulting in what is often called technological lock-in. Simply raising the price on emissions is most likely not sufficient to break the lock-in.

Instead, policy mechanisms are needed to increase the investment level in the breakthrough technology, so that cost reductions due to learning effects can become substantial enough to make the new technology preferable to the conventional alternative. This can be done through direct subsidies to green ammonia producers, or by regulations that increase demand for green ammonia in the agricultural sector and/or emerging new markets, such as the use of ammonia as a fuel in

maritime transport. Such regulations may be administratively costly, so countries should weigh their benefit against more simple directed subsidies.

Forming coalitions or partnerships can also help reduce the economic burden of single countries in developing a new technology. Economic theory applied to the specific numbers relevant for this industry suggest that gains for coalition members are likely to be moderate compared with the gain for non-cooperating countries. However, in the context of heterogeneous countries, both in terms of their possibility to do technological development and of their historical contributions to climate change, this may still turn out to be a good overall solution.

Contents

Chapter 1

Background

Nitrogen fertilizer is an essential component of today's agriculture, but its production and use are associated with significant challenges in terms of energy use, greenhouse gas emissions and pollution to water and air. Going forward, the combination of a growing global population, urgent needs to reduce greenhouse gas emissions and the high environmental burden from nitrogen pollution all call for a major transition in the nitrogen fertilizer economy.

The objective of this thesis is to combine economic theory with technological insight and observations to investigate possible paths forward for nitrogen fertilizer production, while also addressing the implications for nitrogen use and the wider economy. As we will see, nitrogen producers face the choice between conventional production with abatement and what is in environmental economics often referred to as a breakthrough technology, which is currently more costly but may bring additional societal benefits down the line.

1.1 The need for fixed nitrogen

No life can exist without nitrogen, because nitrogen is needed to make amino acids, the building blocks of proteins and DNA. Nitrogen is therefore one of the essential nutrients required for plant growth that needs to be present in sufficient amounts in agricultural soil. Most agricultural systems are limited by the supply of biologically available nitrogen (Vitousek et al., 1997).

Nitrogen constitutes most of our atmosphere, but in the molecular form N_2. This is unavailable to plants due to the strong chemical N-N bond. In order to become available for plant uptake, the N-N bond must be broken and nitrogen transformed to another chemical form through processes known as nitrogen fixation.

Figure 1.1 shows an overview of the major reservoirs and flows of nitrogen in the Earth system. In the biological nitrogen cycle, fixed nitrogen moves from the soil through plants, via animals and humans, and back to the soil via plant residues, animal manure and food and human waste. Nitrogen is lost from this cycle through leaching from soil and wastes to water, and through gaseous losses to the atmosphere. The biological processes of denitrification, used by some organisms as a source of energy, can also return fixed nitrogen to forms unavailable to plants. Therefore, both natural and agricultural ecosystems rely on processes that continuously supply new fixed nitrogen.

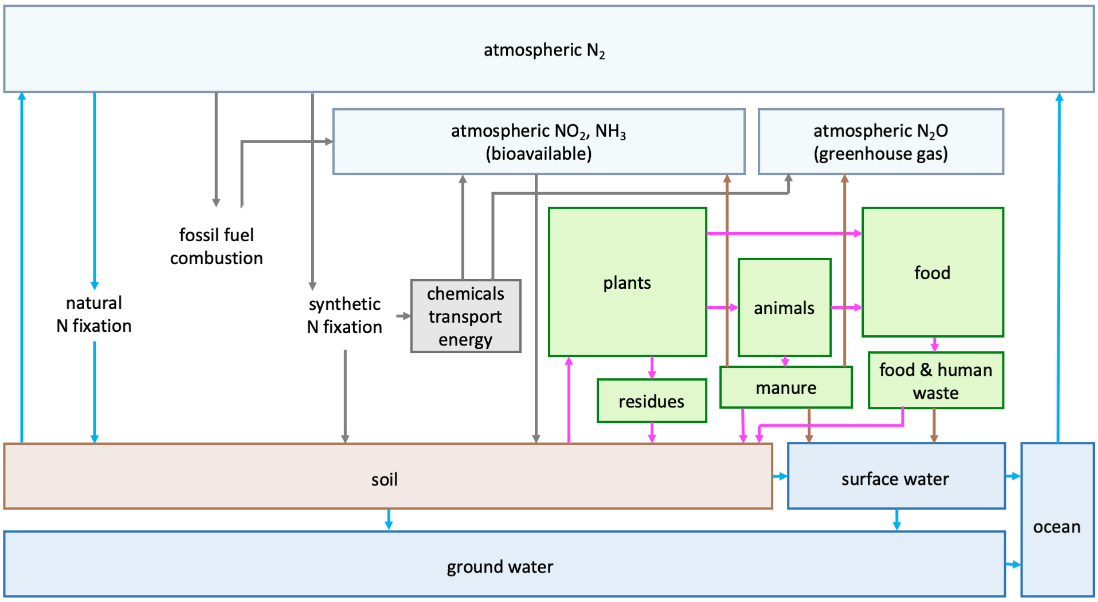

Figure 1.1: The main reservoirs (boxes) and flows (arrows) of nitrogen, including natural, agricultural and industrial systems. Arrows indicate directions but not sizes of flows, and the box size is arbitrary, not reflecting the individual sizes of reservoirs. Although individual flows arise from a mix of origins, flows are grouped by their predominant role in the 1) biological nitrogen cycle through soil, plants and animals (pink arrows); 2) natural nitrogen cycle through soil, waters and atmosphere (blue arrows); 3) anthropogenic (industrial) nitrogen flows between atmosphere and soil (grey arrows) and 4) anthropogenic (agricultural) flows to water and atmosphere (brown arrows). The atmospheric reservoir is subdivided by nitrogen chemistry.

In nature, nitrogen fixation taks place through two processes: lightning, which produces nitrate (NO_3^-), and biological nitrogen fixation, which produces ammonium (NH_4^+). Both types of fixed nitrogen are available to plants, and microbiological processes in soils convert nitrogen between one fixed form and the other. Biological fixation is performed by some prokaryotes (nitrogen-fixing prokaryotes are called diazotrophs) that exhibit the nitrogenase complex. Diazotrophs can be free-living or exist in symbiotic relationships with eukaryotes, such as the bacteria found in root modules of legume plants (Pankievicz et al., 2019).

However, natural nitrogen fixation processes are slow and far from sufficient for today's agriculture. Agricultural ecosystems are therefore dependent on nitrogen that has been fixed through industrial methods and supplied to plants in the form of synthetic fertilizer. It has been estimated that about half of the nitrogen in protein produced in agriculture today comes from industrial fixation (Rosa and Gabrielli, 2023). Natural and agricultural ecosystems also receive a significant amount of fixed nitrogen from the atmosphere (through precipitation) from fossil fuel combustion processes that produce nitrogen oxides as by-products (Galloway and Cowling, 2021).

1.2 Current production and use of nitrogen fertilizer

Most nitrogen fertilizer production today is based on the Haber-Bosch process, developed by Fritz Haber and Carl Bosch in Germany in the early 1900s. This process uses high temperature and pressure to synthesize ammonia (NH_3) from molecular hydrogen (H_2) and nitrogen (N_2) in the presence of a catalyst.

Since the 1940s, natural gas has almost completely taken over as both the hydrogen feedstock and the energy source for this process. This is the case for all parts of the world except for China, where the Haber-Bosch process mainly uses coal as a feedstock (IEA, 2021).

Figure 1.2 shows a simplified flow chart of nitrogen fertilizer production using the Haber-Bosch process. In the first step, steam methane reforming, natural gas is used as both an input and a fuel in the process of producing H_2 and separating N_2 from the air, with pure CO_2 as a by-product. This is, by far, the most energy intensive step of the fertilizer production process. Ammonia is synthesized in the Haber-Bosch step of the process, where most of the energy required comes from the reaction itself, and just a small amount of electricity is needed to power equipment such as motors and heat exchangers (IEA, 2021).

Only in the US is ammonia used directly as a fertilizer (Yara, 2018). The produced ammonia can be further combined with some of the CO_2 from the steam methane reforming to produce the fertilizer urea ($CO(NO_2)_2$), or transformed to nitrate to produce ammonium nitrate (NH_4NO_3) or other nitrate fertilizers such as calcium ammonium nitrate. More than 50% of global nitrogen use in agriculture is

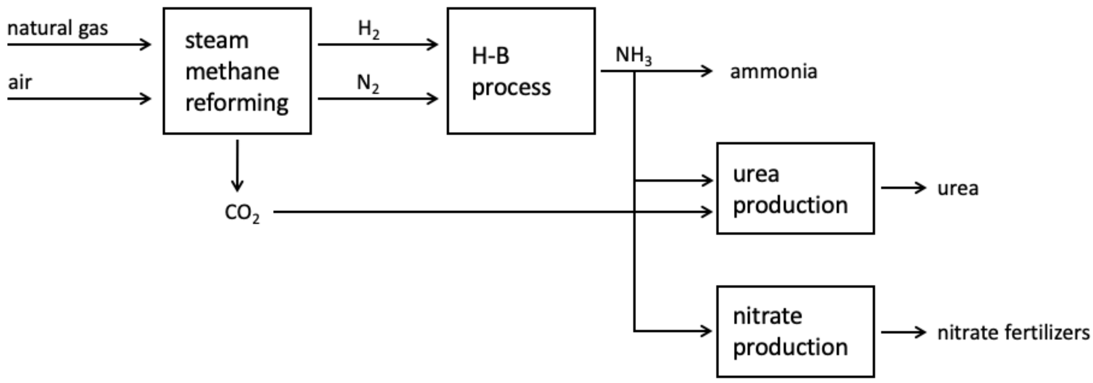

Figure 1.2: Simplified flow chart of nitrogen fertilizer production from natural gas through steam methane reforming and the Haber-Bosch process.

in the form of urea, particularly in Asia (Yara, 2018). Urea is easily transported. Nitrate products are more commonly used in Europe, but they are less attractive for transport both due to their lower nitrogen content by weight and due to safety concerns. Ammonium nitrate is also used as an explosive, and has been used in terrorist attacks such as the Oslo bombing in 2011 as well as in detrimental accidents such as the explosion in the port of Beirut in 2020 (Sabaghi, 2022).

Today, the three main crops wheat, rice and maize consume about 50% of all fertilizer globally. This is followed by cash crops such as vegetables, fruit, flowers and vines (Yara, 2018). Much of the grains are used as animal feed.

The global demand for synthetic nitrogen was 183 MtNH_3 in 2020, of which 85% or 156 Mt was used for fertilizer purposes. The reminder is used for industrial purposes such as textiles, refrigeration, explosives, pharmaceuticals and as an additive in combustion engines to reduce NO_x emissions (IRENA and AEA, 2022).

The use of fertilizer is very heterogeneously distributed in the world. On a per hectare basis, China is the largest fertilizer consumer with more than 340 kg/ha. Brazil is second at 246 kg/ha, while Sub-Saharan Africa consumes less than 20 kg/ha, far below what is recommended for improving yields (USDA, 2022).

1.3 Upstream challenges

In the flow chart of Figure 1.2, ammonia production is by far the most energy demanding part of all nitrogen fertilizer production. I will therefore focus on ammonia production in the discussion of upstream challenges.

Ammonia production requires significant ammounts of energy. It has been estimated that ammonia production accounts for more than 50% of total energy use in commercial agriculture (Woods et al., 2010) and about 1% of global energy consumption (Capdevila-Cortada, 2019). The theoretical minimum energy requirement for the production of ammonia through the Haber-Bosch process is 21.2 GJ/tNH_3, out of which 2.5 GJ/tNH_3 is residual heat that can be used for other purposes. The average net efficiency of ammonia plants in 2008 was 36.6 GJ/tNH_3, with the top quartile performing in the range 28 to 33 GJ/tNH_3. Modern ammonia production plants are very efficient, and further reductions in energy use are expected to be modest (Batool and Wetzels, 2019).

We can illustrate the magnitude of energy requirement by considering the 2020 global demand for synthetic nitrogen of 183 MtNH_3. Producing this amount from natural gas with the best available technology would have required an energy input of 1420 TWh. This corresponds to around 1 % of global energy consumption, 3.7 % of global natural gas consumption and 17 % of the current global production of renewable electricity (Ritchie et al., 2022).

Today, natural gas is used both as en energy source and as a feedstock for hydrogen production in all parts of the world except China, where coal is used predominantly. It has been estimated that ammonia production is responsible for about 2% of global fossil fuel consumption (Ornes, 2021). This situation makes ammonia production highly dependent on natural gas prices, something that has been made visible by the increasing prices and supply constraints following Russia's invasion of Ukraine in 2022 (USDA, 2022).

The use of fossil fuels also contributes to greenhouse gas emissions. CO_2 emissions from European plants, which have the lowest emissions, are about 1.33 tCO_2/tNH_3 (Batool and Wetzels, 2019) and more than 300 MtCO_2, nearly 1% of global CO_2 emissions from fossil fuels, are emitted globally each year from nitrogen fertilizer production (Rosa and Gabrielli, 2023). In addition, methane emissions from natural gas production, processing and transport have been estimated to add up to 0.9 tCO_{2eq}/tNH_3 (IRENA and AEA, 2022), increasing the climate footprint of ammonia production to around 500 MtCO_{2eq}.

