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BRIEFING PAPER

MARKET COORDINATION OF DYNAMIC ENERGY FLOWS

THE FUTURE INTERPLAY OF SOLAR & WIND ELECTRICITY AND HYDROGEN INFRASTRUCTURES

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INTRODUCTION

Over the past twenty years, many discussions on the energy transition have had a particularly strong focus on only one part of the energy system – the electricity sector.

The energy transition became visible, first and foremost, through the changes in the electricity sector, as an expanding number of wind farms and solar fields began to dot the European landscape. The resolve to increase the share of renewables in the mix in recent years resulted in many solar and wind-power facilities being connected to the electricity grid, greatly changing the nature of the electricity system in many parts of Europe. Market liberalisation of the electricity sector, privatisations, and ground-breaking 'feed-in' schemes, such as Germany's EEG, enabled a wide range of actors to participate in this change.

In 2008, the European Union (EU) established the European energy and climate framework for the years leading up to 2020. Policy and legislative efforts of the European Commission (EC) and national governments were geared towards achieving the so-called 20-20-20 policy goals. Energy efficiency policies were aimed at all sectors of the economy. The pan-European CO_2-emission trading scheme (ETS) targeted the power sector and industrial energy use. Strong renewable energy policies aimed to increase the share of renewables –in practice, mainly solar and wind– thus greatly impacting the power sector.

Although increased use of bioenergy was also on the agenda, this proved to be more controversial due to concerns over the sustainability of biofuels. Additionally, due to the economic slowdown in the wake of the great financial crisis of 2008 and the subsequent euro-crisis in 2011, and because of a surplus of unused emission allowances in the trading scheme, the ETS did not include the CO_2 cost signal that many advocates of the energy transition had wished for.

The somewhat troublesome history of the ETS and the controversy over the sustainability of biofuels stood in stark contrast to the spectacular progress in wind and solar technology, which led to impressive cost declines, rising shares of solar and wind energy, and growing ambitions to expand capacity.

By 2020, it was clear that the prime public policy challenge to achieve by 2030 was not so much the reduction in costs of electricity production from solar and wind but, rather, how to integrate the electricity that is now affordable, but not available 24/7/365 into the energy system. The challenge is to turn low-cost electricity into a clean, affordable, and secure energy service throughout the year for a great variety of energy users. These users need energy for personal mobility or the transportation of goods, high-temperature heat for industrial processes, essential feedstocks to produce materials, or low-temperature heat for comfort in all types of buildings, including homes, offices, schools, and stores.

CIEP has, therefore, called for an *integrated energy system transition* that recognises the need to consider energy use and feedstock requirements in all sectors of the economy, as well as the delicate interrelationships between those sectors, often facilitated by complex energy infrastructures that gradually evolved over a period of many decades in the 20th century.[1] More recently, CIEP contributed to the discourse by exploring how the energy system can benefit from a hydrogen backbone and how a hydrogen market can be developed.[2]

This paper demonstrates a vision of how energy flows in the future electricity-hydrogen backbone can eloquently interact, in the spirit of the EU internal energy market. We use two future situations to illustrate this: a calm sunny day in spring, and a windy grey November day. Both cases demonstrate the interactions between electricity and hydrogen infrastructures in the future energy system.

It must be stressed that the road to the new market structure envisioned in these two examples is still long, and EU and member state policies and regulations must acknowledge that an immature hydrogen market, beyond today's hydrogen market in the petrochemical industry, cannot be approached in the same way as the fully developed hydrogen market sketched in this vision. This conviction was at the heart of the aforementioned CIEP hydrogen paper.

1 See the speaking notes of CIEP director Coby van der Linde at the CIEP/NOGEPA Gas Day 2017, available at https://www.clingendaelenergy.com/publications/publication/speaking-notes-integrated-energy-system-transition

2 CIEP (2019), Van Onzichtbare naar meer zichtbare hand? Waterstof en Elektriciteit: naar een nieuwe ruggengraat van het energiesysteem; and the translation into English, CIEP (2019), From an Invisible to a more Visible Hand? Hydrogen and Electricity: Towards a New Energy System Backbone.