1.4 Downstream challenges

One would think that with the upstream challenges related to nitrogen fertilizer production, this product would be used with care to eliminate any wasteful processes. However, this is not the case. In fact, it has been estimated that only 20% (Rosa and Gabrielli, 2023) or as little as 15% (Galloway and Cowling, 2021) of the synthetic nitrogen that is produced as fertilizer actually ends up in food that is eaten. The rest is lost through food waste, crop losses and through inefficient nitrogen use and thus lost to the environment; what has been eaten is also ultimately lost to the environment as human waste (Galloway and Cowling, 2021) as shown in Figure 1.1.

Nitrogen use efficiency refers to the ratio of nitrogen taken up in plants to that applied to the fields. The ongoing global increase in animal protein intake is leading to a decline in overall nitrogen use efficiency which is currently at a global average of about 46% (Rosa and Gabrielli, 2023), although highly dependent on location, environmental conditions, agricultural methods and crop type.

Human agriculture has caused the amount of fixed nitrogen available in natural ecosystems to roughly double; this is both due to the application of synthetically produced nitrogen and due to the growing of legume crops (Smil, 1999). It has been estimated that human activities contribute to nitrogen fixation at a rate that is around three times higher than the estimated planetary boundary, which is the upper level of human disturbance to the nitrogen cycle that can be tolerated without causing irreversible damage (Wolfram et al., 2022). This means that the environmental footprint of nitrogen use needs to be substantially reduced in order to become sustainable.

Microbiological processes in soils and waters can transform nitrogen between nitrate (NO_3^-), ammonium (NH_4^+), molecular nitrogen (N_2), nitrous oxide (N_2O) and other forms of nitrogen oxides (NO_x). Nitrate is water soluble, and heightened levels of nitrate in ground waters is a public health hazard. In lakes and coastal waters, increased nitrate levels can cause eutrophication and hypoxia, leading to ”dead zones” which are increasing globally in both number and geographical area. Nitrous oxide in the troposphere is a potent greenhouse gas, adding to the climate footprint of the agricultural sector, and in the stratosphere it has adverse effects on the ozone layer (Galloway and Cowling, 2021). The ammonium ion (NH_4^+) can be converted to gaseous ammonia (NH_3) and lost to air, leading to pollution and spreading of nitrogen to other ecosystems. Terrestrial ecosystems have recently been found to be more sensitive to nitrogen than previously thought, and in 2022 a UN commission on air quality recommended lowering the regulatory limits on nitrogen emissions to air (Omsted, 2022).

On the other hand, the use of fertilizers lead to higher agricultural yields per unit area, which means that higher fertilizer use gives a smaller area requirement for a given crop output. Agricultural land use in itself has substantial negative effects on biodiversity and climate, which means that nitrogen fertilizer use also has positive effects that need to be weighed against its negative aspects.

1.5 Summary: Need for change

There are two major drivers for change of nitrogen fertilizer production. The first is the finiteness of fossil fuels, which will mean that current production methods cannot be sustained indefinitely. The second, and more urgent, is the issue of climate change. Projections presented by the IPCC show that in order to stay within the 1.5° goal of the Paris agreement, net global CO_2 emissions need to go to zero within a few decades. If the fertilizer industry is to be part of this transition, production methods will need to change.

At the same time, there is an ever increasing demand for nitrogen fertilizer. Due to socioeconomic and demographic changes, global crop demand is projected to increase by between 60 and 100% of its 2005 value by 2050 (Brunelle et al., 2015). In addition, new uses of ammonia for energy purposes (as a shipping fuel and hydrogen carrier) may become even more important than the use for fertilizer. IRENA and AEA (2022) have projected that in a scenario where global warming is limited to 1.5 °C, the total ammonia demand in 2050 will be 688 Mt, of which only 267 Mt is for fertilizer purposes. The total is almost 4 times higher than the current demand for ammonia.

The challenge for the nitrogen fertilizer industry can thus be summarized as follows: shifting to low- or zero carbon production methods within a few decades while massively increasing production. At the same time, downstream effects resulting from the use of nitrogen fertilizer need to be reduced from today's levels.

In the next chapter, I will look more closely at the technological options for ammonia production. Chapter 3 introduces the relevant economic theory. This is subsequently applied to the current problem using real-world data in Chapter 4, where we also discuss assumptions and limitations of the model. Implications for the wider economy and for downstream issues involving farmers and food production are discussed in Chapter 5, before I conclude in Chapter 6.

Chapter 2

Technological alternatives

We will now go through the most relevant technological options for future ammonia production. For this, we can rely on roadmaps and forecasts published by industry organizations such as IRENA and AEA (2022) and IEA (2021), as well as several published research papers.

At the moment, most announced alternatives for low-carbon nitrogen fertilizer production still rely on the Haber-Bosch process. In addition there are some other, less tested alternatives that have not been proven at scale. According to MacFarlane et al. (2020), upcoming transitions in ammonia production will likely take place in two stages: first processes that rely on Haber-Bosch technology, and then direct electrochemical reduction of N_2 to ammonia. The latter option is still at the research stage.

2.1 Carbon capture and storage

CO_2 emissions from fossil fuel-based ammonia production can be cut significantly by installation of systems for carbon capture and storage (CCS). This can be done through retrofits to existing plants, if there is enough space and available infrastructure, or by CCS integration in new plants.

In ammonia plants based on natural gas, there are two waste streams that contain CO_2. The first, comprising two thirds of the CO_2, comes from the hydrogen production process. This is a pure gas stream which is easy to capture; today, it is often used for other purposes such as urea production and in the food and beverages industry (IEA, 2019). This can be a source of revenue for ammonia producers, but does nothing to reduce the climate footprint as the CO_2 is released to the atmosphere after use.

The remaining third is a dilute stream. It is possible to capture CO_2 from this stream as well, giving an overall capture rate of up to 95% or up to 98% if electricity is used to supply heat to the steam methane reforming or through the use of autothermal reforming, where hydrogen production and heating is combined in a single reactor, resulting in a single concentrated CO_2 stream (IRENA and AEA, 2022).

CCS does nothing for the reliance on fossil fuels, and it does not address the climate impact that comes from upstream methane leaks. As a result the reduction of total emissions available in this system may be limited to 60-80% (IRENA and AEA, 2022).

Fossil-based ammonia with CCS is thought to be an interesting alternative for regions with low natural gas prices and access to CCS infrastructure. Due to high cost, CCS with coal based ammonia plants are not thought to be a significant option (IRENA and AEA, 2022).

The total energy cost of capturing CO_2 from both concentrated and diluted waste streams at an ammonia facility in the Netherlands has been estimated to be about 3.7 GJ/tCO_2 captured (Batool and Wetzels, 2019). This is around a 12% increase from current energy use. Given an emissions rate of 1.33 tCO_2/tNH_3 (Batool and Wetzels, 2019) and the 2020 global consumption of 183 $MtNH_3$, a capture rate of 98% today would entail an additional energy cost of 883 PJ or 245 TWh. For comparison, this is about 20% of Norway's natural gas production in 2021 (Statistisk sentralbyrå, 2022).

2.2 Hydrogen from electrolysis

Instead of getting the hydrogen required for ammonia production from steam reforming of methane, it is possible to use electrolysis to obtain hydrogen from water. A simplified flow chart of this process is shown in Figure 2.1. Comparing with the conventional ammonia production flow chart in Figure 1.2, there are two major differences. The first is that the steam methane reformation step is replaced by electrolysis, which has electricity and water as the main inputs and O_2 as a by-product. The second is that urea production now requires input of CO_2 from an external source, since CO_2 is no longer a by-product from the ammonia production process. If urea is to be produced without greenhouse gas emissions, then this CO_2 needs to be produced by capture directly from the air, which is extremely energy intensive, or from biological sources.

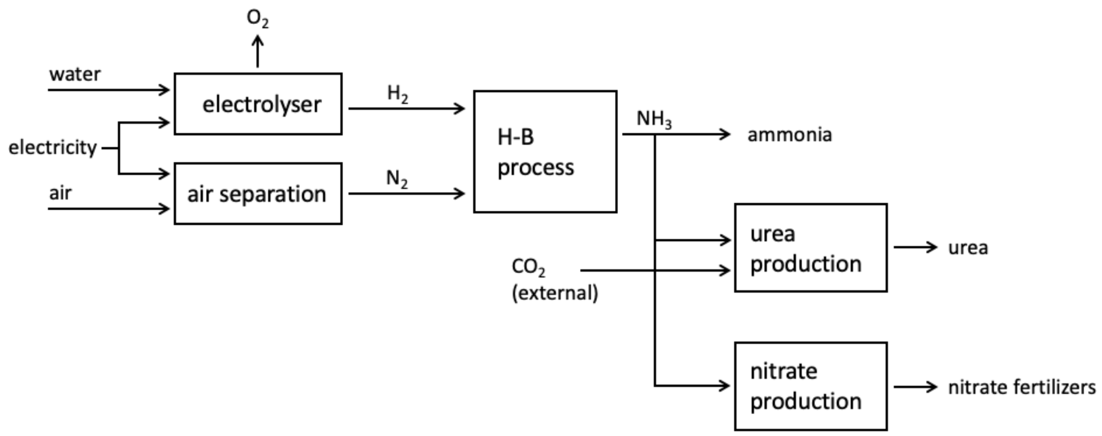

Figure 2.1: Simplified flow chart of nitrogen fertilizer production based on electrolysis.

Batool and Wetzels (2019) estimates the energy requirement for electrolysis to be 40.2 GJ/tNH_3, significantly higher than for steam reformation. This means that replacing all 2020 ammonia production with electrolysis would require about 2040 TWh of renewable electricity or 24 % of current global renewable electricity production (Ritchie et al., 2022).

2.3 Direct synthesis

While the Haber-Bosch processes was an enormous technological breakthrough that for the first time enabled the synthesis of ammonia from available feedstock, it is theoretically not the only pathway for ammonia synthesis. A more desirable option would be to produce ammonia directly from atmospheric nitrogen and water, without the need to produce molecular hydrogen first. This is why electrochemical and other methods for direct ammonia synthesis have received substantial research interest over the past few years. For example, Bennaamane et al. (2022) have demonstrated a promising pathway for low-temperature, low-pressure ammonia synthesis using boron-centered radicals.

An attractive feature of direct electrolysis plants is that they can potentially be made to operate efficiently at much smaller scales than current Haber-Bosch-production. This can enable more decentralized production compatible with intermittent energy resources (Allen et al., 2021), although so far with a higher energy demand than conventional electrolysis routes.

2.4 Plasma nitrate production

When Birkeland and Eyde first started fertilizer production in Norway in 1907, they used a method inspired by the natural process of lightning, where nitrogen and oxygen from the air are combined to form nitric acid in a plasma. However, this process was quickly found to be more costly than the Haber-Bosch process and ammonia production in Norway was converted to Haber-Bosch in the 1920s (Johnson, 2022).

Known nitric acid production methods require about three times more energy per ton of nitrogen output than the Haber-Bosch process. Still, smaller on-farm nitric acid facilities run by solar energy have been demonstrated (Pinkowski et al., 2022; Billing, 2022). According to Yara (2018), nitrates are more readily absorbed by plants and thus the most efficient and reliable source of nitrogen in agriculture. This is in contrast with the dominance of urea used particularly in Asia, even though the benefits of nitrates may be even larger in the tropics than in colder climates (Yara, 2018).

2.5 Biotechnological methods

In nature, nitrogen fixation is performed by diazotrophs in symbiosis with other organisms. A long-standing goal in research has been to engineer methods for common crops to either develop this type of symbiosis or to incorporate the nitrogen-fixing ability directly into the plants. This could potentially make crops self-sufficient in nitrogen from the atmosphere.

However, nitrogen fixation is energy intensive, even for living organisms. In symbiotic relationships, this energy is taken from photosynthesis. Legumes dedicate about 10-20 % of their carbon to root nodules (Pankievicz et al., 2019). This means that for the same photosynthetic efficiency, a crop that needs to spend energy to produce its own fixed nitrogen will have lower yield than one that is fertilized by externally produced nitrogen.

Biological nitrogen fixation is controlled by the nitrogenase complex which is highly vulnerable to molecular oxygen. Diazotrophs therefore need sophisticated methods for regulating their internal oxygen tension in order to supply aerobic respiration while limiting harm to the nitrogenase (Pankievicz et al., 2019). This is one reason why engineering nitrogen fixation is so difficult to achieve in practice, and self-sufficient crops are still decades into the future.

2.6 Summary: Three colors of ammonia

Based on the review of technological options, the two possibilities that are most ready to be implemented are CCS and hydrogen from electrolysis. We will follow industry conventions and refer to these by the use of colors: grey (fossil-based, unabated production), blue (fossil-based production with CCS) and green (electrified production). Green ammonia is sometimes subdivided into yellow (based on renewable electricity, sometimes only based on solar power) and pink (with electricity from nuclear energy), but I will not use these here.

Blue ammonia is currently less costly than the green option, but it does not change the reliance on fossil fuels and does not mitigate all emissions. It also requires infrastructure for CO_2 transport and storage which is currently not in place in most parts of the world. Fertilizer production with CCS will be vulnerable to the price of energy in the form of natural gas.

Green ammonia relies on a massive scale-up of electrolyser capacity, where it will compete with other applications of renewable hydrogen such as steel production and energy storage. It will also need a very large increase in supply of renewable electricity and be vulnerable to the electricity price.

Plasma nitrate production and direct synthesis methods may become attractive in the future, but currently suffer from a larger energy need than other alternatives. The possibility of making off-grid, on-farm systems that operate with much less price volatility than grid-connected systems may make these options more attractive in some parts of the world, but probably not at very large scales.

Biotechnological methods are at a low technological readiness level and will probably lead to lower yields per area due to the energy cost to the plants, but may in the future become a way to reduce the total nitrogen use in agriculture.

In the next chapter, I will use economic theory to address possible drivers, barriers and policy options for the transition from grey to blue or green ammonia production in the upcoming years.

Chapter 3

Economic theory

Given the goal of cutting emissions to (near) zero, producers currently face the choice between two technological avenues: conventional production with CCS (blue ammonia), or electrified production with hydrogen production from electrolysis (green ammonia). In this chapter, I will use economic theory combined with technological insight to assess which of these options may be desirable in terms of social benefit, and possible mechanisms that can drive adoption of one or the other technology.

3.1 Abatement through emissions pricing

A natural place to start is to internalize the negative externality of greenhouse gas pollutions through a pricing mechanism. We will do this through a quota price τ, but a Pigovian tax on emissions will give identical results in the current set-up.

We start by establishing production functions for our technology options. The dominant input to ammonia production is energy in the form of electricity and/or natural gas. Other inputs such as labor, water, air and catalyst materials are for now judged to be of minor importance. This gives us an ammonia output y as a function of input energy $X$and an energy productivity γ on the form $y = X\gamma$.

In natural gas based production, greenhouse gases can either be captured and stored through CCS, or released to the atmosphere if the producer holds a sufficient emissions quota. If the total amount of CO_2 produced per unit of produced ammonia from natural gas is g and $c \in [0, 1]$ is the capture rate, then an amount cg is captured and stored while $(1 - c)g$ is emitted. The producer needs to have access to both sufficient capture and storage capacity and a sufficient emissions quota for a chosen value of c in order to produce a given output.

In practice, there are two different gas streams to capture emissions from (IRENA and AEA, 2022). The first is the pure CO_2 stream of process emissions, which comprises a fraction c_P of total emissions from the plant. The capture of this stream requires a modest energy input e_P per unit of produced ammonia in the form of electricity for compressors. The other is the mixed stream where a total of c_M can reasonably be captured; the exact amount is given by the chosen technology. Capturing these emissions requires an energy input of αN in the form of heat produced from natural gas, as well as additional electricity. The electric energy cost of the total capture of $c_T g = (c_P + c_M)g$ is $E = e_T g$ where $e_T > e_P$.

We assume that producers only need emissions quotas for their scope 1 emissions, so that any scope 2 emissions for electricity production, in the case that electricity is bought from the local grid, is included in the cost of electricity. We also assume that if producers choose to produce their own electricity for green ammonia this is done using only renewable electricity generation. Green ammonia therefore has no emissions in this model. Along the same lines, scope 3 methane leaks and other upstream emissions are assumed to be the responsibility of the natural gas supplier and are therefore not included in this model.

This gives us the following Leontief production functions for in all 4 different choices of technology:

$$\begin{aligned}
\text{Grey}:&\ y = \min\{\gamma_N N, g\} \\
\text{Blue (low CCS)}:&\ y = \min\{\gamma_N N, \frac{E}{e_P}, (1 - c_P)g, c_P g\} \\
\text{Blue (high CCS)}:&\ y = \min\{\gamma_N N(1 + \alpha), \frac{E}{e_T}, (1 - c_T)g, c_T g\} \\
\text{Green:}&\ y = \gamma_E E
\end{aligned}$$

where γ_N and γ_E denote the output of ammonia per unit of energy input in the form of natural gas or electricity, respectively.

We can now find expressions for the marginal cost of ammonia production. Introducing price p_j for input j, unit cost p_C of CO_2 capture, transport and storage, and a quota price of τ, the short run marginal costs for these four options become

$$
\begin{aligned}
\text{Grey: } & \frac{p_N}{\gamma_N} + \tau \\
\text{Blue (low CCS): } & \frac{p_N}{\gamma_N} + p_E e_P + p_c c_P + \tau(1 - c_P) \\
\text{Blue (high CCS): } & \frac{p_N(1+\alpha)}{\gamma_N} + p_E e_T + p_c c_T + \tau(1 - c_T) \\
\text{Green: } & \frac{p_E}{\gamma_E}
\end{aligned}
\tag{3.1}
$$

Short run marginal costs and built-out capacities are what determine the supply curve at any moment in time, and through this, the market price given the market demand function. Consumers will benefit from having a large amount of established capacity with low short run marginal costs.

In the long run, however, producers face decisions of changing their plant portfolio through replacing old plants by new ones, or by retrofits to existing plants. For any investment to be viable, the producer needs to weigh expected income against total costs over the lifetime of the plant. This includes installation and other fixed costs, which were not considered in the short run because they can be regarded as sunk cost that are not affected by the decision to produce one additional unit of ammonia.

If we assume for simplicity that a plant needs an investment I_i per unit annual output in order to be established, then the annual costs of capital at a real interest rate r will be rI_i and the long run marginal costs of the plant can be written as

$$LRMC_i = rI_i + SRMC_i \tag{3.2}$$

Figure 3.1 illustrates how the long run marginal costs vary with quota price τ for an example set of parameters. In this figure, the curves intersect so that each natural gas-based option has the lowest marginal cost at some τ. This may not always be the case in practice.

In the current situation, the carbon price τ is low enough that virtually all production takes place without mitigation. However, the anticipation of a higher future τ is already causing ammonia producers to consider mitigation options for their future portfolio (IRENA and AEA, 2022). As τ increases, we can reach the point τ_m^0 where mitigation becomes the best option for producers because it has the lowest LRMC. At even higher τ, more costly mitigation options become preferable.

As this illustrates, a price on emissions can indeed lead to emissions abatement. When producers face the choice of technology for a new plant, they need to consider

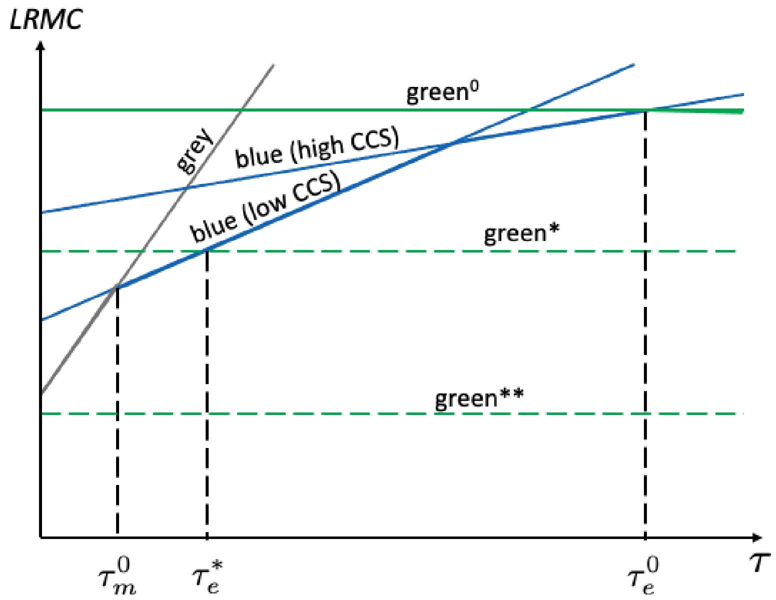

Figure 3.1: Long run marginal costs of production for different ammonia production options as a function of quota price τ. The thick line shows the lowest marginal cost at different τ, and the horizontal dashed lines show possible future lower LRMC of green ammonia production. All values used are chosen for illustrative purposes.

the net present value of the cash flow of the plant over its lifetime. This means that in order to choose to invest in a lower emissions technology, they need a good reason to believe that the quota price will remain high in the future. Policy makers can increase confidence in this through instruments that guarantee some minimum quota price level.

The choice of doing CCS is critically linked to the current quota price. Even when CCS capabilities are installed on the plant, producers have a choice between capturing or emitting CO_2, because CCS will always be an additional cost with no added value. This means that, as pointed out by Vogl (2023) in the context of steel production, a sustained high carbon price is needed to keep future emissions low when abatement is based on CCS. CCS can also never cut emissions by 100%, particularly when including upstream emissions. The end state of transition to blue ammonia is therefore ammonia production with increased cost relative to today, and with continued residual greenhouse gas emissions.

With current costs, green ammonia only becomes the preferred option at a very high quota price τ_e^0. Curiously, though, the current trend in industry is more investment in green than blue ammonia production capacity (IRENA and AEA, 2022). This suggests the presence of drivers that push ammonia producers in the direction of electrification instead of CCS.

There are, in fact, several mechanisms that may cause the LRMC of green ammonia production to fall in the future. These will be the topic of the following subsections, but for now, we illustrate possible future scenarios with the dashed lines marked green* and green** in Figure 3.1. A reduction of costs to green* would give a cross-over from natural gas based to electrified production at a lower quota price τ_e^*. Given sufficient cost reductions, future costs of green ammonia may even fall below the cost of grey ammonia (green**). If so, electrified production would take over as the dominant technology even without a price on emissions, and result in an overall welfare gain.

3.2 Taking advantage of intermittent electricity production

Comparing the marginal costs in Equation 3.1, we see that the relative prices of electricity and natural gas have a large effect on the relative marginal costs of green and blue production. Lower future electricity costs may therefore be a powerful driver for a shift towards green ammonia.

In their innovation outlook, IRENA and AEA (2022) project that costs for green ammonia production will decrease by more than 30 % within the next decade, and that 90 % of this reduction will be due to lower costs of renewable electricity production. However, even though the levelised cost of electricity from renewable sources is projected to keep declining as capacity is ramping up, it is not clear that this will translate to a decline in market electricity prices. There are many sources of friction, such as public acceptance challenges, in the efforts to establish more renewable energy generation capacity; at the same time, demand will increase as many sectors are aiming towards electrification. On top of this, we can expect electricity prices to be correlated with natural gas prices as long as natural gas forms a significant part of the electricity mix, so that the difference between natural gas and electricity price may not become significantly higher than today. Waiting for electricity prices alone to drive the shift to electrified production is therefore a gamble with high uncertainty.

On the other hand, green ammonia is part of a larger transition in the economy where we may expect intermittent renewable energy resources (solar and wind) to comprise a much larger part of the energy system than today. This means that electricity prices are likely to exhibit more fluctuations over the course of hours and days than in the current situation.

An advantage of electrolysers is that they can easily be ramped up and down without loosing much efficiency (Zenith et al., 2022). This means that producers can choose to use their electrolysers more variably to take advantage of fluctuating electricity prices.

In a world of constant input prices, it will always be beneficial to have as little downtime as possible in order to minimize capital costs per unit produced. With fluctuating prices, producers can choose to limit hydrogen production at some cutoff electricity price. It would not, in fact, matter if producers own their electricity generation facilities or they buy electricity on the market. As long as they are connected to the grid, they could still choose to sell electricity at the market price instead of using it to produce hydrogen when prices are high.

The situation is illustrated in Figure 3.2 where electricity prices fluctuate around a mean value $\underline{p_E}$ for a period of time. If producers choose to limit electrolysis above a price p_E*, they will pay a lower average electricity price $\underline{p_E*}$ but the electrolyser will also operate at a lower capacity factor. The producer can then choose their cutoff value p_E* in order to get the lowest cost per unit of hydrogen produced while taking into account the extra expenses involved in intermittent production.

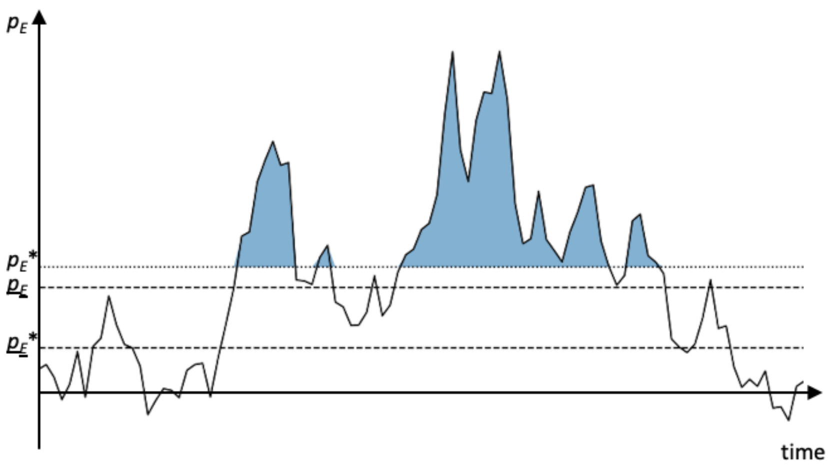

Figure 3.2: Illustration of intermittent hydrogen production where production is cut off (marked as shaded regions) when the electricity price exceeds a threshold p_E*.

The Haber-Bosch process, where hydrogen is combined with nitrogen to produce ammonia, is best suited for more or less continuous operation. This can be achieved by combining intermittent hydrogen production with hydrogen storage, which requires extra installation cost and an additional energy input in the form of electricity per unit of produced ammonia (Zenith et al., 2022).