A BEAUTIFUL DAY IN MAY

On a beautiful day in May, abundant sunshine in Europe's interior depresses prices for German power traded on the European Energy Exchange (EEX). This is not the case for Dutch power traded on the Amsterdam Power Exchange (APX) or Danish power traded on Nord Pool, due to increased cloud coverage and low wind speed conditions in the North Sea region.

Existing electricity market coupling and the resulting electricity imports and exports (exchanges of electricity between the various price zones) will have a converging effect on prices for Dutch, Danish, and German power, but only to an extent that is facilitated by the cross-border electricity transmission capacities. On this day in May, prices start to diverge because cross-border electricity transmission capacity is fully used. Electricity price signals are put to work, with substantially higher prices for Dutch and Danish electricity than for German electricity (where central European solar is on offer). Now, the hydrogen backbone can start contributing to balancing North-western -European energy markets.

Before turning to the contribution of hydrogen storage facilities, the role of intelligent but straightforward market-based 'demand-side responses' must be highlighted. Specifically, on this day in May, hybrid (electric/hydrogen) boilers in German industries are signalled to consume electricity and not hydrogen since German power is abundantly produced and cheaply available on the EEX for large consumers. This is not the case for Dutch and Danish electricity, so industrial energy consumers in the Netherlands and Denmark prefer to tap into the hydrogen backbone rather than consuming expensive Dutch and Danish electricity. Their hybrid boilers will be fuelled by hydrogen. This has a moderating effect on price divergence in the electricity markets, levelling the playing field for North-western European industries.

On this day in May, the switch from the use of electricity to hydrogen by a wide range of energy consumers is not sufficient to balance the electricity market. Unfortunately, in this example batteries connected to the grid in the region cannot supply electricity, as they had already been depleted the night before. The high electricity prices do, however, signal postponed recharging, avoiding some of the usual electricity demand. Power plants start to tap into the hydrogen backbone in

Denmark and The Netherlands in order to produce electricity. The plants make it possible for economic actors to arbitrage between the regional hydrogen and regional electricity markets. The price signals in Europe's liberalised energy markets are further put to work here.

The required clean electricity is produced, making up for limited solar and wind electricity production, so that sufficient Dutch and Danish power is offered to buyers on the APX and Nord Pool. If hydrogen prices go up substantially because of rising hydrogen demand, the response is to release fuel from the storage facilities – fuel that had been stored by smart traders who purchased the hydrogen when it was cheaply available in the previous days and weeks. Some large energy consumers in the Netherlands and Denmark prebooked this service in order to hedge against the risk of low availability of solar and wind in their regions. Utilities also took a position in hydrogen storages, in order to offer reliable and affordable supply contracts to a great range of electricity consumers in the two countries – customers who did not want to be exposed to any energy market price risk for fixed periods of time. This service was, fortunately, available to Dutch and Danish homeowners who have otherwise run into trouble on this day, now that their private solar rooftop systems were not producing sufficient electricity, and their home batteries had been depleted, just as the commercially-owned grid-connected batteries had been.

A GREY DAY IN NOVEMBER

On a November day characterised by iconic grey skies over northern Europe and by strong Atlantic winds in its coastal regions, the tables have dramatically turned. Abundant offshore wind electricity production on the Danish and Dutch continental shelf depresses power prices immensely in these relatively small electricity markets with enormous installed offshore wind capacities. Electricity flows from the two countries into Germany, but the abundance of clean electricity congests the electricity interconnections, leading prices to diverge once again. This time, however, Danish and Dutch power is traded at the APX and Nord Pool for low prices, while German power is traded at substantially higher price levels on the EEX.

Hybrid boilers are signalled to switch to electricity in the Netherlands and Denmark since it is readily available at low cost to large consumers through the APX and Nord Pool. Demand for hydrogen from energy consumers in the Netherlands and Denmark is, therefore, relatively low, which is good news for energy consumers in other European countries.