In our model, the result of adapting to intermittent production would be higher fixed costs I_{el} and lower efficiency γ_E (Equations 3.1 and 3.2), but reduced effective electricity prices p_E. The effect in Figure 3.1 would correspond to shifting the curve for electrified production downward, from green^0 toward green*. If producers anticipate a higher future quota price τ, considering intermittency will increase their chances of choosing green production even when electricity prices are high and correlated with the natural gas price.

Uncertainty about the future development of the integrated electricity market, and how countries choose to address intermittency, implies that this may not form a very strong incentive for producers unless they are met with policy instruments that give some sort of guaranteed minimum payment for grid services.

3.3 Learning effects

Green ammonia production is an immature technology with ample potential for cost reductions through technological development, often referred to in literature as ”learning”. Learning can take place through research and development (lab or pilot scale, prior to commercial scale deployment) or by deployment, where costs go down as a function of installed capacity through what is called ”learning by doing”. Depending on intellectual property regulations, learning may diffuse to other producers or countries, and also to adjacent sectors.

Learning by doing is typically measured by analysing cost as a function of installed capacity Γ, and the learning curve can be written with the unit cost c as

$$c(\Gamma) = c_1 \Gamma^{-\beta}$$

where c_1 is the unit cost at cumulative installed capacity $\Gamma = 1$, and β is the learning elasticity. A doubling of installed capacity decreases the cost by a factor $2^{-\beta}$, where $1 - 2^{-\beta}$ is often called the learning rate: the percentage reduction in unit cost for a doubling of cumulative installed capacity (McDonald and Schrattenholzer, 2002). The learning curve can also be written with more factors, for instance to separate between learning by research and doing, as

$$c(M, \Gamma) = c_1 M^{\beta_M} \Gamma^{-\beta_\Gamma}$$

where M is the investment in R&D.

Learning effects are increasingly addressed in economic literature through theories of directed technological change where technological development is endogenous to the model (Hémous and Olsen, 2021). These models typically show that a Pigovian tax is not sufficient to obtain the first best outcome when the cleaner technology option needs development; short-sighted market forces will direct investment toward the larger, more established technology. This effect, also called technological lock-in, is why subsidies for technology development is often called for. However, research investment or subsidies for immature technology implementation can be too much for a single country to take on by itself. This induces a free-rider problem that has been addressed by researchers through the use of game theory, which is the subject of the next section.

3.4 Coordinated adaptation of a breaktrough technology

A classical problem in environmental economics is the situation where N countries can each choose to abate an amount q_i of their emissions (in our case, this would correspond to capturing emissions through CCS or avoiding them altogether through electrification). Total abatement is $Q = \Sigma_{i=1}^{N} q_i$, which has a benefit for all countries involved. On the other hand, the marginal cost of abatement increases with q_i (in our case, this would be because higher CCS rates require more energy, or because a massive build-out of electrified production could give high installation costs due to a high electrolyser demand relative to supply).

As shown by Barrett (2006), if the payoff to country i can be written as $\pi_i = b_0 Q - c_0 q_i^2/2$, and each country chooses its abatement level independently, then there exists a unique Nash equilibrium where each country abates an amount $q_i = b_0/c_0$. This is smaller than the abatement level in full cooperation, which would be $q_i = b_0 N/c_0$, illustrating the basic motivation for climate treaties or other forms of collaboration to achieve international ambitions on climate. However, as discussed by Barrett (2006), in a simple stage game where 1) countries decide on participation, 2) signatories decide their abatement level and 3) non-signatories decide on their abatement levels, the Nash equilibrium coalition size is as low as 3 countries. This gives a very small increase in total abatement and illustrates that other political mechanisms may be needed.

Barrett (2006) proposes that a more effective alternative to simply collaborating on abatement levels would be to collaborate on the development (R&D) and adoption of a breakthrough technology. In his model, the breakthrough technology gives zero emissions (this could be renewable energy technology in the power sector, or, in our case, green as opposed to blue ammonia) and each country can choose either to adapt the new technology or to abate an amount q_i using old technology.

Given a situation where costs and benefits are so that all countries would be collectively better off if everyone adopts the breakthrough technology, but the cost of adoption for a single country is higher than the cost of abating an amount b_0/c_0, then the Nash equilibrium will still be that each country abates the minimum amount using the old technology. Barrett (2006) shows that a stage game can result in adoption by an equilibrium coalition of size k^*, and that collective financing of the required development will be sustained by the coalition provided that total development costs are less than the collective gain of realizing the new technology. However, as in the classical abatement problem, the total increase in abatement will be modest.

If, however, the breakthrough technology displays increasing returns to adoption, Barrett (2006) finds a different situation. In this case, the more countries adopt the technology, the less costly it is, until at some point it becomes beneficial for all countries to implement it because it has become less costly than the alternative abatement option. As before, development will be funded as long as total benefits outweigh the cost. Barrett (2006) shows that if the benefit of implementation of the breakthrough technology for one country in a coalition of z out of a total N countries can be written as $bz - \frac{c}{N}(N - z + 1)$, then the tipping point for full adoption is the smallest integer z^* greater than or equal to $N(b_0^2/2c_0c + 1 - b/c)$.

In our case, we can view learning by doing as a form of increasing returns to adoption. This implies that if the learning effect for green ammonia is sufficiently prominent, then a coalition focused on developing and implementing this technology may have a greater climate effect and societal benefit for the ammonia production industry than simply relying on a higher quota price.

3.5 Decreased adaptation costs through R&D

In the model of Barrett (2006), adoption of the breakthrough technology takes place in stages: 1) investment of development cost M, and then 2) adoption at a cost that may decrease with scale. In practice, however, there is usually no absolute, given threshold for the development that is required before a technology can be adopted. If commercial scale implementation takes place with immature technology, initial adaptation will be costly, but learning effects will be stronger. Research scale development can be expected to proceed more slowly.

Hoel and de Zeeuw (2010) have extended the model of Barrett (2006) to account for the fact that adoption costs c can decrease with the investment in development M, so that $c = c(M)$ with $c' < 0$ and $c'' > 0$. Instead of a fixed threshold, we now have a trade-off between development costs and costs of adoption. Hoel and de Zeeuw (2010) show that under these conditions, it is actually possible to come to a non-cooperative solution that gives full adaptation of the breakthrough technology. The requirement for this is that there exists an investment level $\bar{M}$ where $c(\bar{M}) = b$ and $\bar{M} \leq Nb(N-1)$, and that each country will invest $m_i = \bar{M}/N$.

The social optimum in the Hoel and de Zeeuw (2010) model is that countries minimize $Nc(M) + M$, so that each country receives a net payoff of $\pi_N = bN - \min_N[c(M) + \frac{M}{N}]$ at full adoption. This may be different from the payoff received in the non-cooperative solution, where each country invests just enough for full implementation to take place, not to minimize total cost. Hoel and de Zeeuw (2010) therefore go on to investigate whether a coalition can lead to a better outcome. It turns out that under the assumptions of the model, there exists a stable coalition that can give a higher social outcome for all parties. The increase in net benefit is small for coalition members and large for those outside the coalition. This means that the costs of coalition formation will need to be small in order for this to be a viable solution in practice. Hoel and de Zeeuw (2010) also find that there exists a stable coalition that will invest and adopt also when $\bar{M}$ does not exist, but that this coalition achieves very little in terms of total abatement. The main outcome from this model may therefore be the non-cooperative equilibrium: that when implementation costs can be significantly reduced through R&D, then it can be beneficial for all countries to invest sufficiently in development.

Green ammonia is still at a low technology readiness level (TRL), which means that R&D investments can lower the costs of adoption, both through technological progress and through validation and documentation of the most promising methods, in order to advance on the TRL ladder. This can increase the net present value of an investment because technologies at a low TRL level face higher costs of capital due to the higher risk inherent in an immature technology.

What the Hoel and de Zeeuw (2010) model implies for our case is that all actors can be better off by investing a certain amount in R&D, or that some actors can form coalition to carry out the necessary effort to reach the social optimum and full implementation, in which case they would provide a substantial welfare gain to non-signatories. This may be a relevant discussion in terms of developing and developed countries and different responsibilities for climate mitigation. The presence of heterogeneous actors will be further explored in the next subsection.

3.6 Technology diffusion among heterogeneous actors

Since the gains from coalition formation for breakthrough technology development in practice seem to be modest (Barrett, 2006; Hoel and de Zeeuw, 2010), it is worth investigating whether simply unilateral technology development can be a better strategy for countries who wish to be seen as forerunners in the climate mitigation game. This has been investigated by Brandt and Svendsen (2022) in a model where they include the effect of differences between countries.

In their model, Brandt and Svendsen (2022) account for the characteristics of each country i through a vector $\gamma_i = \{\gamma_i^E, \gamma_i^2, \ldots, \gamma_i^N\}$ where γ_i^k denotes the value along a specific dimension such as infrastructural development or political conditions. The cost of adaptation in country i after an investment M_i will be $c_i(M_i)$ while the cost in country j for adopting the technology developed in country i will be $c_{ij}(M_i, d(\gamma_{ij}))$, where the specification distance between i and j is

$$d(\gamma_{ij}) = \Sigma_k |\gamma_i^k - \gamma_j^k|$$

The more similar the two countries are, the easier it will be to transfer the technology from one country to the other.

Brandt and Svendsen (2022) describes how from the standpoint of country i, there will be a threshold investment level $\bar{M}_{ij}$ where $c_{ij}(\bar{M}_{ij}, d(\gamma_{ij})) = c_j^0$, that is, the cost of adapting the new technology is equal to the installation cost for the old alternative in country j. In our case, this would be where the LRMC of green ammonia is equal to that of natural gas based ammonia production.

The objective for the technology developing country i will be to maximize the payoff, given by the number of countries adopting the new technology and the cost of development. Building on the model by Hoel and de Zeeuw (2010), we can write the payoff to country i as

$$\pi_i = bn(M) - c(M) - M$$

where $n(M)$ is the number of countries that will adopt the technology for a particular investment level M. We know that $n' > 0$ and $c < 0$, which means that there will be a solution M^* that gives $bn'(M^*) - c'(M^*) = 1$. If we also have $n(M^*) \leq N$, then country i will have a positive payoff and it will be a rational choice to pursue unilateral technology development.

Whether unilateral development is the best choice for country i, however, depends on the specifications of the different countries and on the exact shape of the learning curve. These factors are uncertain and impossible to know fully for country i. Brandt and Svendsen (2022) discuss how the uncertainty in country specific factors can be reduced by entering partnerships, where either country i learn about country j and use that knowledge to tailor the technological development to optimize for adoption in both countries, or where both countries collaborate on developing a technology that is a good fit for both of them.

3.7 Increased willingness to pay through new markets

We have so far looked at how individual countries may choose to invest in development in order to promote large-scale adoption of a breakthrough technology. We have not discussed details about this funding, but since our actors are countries, we can regard it as some form of subsidy. Alternatively, we could regard the actors as (multinational) corporations who use their investment budget. The theory would essentially give the same result.

However, market effects can also provide funding through an increased willingness to pay in niche or alternative markets. This can be an important future pathway for ammonia production. The reason is that in some future scenarios for decarbonization, green ammonia plays an important role as a fuel for both long-distance transport and power plants (IRENA and AEA, 2022). This means that the demand for ammonia can potentially become much higher than that for agricultural purposes alone.

As discussed by Kalkuhl et al. (2012), technological lock-in (continued use of an inferior technology as a result of not overcoming the investment threshold required from learning in the immature technology) is a particular problem for goods with high substitutability. For perfect substitutes, consumers will always buy the cheapest alternative, whereas with a lower elasticity of substitution, product differentiation can occur where consumers choose to pay more for a superior product. Using an intertemporal general equilibrium model, Kalkuhl et al. (2012) show how technological lock-in in a situation with high elasticity of substitution can cause a delay of several decades for the superior technology to become dominant. This market failure causes a loss of welfare that is significant when learning rates are high, but small for low learning rates.

Grey, blue and green ammonia are all molecularly identical. As such, we should expect green ammonia to be a perfect substitute for ammonia produced from natural gas. However, demand for ammonia for transport or the power sector may be directed toward green ammonia alone, because the reason for switching to ammonia in these sectors is to avoid emissions. This means that there will be a lower elasticity of substitution between green and grey/blue ammonia in these sectors, allowing a niche market to develop where prices of green ammonia can be higher than for the alternatives.

These findings suggest that if countries can expect new markets to become significant and display a high willingness to pay, then this niche market effect could make up the role that subsidies would otherwise have taken. It leaves the dynamics and financing to the market, but policy makers can encourage this development by demanding drastic emission cuts in the transport sector.

3.8 Summary: Carbon price is not enough

In this chapter, we have seen that a sufficiently high price on emissions can induce the industry to choose a lower emission technology. Under current conditions, this is likely to be blue ammonia where abatement takes place via CCS. However, CCS will always be more costly than conventional production and will be turned off by producers if the quota price is reduced in the future. On the other hand, green ammonia can be a breakthrough technology that in the longer term has the potential to become a less costly alternative, with zero emissions, that can also take advantages of new market opportunities when intermittent renewable electricity production becomes more prominent in the energy mix.

Green ammonia needs learning by doing and/or research to become a favorable option. We have seen that this can take place through a coalition, provided that the learning effect is prominent enough, but that the gains from a coalition may not be very large. Another option is unilateral development by countries who choose to act as forerunners. Provided that the learning effect will be large enough and that differences between countries are not too pronounced, this can be enough to drive full adoption of electrified technology and result in a substantial welfare gain compared with being locked-in to the current technology.

It is also possible that the transition to a low carbon economy will create a demand for emission free ammonia and a higher willingness to pay from actors in sectors outside agriculture. This may be enough to provide the funding needed for learning by doing instead of direct government subsidies.

In the next chapter, we will use numbers from literature to address the likelihood of the different options. We will also discuss assumptions and limitations of our model.

Chapter 4

Application and discussion

We are now ready to apply the economic theory introduced in Chapter 3 to the real world example of ammonia production. The roadmaps and studies introduced in Chapter 2, such as IRENA and AEA (2022) and IEA (2021), provide data like typical investment costs.

As we saw in the previous chapter, the potential for learning in green ammonia production is a key factor in assessing potential drivers in the transition to lower emissions. We should therefore investigate what learning rates might be expected.

Solar PV is often used as an example of learning by doing, with learning rates estimated around 20% (Leonidas et al., 2017). Electric vehicles have been estimated to achieve more learning from research (27%) than from doing (8%) (Leonidas et al., 2017). These are examples of goods that are sold to individuals and produced in very large volumes. On the other hand, energy technologies that are typically built as large, one-off units see much lower learning rates, such as 1.4% for hydroelectricity; in the case of nuclear energy, learning rates have even been found to be negative (Leonidas et al., 2017), something that is probably related to changing regulatory conditions.

The most important capital cost unit in green ammonia production is the electrolyser. While not comparable in number of produced units relevant for electric vehicles, electrolyser technology may become central in many different industries and built out in a relatively large volume, thus making the comparison with PV or electric vehicles (on the order of 20% learning rate) more relevant than hydroelectricity and nuclear energy. In literature, we find learning rates for electrolyser technology around 18%, with individual estimates ranging from 12 to 20 % (Detz and Weeda, 2022) without distinguishing between learning by research or doing.

The fertilizer industry is well aware of their upcoming challenges when it comes to greenhouse gas emissions, and several of the largest ammonia producing companies globally, including CF Fertilisers, Yara, Sinopec and BASF, have made targets for net zero emissions or climate neutrality by 2050. Together, these acoount for close to 15 % of global ammomia production. Other companies have made shorter-term targets for major emissions cuts by 2030, and the International Fertilizer Association has established an ambition to reduce greenhouse gas emissions from nitrogen fertilizer production by at least 30 % per unit ammonia produced by 2040 (IEA, 2021). The shift toward electrolysis is currently stronger than than for CCS. More than 60 ammonia plants based on electrolysis were announced during 2020 and 2021, and only 10 new fossil-based plants with CCS (IRENA and AEA, 2022).

4.1 Pricing emissions

We can now use cost estimates from literature to calculate the LRMC as a function of quota price according to Equations 3.1 and 3.2, and get an empirically based version of Figure 3.1. Values for installation costs and energy requirements can be found in IEA (2021). A challenge, however, is that energy costs are highly volatile, and have been particularly so since 2021. For instance, the natural gas price in Western Europe was more than 25 times higher in April 2022 than in June 2020 (IEA, 2022). European electricity market prices fluctuated between 20 and 60 EUR/MWh between 2015 and 2020, but reached more than 600 EUR/MWh in some European countries during the summer of 2022 (Bundesnetzagentur, 2023). The price excursions from 2021 onward follow from a combination of post-pandemic economic rebound, weather-related factors resulting in higher demand and lower supply, and Russia's invasion of Ukraine (IEA, 2022). As highlighted by IEA (2022), large investments are needed in the energy sector in order to avoid high energy prices and volatility in the short and mid term future.

Around a quarter of all global greenhouse gas emissions are now covered by some sort of carbon price, either in the form of quotas (emissions trading schemes, ETS) or carbon taxes, with prices increasing sharply during the last few years (World Bank, 2022). The highest carbon prices are currently found in Europe, where in April 2022 the EU ETS price was 87 USD/tCO_2, up from 24 USD/tCO_2 in 2019 and only 8 USD/tCO_2 in 2015 (World Bank, 2022).

The EU ETS includes a mechanism where industries that are at risk of carbon leakage (meaning that production can easily be moved to regions with less stringent emissions regulations) can be allocated free allowances. This means that all ammonia production in the EU is currently allocated free allowances, which are going to be progressively phased out until 2034 (Bonnet-Cantalloube et al., 2023). Mechanisms are also underway for border adjustments in order to avoid shifting production to areas with lower carbon prices (European Commission, 2023).

Figure 4.1 shows the LRMC of four different options of ammonia production based on low (top panel) and high (bottom panel) values of natural gas and electricity prices and other literature values given in Table 4.1. The marginal costs are shown as a function of quota price τ ranging up to 500 USD/tCO_2. For reference, the dashed box shows the range of typical recent quota prices in the EU ECTS system (25-85 USD/tCO_2) (World Bank, 2022).

IRENA and AEA (2022) have found that a carbon price of around USD 150 per ton CO_2 is required for green ammonia to be competitive with grey ammonia. This is only slightly higher than what we find in the low energy case in Figure 4.1, suggesting that our simplified model captures the most important aspects of the problem.

Table 4.1: Literature values used in Figures 4.1 and 4.2. Symbols refer to Equations 3.1 and 3.2.

Parameter	Symbol	Value	Unit	Reference
Installation cost, new conventional plant	I_{grey}	1675	USD	IEA (2021) Box 1.4, 875 kt plant.
Installation cost, new plant with CCS	I_{blue}	1850	USD	IEA (2021) Box 1.4, 875 kt plant.
Installation cost, new plant with electrolysis	I_{green}	2065	USD	IEA (2021) Box 1.4, 875 kt plant.
Real interest rate	r	5	%	assumed
Natural gas price, low	p_N	2	USD/MBtu	IEA (2022)
Natural gas price, high	p_N	28	USD/MBtu	IEA (2022)
Electricity price, low	p_E	20	EUR/MWh	Bundesnetzagentur (2023)

Continued on next page

Table 4.1: Literature values used in Figures 4.1 and 4.2. Symbols refer to Equations 3.1 and 3.2. (Continued)

Electricity price, high	p_E	300	EUR/MWh	Bundesnetzagentur (2023)
Natural gas productivity	γ_N	27.6	GJ/tNH_3	IEA (2021) Table 1.2
Electric energy productivity	γ_E	34.4	GJ/tNH_3	IEA (2021) Table 1.2
Electricity requirement, low CCS	e_P	0.1	MWh/tNH_3	assuming lower than for high CCS
Electricity requirement, high CCS	e_T	0.35	MWh/tNH_3	Rosa and Gabrielli (2023)
Capture rate, low CCS	c_P	67	%	IRENA and AEA (2022)
Capture rate, high CCS	c_T	98	%	IRENA and AEA (2022)
Natural gas energy requirement, high CCS	α	6.2	%	IEA (2021) Table 1.2; (32.1-3.1)/(32.1-4.)-1
CO_2 transport and storage cost	p_c	50	EUR/tCO_2	Roussanaly et al. (2021)

First of all we see, unsurprisingly that the marginal costs of production vary significantly with energy prices. This is a well known phenomenon in the industry and a source of volatility in ammonia prices today. For reference, US market prices of ammonia reached over 1600 USD/tNH_3 in 2022 after having fluctuated between 400 and 900 USD/tNH_3 from 2009 to 2021 (Schnitkey et al., 2023).

We see that under the assumption of low energy prices, the current EU ETS price should in fact be sufficient to induce mitigation. This makes it a bit surprising that there is not more CCS investment in the pipeline for European facilities. One reason may be that ammonia producers currently get free emissions allocations; however, given the alternative cost of selling these quotas to other sectors, it should not really matter that these allowances were free to begin with. Another, more

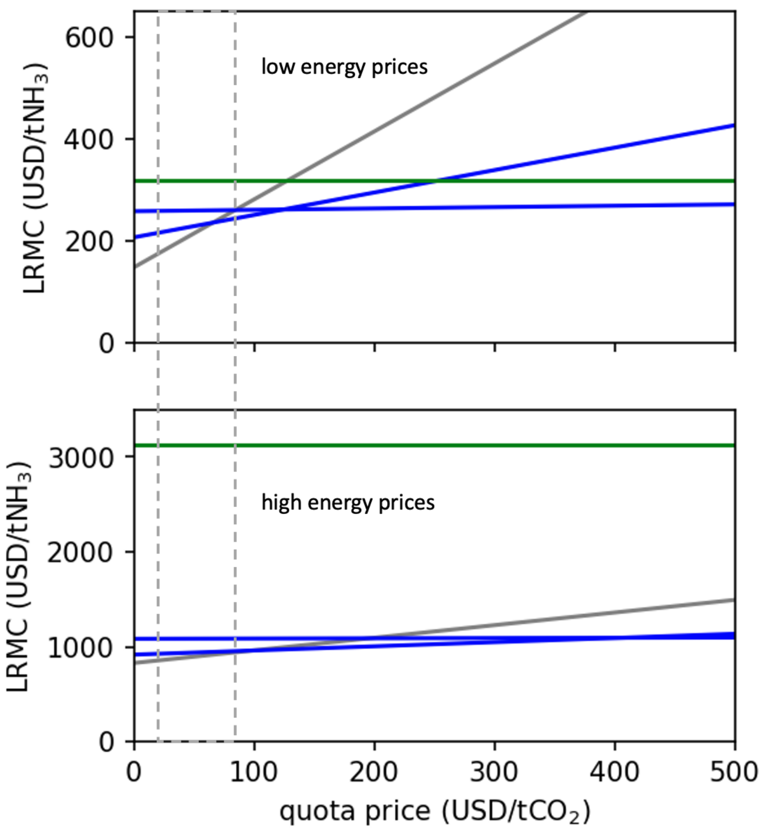

Figure 4.1: Long run marginal costs of production for grey, blue (low and high CCS rate) and green ammonia production as a function of quota price τ under assumptions of low (top panel) and high (bottom panel) electricity and natural gas prices. Recent values of quota price (EU ECTS) are shown by the dashed square. All costs are calculated using Equations 3.1 and 3.2 and the values given in Table 4.1.

plausible explanation is the lack of available CCS infrastructure.

Higher energy prices make the quota price required for mitigation higher, and much higher to induce the highest level of CCS. We also see that green ammonia under the current assumptions is never going to be preferable to grey or blue ammonia, in particular with high energy prices. This is partly because of the nearly flat slope of the high CCS cost curve, due to the high capture rate assumed.

However, only moderate technological improvements are required to make green ammonia a more desirable option. Figure 4.2 shows that a 50 % increase in energy efficiency is sufficient to make green ammonia less costly than the high CCS option under assumptions of low energy prices (dashed line), and that if in addition both installation costs and effective electricity prices are reduced by 20%, green ammonia becomes the best mitigation option and relevant even at today's quota prices (dotted line). Reduction of effective electricity prices could be a result of taking advantage of intermittent energy production; this requires a higher capacity for a given annual output, meaning that installation costs per unit capacity need to be reduced by substantially more than 20 % for the installation cost per unit output to be 20% lower in this scenario. While Zenith et al. (2022) have shown that grid services in some cases can significantly improve the economy of hydrogen production plants, there is currently insufficient data to say anything more precisely about the value of this effect for ammonia production.

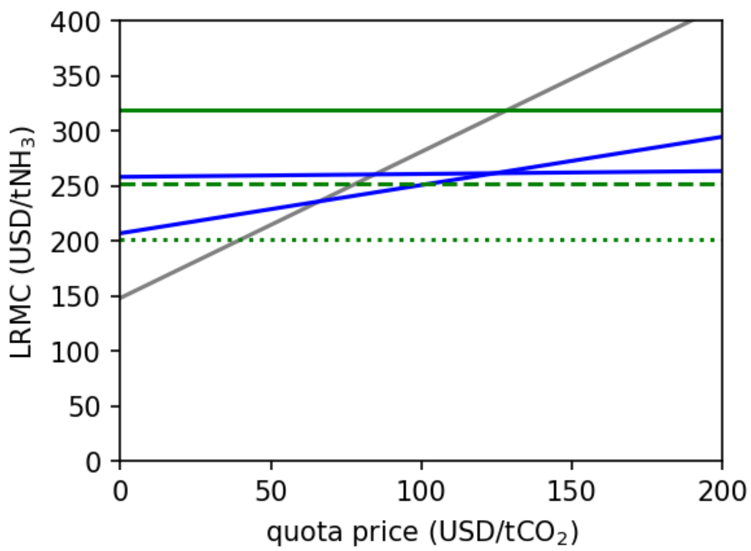

Figure 4.2: LRMC as a function of quota price under the low electricity price assumptions as in the upper panel of Figure 4.1, but also showing the LRMC of green ammonia with 50 % higher energy efficiency (dashed line) and a combination of 50% higher energy efficiency and 20% lower costs for both installation and electricity (dotted line).

It is important to note that in this section, we have used single numbers for all costs except energy prices. In practice, installation costs are highly uncertain. With the values used here and low energy prices, a 20 % change in installation costs corresponds to a 13 % change in LRMC for gray and 7.4 % for green ammonia.