It is not only low consumption of hydrogen in the Netherlands and Denmark that contributes to balanced energy markets in North-western Europe on this day in November. Additional hydrogen is actually injected in the backbone since electrolysers in the Netherlands and Denmark have access to cheap Dutch and Danish electricity traded at the electricity exchanges. Earlier investments in electrolyser capacity in the small North Sea nations proved valuable for energy consumers in the other countries in the region. Hydrogen is available at reasonable prices to industrial consumers in the Ruhr Area, southern Germany, and elsewhere, while power plants fuelled by hydrogen in the Southern states of Germany ensure that power prices in that part of the country stay at levels affordable to local businesses and private consumers.

On this day in November, some traders in the market anticipate higher hydrogen prices in the following week, given the weather forecasts that project calmer North Sea winds coming in, while daylight hours are shortening and the sun is not strong in the region so late in the season. Thus, these traders start to fill storage facilities with hydrogen, so that they can resell it in the following weeks for better prices. Winter is coming, and with it, increased energy demand for heating buildings.

Utilities integrate this approach in their electricity supply offers to electricity consumers, having prebooked access to storage capacities, as they did with natural gas storage in the past. The knowledge of constant variability in weather patterns had greatly underpinned the investment case for developing hydrogen storage facilities throughout the region, in preparation for the days when grid-connected batteries are depleted, and hydrogen demand rises.

Cross-border electricity transmission lines between the small North Sea nations and Germany are utilised at maximum capacity in this example. But the threat of congestion looms larger on this day in November. The onshore electricity transmission systems were never designed for the immense flows of electricity from the North Sea continental shelf to inland energy consumers. Congestion in national power transmission lines would have created a major headache for electricity TSOs had it not been for timely coordination with gas TSOs, resulting in strategically located electrolysers in North Sea ports and industrial areas. The invisible hand of the Dutch electricity TSO does not have to be used on this day in November, saving greatly on the redispatching costs that plagued German TSOs in the 2010s so much.[3] All TSOs had learned from this experience. On this day in November, congestion in the electricity grids was limited, thanks to the coordinated development of electricity grids and pipelines in the region in the preceding years – thus facilitating energy trade on energy exchanges throughout the region, in the spirit of the EU's internal energy market.

3 In the 2010s, redispatching costs rose substantially when the German TSOs were unable to transport sufficient electricity from Germany's North to its South, while the German electricity market was organised in one single bidding zone. The latter implies that 'German power' can be traded on the EEX as if there are no limitations to electricity transport within the country's borders, ignoring the limited physical North-South transmission capacities. In the 2010s, when wind producers in the North sold large volumes of 'German power' on the market, while consumers in the south bought 'German power' on that market, the TSOs had to step in frequently. Wind turbines in the North were forced to stop production, and TSOs bought electricity from higher-cost producers in the South, which could, in fact, be transported through the grids to consumers in that region.

THE COORDINATING POWERS OF THE EU INTERNAL ENERGY MARKET

The creation of the EU internal energy market paved the way for the efficient coordination of increasingly dynamic energy flows in European electricity and gas grids. The daily operations of production, storage, transport, and consumption in these energy sectors are steered mainly by price signals in liberalised energy markets. These range from spot markets for gas and electricity, to markets for derivatives including futures, to intraday and balancing markets. Having said that, it is important to keep in mind that the idea of liberalised 'markets' coordinating investments did not materialise as envisioned in the 1990s and 2000s due to continuous government intervention, such as the various member state schemes dedicated to promoting investments in selected renewable electricity technologies.

TODAY'S MARKET COORDINATION IN A NUTSHELL

Electricity wholesale prices greatly reflect relative shortages or surpluses of electrical energy in the different bidding zones, or price-zones, across the EU. Prices across zones converge and may be at exactly the same level, as long as the electricity interconnections between the zones allow for it – that is, if they are not fully utilised. Once full capacity is reached, no more electricity can be exchanged between the zones, and prices in the markets are more likely to diverge. By and large, the bidding zones overlap with former national electricity markets, although some countries have split their national markets into multiple zones, recognising limits in electricity transmission capacities between the various parts of the country.[4]