As previously noted, producers need confidence in sustained high carbon prices in order to invest in abatement technology. Vogl et al. (2021) describes a policy instrument in the EU called a carbon contract for difference (CCfD), which is a subsidy agreement between the regulator and a steel producer. The regulator guarantees a constant carbon price for 20-30 years, aimed to lower the risk for the producer. This can reduce financing costs. However, when future cash flows are highly dependent on electricity prices, this instrument may not be enough to ensure profitability. In that case, government-backed electricity price guarantees can be a complementary policy to CCfD.

4.2 Subsidies and coordinated adaptation

We saw in the previous section that under current conditions, green ammonia is unlikely to become the most viable option unless the carbon price is extremely high. Learning effects may drive costs down, but market forces alone unlikely to lead to sufficient learning. This calls for some form of government subsidies in order to develop the immature technology. Could an alternative be to form a coalition that shares the cost of adaptation, driving down the cost per country until electrified production becomes the best option for all countries?

Barrett (2006) showed that such a tipping point can exist if the cost of implementing the breakthrough technology decreases linearly with the number of implementing countries, which can be written as form $c(1 - \frac{z-1}{N})$. This means that if only one country implements ($z = 1$), then the cost is c, while if all countries implement then the cost is shared and equal to $\frac{c}{N}$. In this model, a world with a higher number N of countries gives larger potential for cost reductions, but also a bigger potential benefit because the avoided emissions also scale with N.

Technological learning, on the other hand, is typically written as a power law on the form $c^l(\Gamma) = c\Gamma^{-\beta}$ where c is the cost when the installed capacity is one. This cannot be directly implemented in the model by Barrett (2006), but we can investigate what it would take if the cost of implementing electrified technology indeed decreased linearly with the number of implementing countries.

Barrett (2006) show that the tipping point for full adaptation in his model is reached by a coalition of size z^*, where z^* is the smallest integer greater than or equal to $N(b_0^2/2c_0c + 1 - b/c)$. This applies to the choice between abating using old technology, which in our case would be CCS, and the new breakthrough technology, here electrified production. Producers using CCS do not simply abate the maximum amount that can be achieved technically, they rather choose their abatement level to maximize their payoff. For the sake of the argument, we will assume that producers have installed the technology that is needed for a high CCS level, but that the capture rate is chosen freely.

This model does not include taxes on emissions, but it does include the benefit of avoiding emissions. If we view the carbon tax as a Pigovian tax, reflecting the value that society puts on the benefit of avoiding emissions, then we can use τ as a measure of the benefit in the model. In the model, this translates to setting both $b_0 = \tau$ and $b = \tau$.

The parameter c_0 is the marginal cost of abating through CCS, which in the model increases linearly with abatement level. In Equation 3.1, we model the marginal abatement cost as a step function from low to high capture rate. In order to compare the models, we make the gross simplification that p_c is the marginal abatement cost at an abatement level of 0.5, which gives $p_c = 0.5c_0$ or $c_0 = 2p_c$.

The cost of the breakthrough electrified technology is the difference in LRMC between electrified and conventional production with CCS installed,

$$c = r(I_{green} - I_{blue}) + \frac{p_E}{\gamma_E} - \frac{p_N}{\gamma_N}$$

We can now use numbers from Table 4.1 to find the fraction of countries that need to adapt the new technology, $z^*/N = b_0^2/2c_0c + 1 - b/c$, for different values of the CO_2 price. The result is shown in Figure 4.3 for both high and low energy prices. We see that there coalition size first decreases and then increases with τ. This is because the z^*/N in this model scales quadratically with b_0, since countries using CCS choose their adaptation level based on b_0 and c_0, but only linearly with b.

With high energy prices, we have already seen that green ammonia is so much more costly than blue ammonia that it is unlikely to become a preferred alternative. This insight is repeated here, where only for a limited range of carbon price is there a benefit of a coalition that includes nearly all countries.

Even in the case of low energy prices, at least half of all countries need to implement the new technology in order to reach the tipping point for full implementation when $c_0 = 2p_c$. This result is not all that surprising when we compare with the lower panel of Figure 4.1, where we see that the LRMC for electrified technology needs to be reduced substantially in order to become a

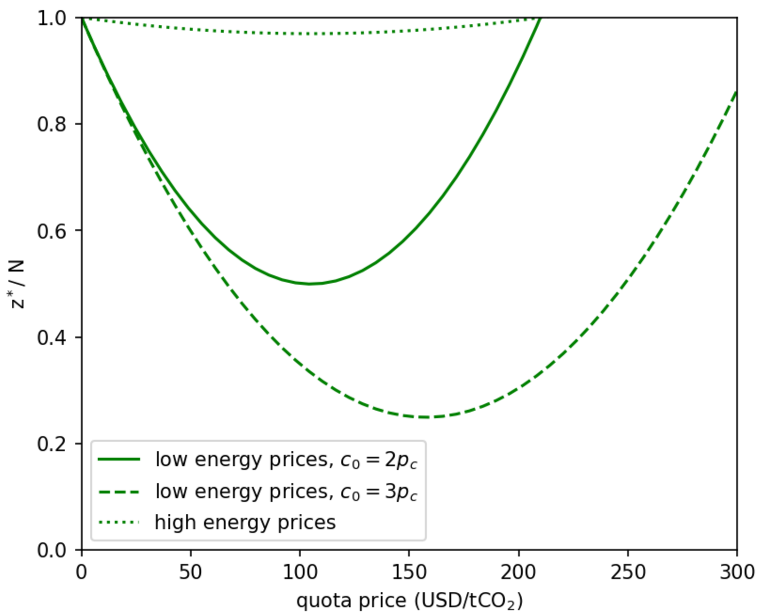

Figure 4.3: Tipping point coalition size z^* as a fraction of number of countries N in the model by Barrett (2006) using values from Table 4.1 under assumptions of low energy prices with $c_0 = 2p_c$ (solid line), low energy prices with $c_0 = 3p_c$ (dashed line) and high energy prices with $c_0 = 2p_c$ (dotted line).

viable alternative to CCS. Half of all countries is a significant and most likely costly coalition, and suggests that under these assumptions and simplifications, coordinated adaptation does not seem like a viable pathway. Our result is, however, highly sensitive to c_0; increasing it to $c_0 = 3p_c$ results in a tipping point coalition size of less than 1/3 of countries. This indicates that there may be at least some regions of the available parameter space where coordinated adaptation could be a promising option.

The model of Barrett (2006) does not include the costs for R&D, which were addressed by Hoel and de Zeeuw (2010). Indeed, if we compare the literature learning rates of electrolysers (around 18%) with those of solar PV (around 20%), electrolyser technology does seem to have significant potential for learning, possibly through both R&D and learning by doing. This means that, as shown by Hoel and de Zeeuw (2010), additional benefit may be gained from forming a coalition that also collaborates on R&D costs.

However, it is important to also note the insight from Brandt and Svendsen (2022) on the differences between countries. This is something that has also been pointed out in the industry roadmap of IRENA and AEA (2022), who discuss how fossil-based ammonia may turn out as the preferred option for regions with abundant natural gas resources, such as countries in North America, the Middle

East and Russia, whereas green ammonia may provide more benefits elsewhere. This means that partnerships or coalition formation is more likely to be successful for groups of similar countries. Coordinated policy development in the EU may be seen as an example of this.

In fact, IEA (2021) point to Europe, India and China as regions where the electricity cost is likely to be low compared with the cost of natural gas, more so than other regions in the world. Combined with increased energy efficiency due to learning, they project that this will lead to green ammonia being dominant among new installations in these regions in 2050 in the IEA sustainable development scenario.

4.3 New markets as an alternative to subsidies

We saw in Chapter 3 that new markets with a higher willingness to pay for green ammonia may induce learning on its own, without the need for subsidies. The pace of growth in nitrogen chemicals for industrial applications is already higher than for nitrogen fertilizers (Yara, 2018), pointing to the importance of alternative markets.

In some projections, it seems like this can indeed be the case. Some sectors, in particular maritime transport, need alternative energy carriers that are compatible with renewable energy. Ammonia is easier to transport than hydrogen, and the technology for shipping and pipeline transfer of ammonia is well established. This makes ammonia a promising candidate in potentially very large markets (MacFarlane et al., 2020). Bicer and Dincer (2018) have shown that even a partial replacement of current maritime fuels with ammonia can lead to a significant decrease in greenhouse gas emissions.

Investigating the potential role of ammonia in a renewable economy, IRENA and AEA (2022) have projected a quadrupling of ammonia demand in a scenario where global warming is limited to 1.5 °C, where more than half is for other purposes than agriculture. However, this massive upscaling of industrial ammonia use is not without challenges. Wolfram et al. (2022) have shown that even modest leakages of reactive nitrogen, which can never be completely avoided, from maritime shipping could lead to exceeding the planetary boundary for nitrogen pollution by 700%, an enormous increase from the already unacceptable 300% today. This means that technological development is still needed to create much cleaner systems if this transition is to take place responsibly.

As illustrated in Figure 2.1, the most significant change from conventional to electrified ammonia production is that hydrogen production takes place using electrolysis of water. Green hydrogen is also projected to be used in other industries, such as metals production (IRENA, 2022), and this additional demand can contribute to learning and cost reductions in electrolyser technology.

It alternative ammonia or hydrogen markets do not reach a significant size, it is also possible to use policy tools to induce demand for green ammonia in the agricultural sector. IEA (2021) argue that governments could apply market share regulations formulated as tradeable quotas, or a certificate system based on information about the embodied emissions of nitrogen fertilizer. However, as discussed by Vogl et al. (2021) in the context of steel production, this requires extensive and continuously updated information from all parts of the value chain, which is a large administrative effort. Certificate-based quantity regulations rest on the creation of a certificate market which also needs monitoring, reporting and verification, as well as sanctions for non-compliance. These costs need to be weighed against simply subsidizing green ammonia development in order to advance along the learning curve.

4.4 Model assumptions and limitations

There are several assumptions in our model that limit its application in the real world. For instance, we have disregarded water as an input, but the demand for water is about three times higher for electrolysis than for conventional production and in many regions of the world, fresh water is a scarce commodity. One option could be to use desalinated seawater, but this comes with a large additional energy cost and requires environmentally safe disposal of brackish water (IRENA and AEA, 2022). Water availability would be another source of heterogeneity in a more realistic model.

An alternative option to hydrogen from electrolysis is to replace natural gas with gas from biomass (IRENA and AEA, 2022), giving what is sometimes referred to as ”turquoise” ammonia. However, as with the use of biofuels, there are numerous concerns around the environmental and climate impact from the use of biomass. As nitrogen fertilizer is used as an alternative to extensive land use in agriculture, relying on input that requires large areas for production can be problematic for the large-scale transformation of the industry and we have therefore not included this option in the model.

We have also only chosen to consider large industrial plants, although more modular, local production is another possible pathway. According to IRENA and

AEA (2022), small-scale ammonia plants may benefit from cost reductions due to modular design and rapid manufacturing. Industrial production typically benefits from large units due to economies of scale, but on the other hand, mass production can lead to cost reductions. The cost reduction potential of modularization vs economies of scale has not been investigated here.

In practice, supply constraints due to finite production capacities may limit the pace of the transition. Odenweller et al. (2022) has shown that unless governments put in place large incentives that generate abnormally high growth in electrolyser installation in the coming decades, electrolyser capacity is going to limit the supply of green hydrogen. This is highly relevant for green ammonia, which would be competing for the same electrolysers.

If global demand in 2050 follows the projections in the net zero scenario by IRENA and AEA (2022), and all ammonia production takes place using electrolysis, then the electricity demand will correspond to around 90% of current global production of renewable electricity. This illustrates the challenge in meeting the energy demand for an electrifying economy. The production of renewable electricity is also forecast to increase, and in the net zero scenario by IEA (2022), 2050 global electricity generation from solar and wind alone are projected to be more than 5.5 times higher than the current renewable electricity production, so that the fraction required for ammonia production will be only 15%. This is still a large share compared with the 1% of global energy consumption by ammonia production today, but not unimaginably large.

4.5 Summary: Policy recommendations

In this chapter, we have seen that we can expect significant cost reductions through learning for green ammonia, making it a candidate for a breakthrough technology that may provide the best social outcome in the long run, but is challenging to transition to due to technological lock-in effects for grey and blue ammonia. In fact, just based on marginal costs, we would have expected the industry to be moving toward mitigation using CCS at the moment. The fact that they are not is probably related to the lack of CCS infrastructure, and also suggests that green ammonia can be a promising pathway.

The promise of sustained higher carbon prices in the future, possibly backed by policy instruments that can guarantee some minimum carbon price, may act as a powerful driver for future mitigation from this sector. However, as we have seen, carbon pricing alone is likely to reinforce the more established technology due to lock-in effects. Other mechanisms are needed to push the development of green ammonia. This could be direct subsidies, preferably in a partnership or coalition of countries with relatively similar characteristics in order to increase the likelihood that implementation will spread to other countries. Governments can also push development more indirectly through market mechanisms by placing regulations on adjacent sectors, such as maritime transport and metals production, in order to increase the demand and willingness to pay for green ammonia and hydrogen. These regulations may be relatively costly due to the need for monitoring and validation, and the benefit should be weighed against more direct subsidy schemes.

A transition to blue ammonia will always give increased costs for ammonia production relative to today, whereas a transition to green ammonia is likely to give increased costs in a transition period before learning effects potentially drive costs down beyond the current level. In the next chapter, we will discuss whether this increase may help reduce the environmental footprint of ammonia use in agriculture, as well as some other important implications of a transition to green ammonia for the wider economy.