In price zones short of electricity supplies, this leads to a price signal to electricity producers to produce, including the more marginal suppliers. In response to rising prices, some consumers are incentivised to reduce their demand since electricity has become more costly to consume.[5] While 'demand-side responses' are often discussed in relation to large and small consumers connected through 'smart grids' as a future mechanism, the wholesale electricity markets that emerged from Europe's energy

4 A notable exception is the joint German-Austrian bidding zone.

5 Historically, electricity demand has been fairly inelastic; supply-side responses have played the largest role in balancing the market.

market liberalisation have, in fact, allowed for such responses by large consumers for many years already.[6]

In the North-western European markets of the 2010s, from time to time, congestion in the interconnections between the different zones or markets led to price divergence between the different price-zones. In the Netherlands, gas-fired power plants were signalled in this way to produce more, so that they could supply consumers in this zone with sufficient electricity. When natural gas prices became more competitive compared to other fuels due to wider gas-to-gas competition on pricing hubs, such as the Title Transfer Facility (TTF) in the Netherlands, and global supply increased compared to demand, gas-fuelled electricity generation benefitted. By 2020, low global and European gas prices and, consequently, low TTF prices enabled the Dutch power market to balance smoothly at a low cost, at price levels similar to those in the German market, which is traditionally balanced largely through supplies from coal-fired power plants. The lack of a serious cost for carbon emissions through the EU ETS in the 2010s allowed coal-fired plants to keep that position for many years, but that cost rose significantly between 2018 and 2020 due to rising prices for CO_2 emission allowances in the ETS.

TOMORROW'S MARKET COORDINATION

The role of current natural gas markets in the region is similar to the role that hydrogen markets will play in North-western Europe once the hydrogen market, hydrogen transport and hydrogen storage infrastructures are sufficiently developed (Figure 1).[7]

Future energy markets can benefit greatly from a regional hydrogen market, thanks to a range of possible technologies linked to a future hydrogen backbone and the electricity grids. Electrolysers can act as the gateway between the grids, transforming electricity into hydrogen and bridging the markets. And power plants fuelled by hydrogen act in a similar but reverse way, converting hydrogen fuel into electricity.

6 Many small and medium-sized electricity consumers have 'all-in' retail contracts with electricity retailers (historically, integrated utilities, but nowadays also new entrants that are not fully integrated with production and trading companies.) Such consumers generally did not have 'dynamic' prices in their contracts to incentivise them to adapt consumption to supplies from one minute to the next. Larger (industrial) energy consumers often have more tailored and advanced contracts with electricity suppliers or even buy their electricity from wholesale markets themselves. Consequently, such consumers have had incentives to adapt their consumption patterns to electricity wholesale prices.

7 Largely, this is not a matter of building entirely new infrastructures, but of repurposing existing natural gas infrastructures.