Chapter 5

Wider implications

Ammonia production cannot be seen in isolation from the wider economy. As shown in Chapter 1, there are significant challenges associated with the downstream use of ammonia and nitrogen fertilizers. Ammonia production is also part of other important value chains, a role that may take new forms as the green transition progresses. I will address some of these wider implications in this chapter.

5.1 Market implications

A transition to green ammonia production will have significant effects on related markets. For example, fertilizer production is currently the major source of high-purity CO_2 for the world market. Out of the 300 $MtCO_2$ currently produced in the fertilizer industry, in 2015 around 120 $MtCO_2$ was used for urea production. Urea is not easily replaced for rice cultivation, the main crop in Asia, and the alternative ammonium nitrate faces safety concerns and regulatory restrictions. Another 28 $MtCO_2$ was supplied to industries such as food, beverages, metals production, water treatment and healthcare (IEA, 2019). This CO_2 is used in short-lived product and thus contributes to climate change after use. If the fertilizer industry is to become emissions-free, it means that the CO_2 for these industries will need to come from alternative, renewable sources. These may include CO_2 from biomass combustion or captured directly from the atmosphere (direct air capture, DAC). However, biomass resources are limited and DAC is very energy intensive. This means that alternative sources of CO_2, at least at scale, are bound to be more costly than today.

Ammonia production accounts for around 45% of global hydrogen consumption today (IRENA and AEA, 2022), but green hydrogen (from electrolysis and renewable electricity) may in itself become an essential part of the energy and industry systems in a decarbonized economy. This means that ammonia producers will face an alternative cost to the hydrogen they produce and could choose to sell hydrogen directly instead of producing ammonia when that is what is most profitable given the combination of ammonia and hydrogen market prices. This could provide a form of insurance against low ammonia prices if ammonia and hydrogen market prices are not completely correlated, and thus provide an economic advantage for green production.

It can also lead to a splitting up of the production. Just as ammonia producers can choose to buy electricity from the grid or produce their own, they could choose to buy green hydrogen from the market or buy their own. Given alternative costs the business case should to the first order be identical. The various options for owning links in the production chain or buying input from the market are illustrated in Figure 5.1. This flexibility can provide a range of novel business cases to be exploited, but these may encounter barriers when facing the established value chains of the existing economy.

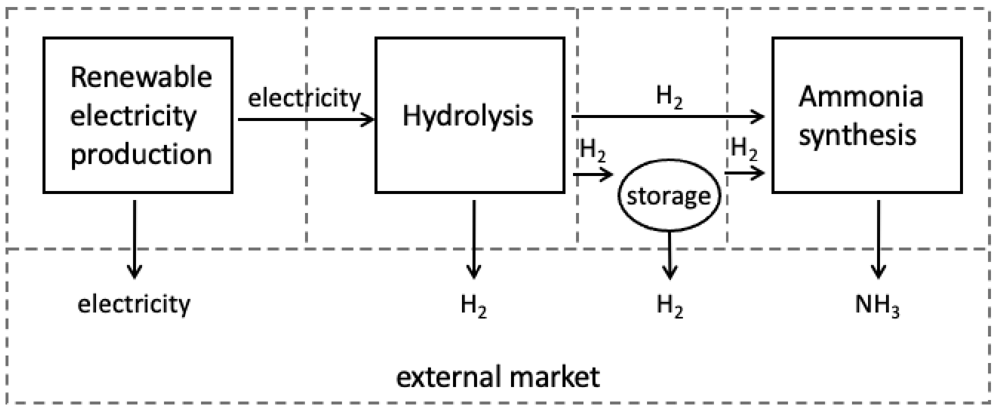

Figure 5.1: Simplified overview of possible market configurations for green ammonia production. The production value chain consists of renewable electricity production, hydrolysis for hydrogen production, hydrogen storage and ammonia synthesis. The ammonia producer can either own all of these components or choose to buy some resources on the market. They may also choose to sell output from any of these components directly to the market or to use them internally for ammonia production depending on relative market prices.

5.2 The environmental footprint of nitrogen in food production

While changes in production technology are required for cutting greenhouse gas emissions, more than half of the climate impact of fertilizer use have actually been estimated to arise in the use phase (Gao and Cabrera Serrenho, 2023). This calculation assigns the CO_2 emissions from urea use to the fertilizer production phase, and do not include the potentially positive climate impacts of higher agricultural yield per area.

Fertilizer use also leads to significant local pollution challenges that are challenging to deal without without disruptions to the agricultural economy and farmers' livelihoods. As an example, in 2022, the Dutch government proposed massive cuts in nitrogen emissions from livestock farms before 2030 in order to comply with EU water quality regulations. This has led to large-scale protests from farmers who feel forced to close their activities (Reuters, 2023) and illustrates the challenges of putting reactive nitrogen in wastes to use in the fertilization of crops instead of becoming an environmental problem.

Gao and Cabrera Serrenho (2023) estimate that it is possible to increase the global average nitrogen use efficiency globally from 42 % to 67 %. Measures to achieve this include proper irrigation, adopting improved plant breeding in order to develop and use crops that use nitrogen fertilizer more efficiently, and what the fertilizer industry refers to as the "4Rs": applying the right fertilizer type at the right time, right place and in the right amount. Farmers who seek to reduce their nitrogen emissions may adopt measures such as decision support systems based on databases, simulation models and soil and crop testing, combined with advice from agronomists and knowledge exchange among farmers (IEA, 2021).

Gu et al. (2023) found that better agricultural practices may reduce nitrogen losses from croplands by as much as 30-70 % while also increasing crop yield and nitrogen use efficiency. They suggest implementing policy instruments to promote the adoption of these practices and find that the total benefits to society, considering crop yield, human health, ecosystems and climate change, will be around 25 times higher than the costs of implementation. Along the same lines Mérel et al. (2014) have found, using a complex bioeconomic model, that a tax on nitrogen fertilizer could lead to a sizable reduction in nitrate leaching, achieved at a low social cost. This suggests that a higher fertilizer price may in itself be beneficial to the environmental effects of nitrogen fertilizer use.

However, it can be challenging to make farmers change their practices. Although fertilizer use can be a large part of a farmers' total expenses, nitrogen fertilizer is a still relatively inexpensive commodity. The decision to apply more fertilizer is often the least expensive and most efficient option for a farmer to increase yields (Vitousek et al., 1997).

A survey by Fertilizer Canada found that farmers were slow to adapt variable rate fertilization because of the high implementation costs (both in terms of money and time investment), some negative experiences of the actual benefit for crops, and also because the technology was constantly changing, making it difficult to compare and evaluate systems from different providers (Mckenzie, 2023).

Houser (2021) has shown that even when best management practices are documented and available, they are often implemented in ways that have adverse effects. In their study, they found that when farmers invested in equipment for more efficient nitrogen fertilizer application, the result was that farmers used more, not less, fertilizer in total, probably in order to earn more profits to pay off their installation costs. This highlights the complex dynamics that limit options for within-system, incremental technical approaches, and also that decisions made by individual farmers can be difficult to include properly in bioeconomic models.

A common characteristic of a farmers' economic choice of fertilizer application is that nitrogen fertilizer displays a flat payoff function over a broad range of application rates. Less fertilizer gives smaller yields but lower fertilizer cost, to the extent that the two effects nearly cancel. The result is that farmers have flexibility in choosing the nitrogen application rate without sacrificing profit, but also that technical measures to increase nitrogen use efficiency will commonly yield limited profits to farmers (Pannell and Pannell, 2017). This means that simply increasing fertilizer prices may not be sufficient to drive significant change.

If more targeted policy is needed, relevant policy instruments may include regulations such as site-specific limitations on nitrogen application or discharge to the environment, requirements to use catch crops, mandatory reporting of fertilizer use and performance standards (IEA, 2021). However, this comes at a large administrative cost. An alternative to placing regulations on farmers could be to regulate fertilizer producers, requiring a certain fraction of their product to be enhanced-efficiency fertilizers such as slow and controlled release and stabilized nitrogen fertilizers. This would have the advantage of regulating fewer units than each individual farmer (IEA, 2021).

5.3 Effects of higher fertilizer prices on farmers and food prices

Nitrogen fertilizer will probably remain central to food production in the coming decades. More unpredictable weather conditions due to climate change will make farming more challenging, and while nitrogen use efficiency can be improved, it is not possible to completely close the nutrient loop through, for instance, organic farming. An example of what not to do was given in Sri Lanka in 2021 when the government banned the use of chemical fertilizers due to high import costs. The combination of the ban and bad weather gave falling yields and contributed to an all-time high inflation, and the ban had to be revoked (PTI News Agency, 2022).

Following Russia's invasion of Ukraine along with other frictions in the natural gas market, fertilizer prices in both the US and Europe have been observed to react strongly to increasing natural gas prices. In Europe, 10 fertilizer plants were closed or had outputs curtailed in July 2022 as a reaction to soaring input prices (Elkin, 2022). The price of ammonia in Western Europe was 5 times higher in September 2022 than the year before (Rapoza, 2022).

The World Economic Forum has listed a possible food supply crisis as one of the top four threats facing the world in 2023. This is partly due to a lagged effect of fertilizer price spikes that may hit global food production in 2023. Fertilizer prices have come down after the major increase between 2020 and the end of 2022, but this is partly because farmers in developing nations have abstained from buying fertilizer, which may now result in significantly lower yields (Broom, 2023).

Brunelle et al. (2015) have forecast that fertilizer prices could rise between 1.8 and 3.6 % between 2005 and 2050, and that this could lead to a 6 to 14 % decrease in crop yields. Lower yields can be alleviated by more extensive use of agricultural land, depending on food prices. To what extent there is enough land available in practice is not clear. In the highest fertilizer price scenario of Brunelle et al. (2015), the result is a 5.3 % increase in food prices. Although this is a modest increase, the effects of higher food prices may be dramatic. It has been claimed that an increase in wheat prices helped spark the Arab spring in 2010 (Zhang, 2017), making rising food prices are a serious cause for concern.

There is, however, an ongoing debate about the direction of causality in previously observed correlations between food and fertilizer prices. On the one hand, increased fertilizer prices lead to increased costs for farmers, which could result in higher market prices for food; on the other hand, higher food prices create incentives for farmers to apply more fertilizer, hence increasing the demand and market price of fertilizers (Ott, 2012; Brunelle et al., 2015). In addition, the agricultural sector is characterized by a very high degree of public intervention, including subsidies on fertilizer and other inputs, production quotas and border regulations such as export subsidies, tariffs and quotas. This makes it challenging to analyse and anticipate effects of changes in both market prices and policy (Hertel, 2002).

Not all farmers have the same ability to adapt to higher prices. When fertilizer shortages posed a problem for smallholder farmers in India in 2021, they ended up producing less crops (Bandyopadhyay and Banerjee, 2021). This was due to sharp increases in natural gas prices, which caused the Indian government's fertilizer subsidy bill to increase by 50 % for 2021. As agriculture is the mainstay of nearly 70 % of the Indian population, a shortfall in supply or high increase in price of fertilizer was bound to have an adverse impact on the economy in rural India (Pandey, 2021).

Most of the worlds' farms are small and family operated. According to Lowder et al. (2016), while small farms (less than 2 ha in size) only operate about 12 % of the world's agricultural area, small farms control 30-40 % of total farmland in low and lower-middle-income countries in Asia and Sub-Saharan Africa. This could make these regions particularly vulnerable to increased fertilizer prices. Developing countries also often have low fertilizer application rates to begin with, especially in Sub-Saharan Africa. In these regions, boosting yields could lead to a direct increase in income per capita (Torero and Hernandez, 2018). Regions with too little use typically have limited access to fertilizers, thus restricting the use even though the economic benefit would have been significant (Gu et al., 2023).

5.4 Summary: The big picture

The challenges discussed in this chapter provide an example of how technological changes in what may seem to be a well bounded sector turn out to have effects that ripple through the wider economy. Ensuring that transitions motivated by climate and sustainability concerns in fact end up with positive and just effects requires attention to the economy as a whole.

Of particular concern in the nitrogen fertilizer economy is the potential effects of higher fertilizer prices. These seem unlikely to lead to a substantially reduced environmental footprint of nitrogen fertilizer use, but can potentially have severe consequences for the poorest farmers and regions or the world. These groups will also be affected by potentially higher urea prices resulting from a transition to green ammonia. Since urea is the most easily transported fertilizer product, it is relatively more difficult to substitute by other products in regions with poor infrastructure.

Chapter 6

Conclusions

This thesis was motivated by a technological challenge: How can the nitrogen fertilizer industry cut its impact on the climate and environment, while contributing to feeding a growing population as well as a possibly massive increase in demand from new markets? I chose to focus primarily on ammonia production, because it is the production step with the largest energy consumption and greenhouse gas emissions, and because economic mechanisms at play in fertilizer production are largely disconnected from those present in fertilizer use.

The transition to low-emission nitrogen fertilizer production faces a choice between two directions: Blue ammonia, which is conventional production with carbon capture and storage added, and green ammonia, where hydrogen is produced through electrolysis of water, a fundamentally different technology from what is currently used. Blue ammonia technology is mature and relatively easy to implement, but CCS will always be more costly than non-abated production and requires a sustained, high price on emissions in order to be continued. It also requires sufficient CCS infrastructure, something that is not currently in place. On the other hand, green ammonia is an immature technology that needs substantial investment to achieve cost reductions through learning, but may give additional benefits in the long run because of how it interacts with the energy sector when intermittent electricity production is taking a larger role.

In this context, it is helpful to view green ammonia as a breakthrough technology: a new technology that starts out as more costly than the current alternative, but that may be the alternative that gives the best societal outcome over time. Economic theory explored in this thesis has shown that simply using a Pigouvian tax to internalize the cost of emissions does not support the development of the breakthrough technology. Market mechanisms will tend to direct investments toward the established alternative in what is called technological lock-in. In our case, this would mean that a higher emission price would be most likely to incentivise blue over green ammonia.

Economic literature suggests that coordination between countries may be a viable option for developing the breakthrough technology. If learning effects can bring the costs down below the established alternative, then development and implementation by a coalition of countries can be sufficient to reach a tipping point where adaptation becomes the preferred option for all countries.

In a practical context, it is important to consider differences between countries. Countries differ in their natural allocation of energy resources, but also in their ability to invest in new technology and in their historical share of greenhouse gas emissions. The latter two factors are highly correlated. This may be a good argument for pursuing the option of technological development in a coalition that can push the breakthrough technology to the tipping point at a small gain for coalition members but substantial gain for outsiders, or even through partnerships or unilateral development.

Countries can develop the new technology through direct subsidies to green ammonia producers, market share regulations that require a given share of green ammonia in products, or by placing strong limits to emissions in sectors where green ammonia may already be a good alternative, such as maritime transport. We have seen that market share regulations may become very costly due to extensive administration, and that ammonia as a transport fuel may lead to a massive increase in nitrogen pollution from the current, unacceptably high level. Direct subsidies may therefore turn out as the best policy option.

Economic literature on endogenous technological development, or directed technological change, has been highly useful for the questions asked in this thesis. However, what is still lacking is an understanding of the role of infrastructure. Blue ammonia should be the best option under current conditions, but is met with very little investment. The best explanation for this is that carbon transport and storage infrastructure is non-existing in most parts of the world. This limits the opportunities for what is otherwise a mature, well understood technology. Infrastructure such as pipelines, roads, ports and electricity networks have a profound influence on the technological development of many industrial sectors, which means that more research into this aspect would be highly useful for understanding more of the mechanisms at play in the green transition of the wider economy.

Bibliography

Allen, J., Panquet, S., and Bastiani, A. (2021). Electrochemical ammonia: Power to ammonia ratio and balance of plant requirements for two different electrolysis approaches. *Frontiers in Chemical Engineering*, 3:765457.

Bandyopadhyay, K. and Banerjee, F. (2021). Potato prices set to soar in Bengal as fertilizer crunch, untimely rain hit production. *Times of India*, December 8, 2021.

Barrett, S. (2006). Climate treaties and "breakthrough" technologies. *American Economic Review*, 96(2):22–25.

Batool, M. and Wetzels, W. (2019). Decarbonisation options for the Dutch fertiliser industry. *PBL publication number: 3657*.

Bennaamane, S., Rialland, B., Khrouz, L., Fustier-Boutignon, M., Bucher, C., Clot, E., and Mézailles, N. (2022). Ammonia synthesis at room temperature and atmospheric pressure from N_2: a boron-radical approach. *Angewandte Chemie International Edition*, page e202209102.

Bicer, Y. and Dincer, I. (2018). Clean fuel options with hydrogen for sea transportation: A life cycle approach. *International Journal of Hydrogen Energy*, 43(2):1179–1193.

Billing, M. (2022). Batteries, urine and seaweed — how startups plan to solve the fertiliser crisis. *Sifted*, 21 March 2022.

Bonnet-Cantalloube, B., Espitalier-Noël, M., de Carvalho, P. F., Fonseca, J., and Pawelec, G. (2023). Clean ammonia in the future energy system. *Hydrogen Europe*, March 2023.

Brandt, U. S. and Svendsen, G. T. (2022). Is the annual UNFCCC COP the only game in town? Unilateral action for technology diffusion and climate partnerships. *Technological Forecasting and Social Change*, 183:121904.

Broom, D. (2023). This is how war in Europe is disrupting fertilizer supplies and threatening global food security. *weforum.org*, March 1, 2023.

Brunelle, T., Dumas, P., Souty, F., Dorin, B., and Nadaud, F. (2015). Evaluating the impact of rising fertilizer prices on crop yields. *Agricultural Economics*, 46(5):653–666.

Bundesnetzagentur (2023). Market data visuals. *SMART Strommarktdaten*, Accessed May 1, 2023.

Capdevila-Cortada, M. (2019). Electrifying the Haber–Bosch. *Nature Catalysis*, 2(12):1055–1055.

Detz, R. and Weeda, M. (2022). Projections of electrolyzer investment cost reduction through learning curve analysis. *TNO Innovatin for life*, TNO 2022 P10111.

Elkin, E. (2022). Nitrogen fertilizer prices are spiking as natural gas soars. *Bloomberg.com*, August 5, 2022.

European Commission (2023). Carbon border adjustment mechanism. *European Commission Taxation and Customs Union*.

Galloway, J. N. and Cowling, E. B. (2021). Reflections on 200 years of Nitrogen, 20 years later. *Ambio*, 50(4):745–749.

Gao, Y. and Cabrera Serrenho, A. (2023). Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. *Nature Food*, pages 1–9.

Gu, B., Zhang, X., Lam, S. K., Yu, Y., van Grinsven, H. J. M., Zhang, S., Wang, X., Bodirsky, B. L., Wang, S., Duan, J., Ren, C., Bouwman, L., de Vries, W., Xu, J., Sutton, M. A., and Chen, D. (2023). Cost-effective mitigation of nitrogen pollution from global croplands. *Nature*, 613(7942):77–84.

Hémous, D. and Olsen, M. (2021). Directed technical change in labor and environmental economics. *Annual Review of Economics*, 13(1):571–597.

Hertel, T. W. (2002). Applied general equilibrium analysis of agricultural and resource policies. In *Handbook of Agricultural Economics*, volume 2 of *Agriculture and its External Linkages*, pages 1373–1419. Elsevier.

Hoel, M. and de Zeeuw, A. (2010). Can a focus on breakthrough technologies improve the performance of international environmental agreements? *Environmental and Resource Economics*, 47(3):395–406.

Houser, M. (2021). Does adopting a nitrogen best management practice reduce nitrogen fertilizer rates? *Agriculture and Human Values*, 39:79–94.

IEA (2019). Putting CO_2 to use. *Technical report, International Energy Agency.*

IEA (2021). Ammonia Technology Roadmap: Towards more sustainable nitrogen fertiliser production. *Technical report, International Energy Agency.*

IEA (2022). U.S. ammonia prices rise in response to higher international natural gas prices. *U.S. Energy Information Administration. Today in Energy*, May 10, 2022.

IEA (2022). World Energy Outlook 2022. *International Energy Agency.*

IRENA (2022). World Energy Transitions Outlook 2022: 1.5 °C pathway. *Technical report, International Renewable Energy Agency.*

IRENA and AEA (2022). Innovation outlook: Renewable ammonia. *Technical report, International Renewable Energy Agency.*

Johnson, B. (2022). *Making ammonia. Fritz Haber, Walther Nernst, and the nature of scientific discovery.* Springer.

Kalkuhl, M., Edenhofer, O., and Lessmann, K. (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics*, 34(1):1–23.

Leonidas, P., Panagiotis, F., Zoi, V., Kostas, F., Hector, P., Richard, L., and Unnada, C. (2017). A technical case study on R&D and technology spillovers of clean energy technologies. Technical study on the macroeconomics of climate and energy policies. *European Commission*, December 2017.

Lowder, S. K., Skoet, J., and Raney, T. (2016). The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Development*, 87:16–29.

MacFarlane, D., Cherepanov, P. V., Choi, J., and et al. (2020). A roadmap to the ammonia economy. *Joule*, 4(6):1186–1205.

McDonald, A. and Schrattenholzer, L. (2002). Learning curves and technology assessment. *International Journal of Technology Management*, 23(7/8):718.

Mckenzie, R. (2023). Why are farmers slow to adopt variable-rate fertilizer technology? *Grainews*, February 6, 2023.

Mérel, P., Yi, F., Lee, J., and Six, J. (2014). A regional bio-economic model of nitrogen use in cropping. *American Journal of Agricultural Economics*, 96(1):67–91.

Odenweller, A., Ueckerdt, F., Nemet, G. F., Jensterle, M., and Luderer, G. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. *Nature Energy*, 7(9):854–865.

Omsted, G. (2022). Nitrogen forurenser mer enn antatt. *forskning.no*, 27 October 2022.

Ornes, S. (2021). Core Concept: Green ammonia could produce climate-friendly ways to store energy and fertilize farms. *Proceedings of the National Academy of Sciences*, 118(49):e2119584118.

Ott, H. (2012). Fertilizer markets and their interplay with commodity and food prices. *European Commission Publications Office*, Report EUR 25392 EN.

Pandey, V. (2021). To support agriculture, India must be self-reliant in production of urea. *Hindustan Times*, December 8, 2021.

Pankievicz, V. C. S., Irving, T. B., Maia, L. G. S., and Ané, J.-M. (2019). Are we there yet? The long walk towards the development of efficient symbiotic associations between nitrogen-fixing bacteria and non-leguminous crops. *BMC Biology*, 17(1):99.

Pannell, D. J. and Pannell, D. J. (2017). Economic perspectives on nitrogen in farming systems: managing trade-offs between production, risk and the environment. *Soil Research*, 55(6):473–478.

Pinkowski, N. H., McEnaney, J. M., Schwalbe, J. A., Rohr, B. A., Jacobson, T., Askan, S., and Hillyer, C. (2022). Solar on-farm fertilizer production for subsurface-irrigated tomatoes. *Upstream Ag Insights*, January 20, 2022:15.

PTI News Agency (2022). Sri Lanka to receive 65,000 MT of urea from India. *The Indian Express*, May 14, 2022.

Rapoza, K. (2022). Europe's other crisis: Fertilizer shortage for farming. *Forbes*, September 19.

Reuters (2023). Dutch farmers and climate activists protest over government policies. *Reuters*, March 11, 2023.

Ritchie, H., Roser, M., and Rosado, P. (2022). Energy. *Our World in Data*, https://ourworldindata.org/energy.

Rosa, L. and Gabrielli, P. (2023). Energy and food security implications of transitioning synthetic nitrogen fertilizers to net-zero emissions - IOPscience. *Environmental Research Letters*, 18.

Roussanaly, S., Berghout, N., Fout, T., Garcia, M., Gardarsdottir, S., Nazir, S. M., Ramirez, A., and Rubin, E. S. (2021). Towards improved cost evaluation of Carbon Capture and Storage from industry. *International Journal of Greenhouse Gas Control*, 106:103263.

Sabaghi, D. (2022). 'They destroyed us because we are Beirut.' Will there ever be justice for Lebanon's port blast? *DAWN*, November 18, 2022.

Schnitkey, G., Paulson, N., Zulauf, C., and Baltz, a. J. (2023). Fertilizer prices and company profits going into spring 2023. *farmdoc daily*, 13(36).

Smil, V. (1999). Nitrogen in crop production: An account of global flows. *Global Biogeochemical Cycles*, 13(2):647–662.

Statistisk sentralbyrå (2022). Produksjon og forbruk av energi, energibalanse og energiregnskap. *ssb.no*, 14 June 2022.

Torero, M. and Hernandez, M. (2018). Food security and sustainable development: Promoting competition in the fertilizer industry and efficiency in the fertilizer use to improve land productivity and sustainability. *www.t20argentina.org*.

USDA (2022). Impacts and repercussions of price increases on the global fertilizer market. International Agriculture Trade Report June 30, 2022, USDA Foreign Agricultural Service.

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H., and Tilman, D. G. (1997). Human alteration of the global nitrogen cycle: Sources and consequences. *Ecological Applications*, 7(3):737–750.

Vogl, V., Åhman, M., and Nilsson, L. J. (2021). The making of green steel in the EU: a policy evaluation for the early commercialization phase. *Climate Policy*, 21(1):78–92.

Vogl, V. L. (2023). *Socio-technical change and the emergent politics of steel decarbonisation*. PhD, Lund University, Lund, Sweden.

Wolfram, P., Kyle, P., Zhang, X., Gkantonas, S., and Smith, S. (2022). Using ammonia as a shipping fuel could disturb the nitrogen cycle. *Nature Energy*, October 5, 2022:1–3.

Woods, J., Williams, A., Hughes, J. K., Black, M., and Murphy, R. (2010). Energy and the food system. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554):2991–3006.

World Bank (2022). ETS & carbon taxes. *Carbon Pricing Dashboard*, Updated April 1, 2022.

Yara (2018). *Fertilizer Industry Handbook 2018*. Yara.

Zenith, F., Flote, M. N., Santos-Mugica, M., Duncan, C. S., Mariani, V., and Marcantonini, C. (2022). Value of green hydrogen when curtailed to provide grid balancing services. *International Journal of Hydrogen Energy*, 47(84):35541–35552.

Zhang, X. (2017). A plan for efficient use of nitrogen fertilizers. *Nature*, 543(7645):322–323.