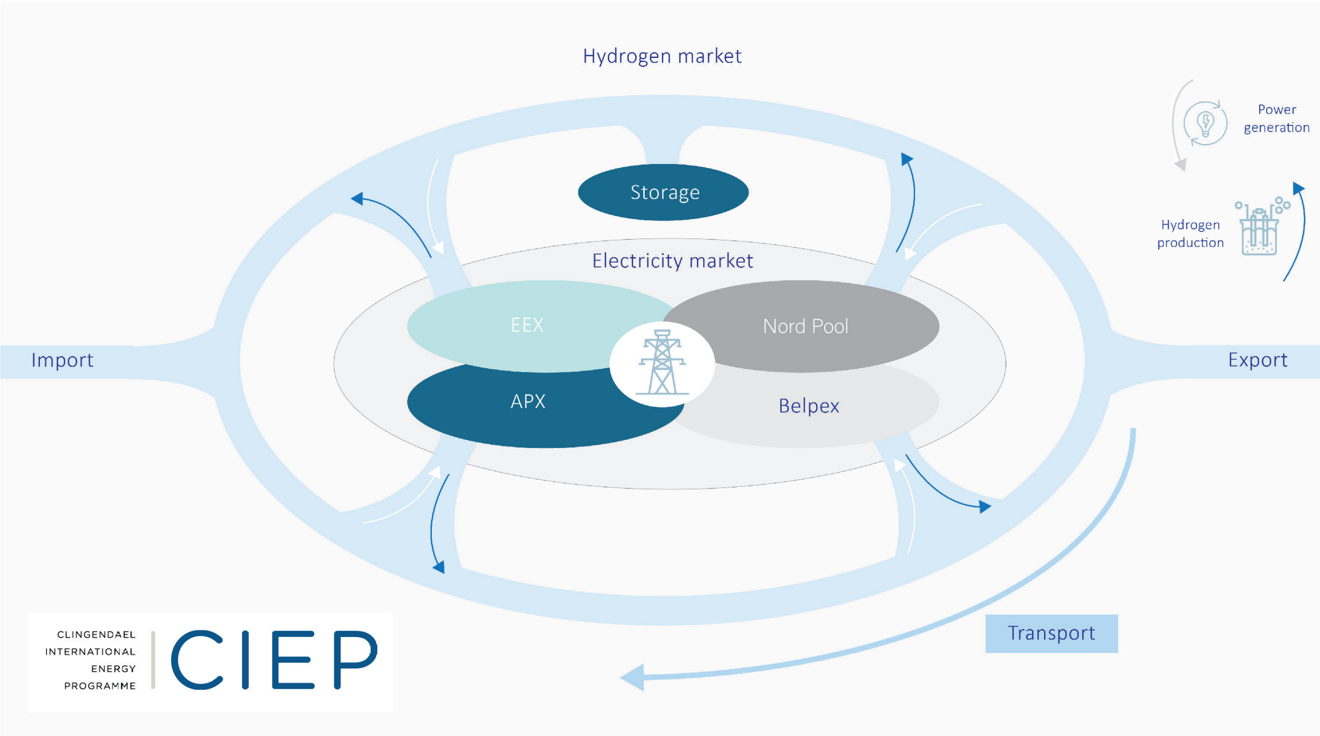

FIGURE 1. MARKET COORDINATION OF DYNAMIC ENERGY FLOWS[8]

Storage in the form of batteries connected to the electricity grid can smoothen variable electricity flows by 'buffering' electricity in the grid for shorter (seconds, minutes) or longer (hours, days) periods of times, often at local levels in distribution networks, but sometimes also in transmission grids. Intraday and balancing markets can largely coordinate the utilisation of these technologies. Batteries in electric vehicles connected to the grid can perform similar roles, just like home batteries that some consumers may choose –often without knowing exactly how the batteries are used– since this can be managed by specialised electricity businesses that offer appealing value propositions to consumers in order to access their storage capacity. Coordination of electricity flows can continue to be done in real time and has a short-term focus, greatly facilitated by continuing improvements in information and communication technology.

Moreover, storage in the hydrogen backbone, in the form of salt caverns, depleted gas fields and line-packing, but also (after conversions) in tanks for liquids and gases or even as bulk solids, can smoothen things out over substantially longer periods of time. Withdrawal of energy from such forms of storage –characterised by massive work volumes that the aforementioned batteries cannot handle– can supply

8 Design graphic: David Milne

consumers with additional energy for days and weeks, and perhaps even months.[9] Some of the stored energy can be directly consumed by end users, while a portion of it is converted into electricity and supplied to the electricity market.

If more stored energy is needed than the regional hydrogen backbone has readily available, hydrogen imports from more-distant areas via pipelines or ships can provide the required commodity, just as the thousands of kilometres of gas pipelines and ships carrying liquified natural gas (LNG) facilitate today.

The installed wind and solar capacities are not evenly distributed across Europe. Moreover, wind and solar energy availability varies from hour to hour, from day to day, from week to week, and even from season to season, so the installed capacities are utilised in a highly dynamic manner. Crucially, while variability can be managed, as weather forecasts accurately tell actors in electricity markets many days in advance when and where solar and wind electricity will be available, production simply cannot occur when the resource is not there. In other words, the variable electricity flows from solar and wind capacities can be forecast but not planned. This is why the other technologies mentioned here are so essential for the markets to function and to match demand and supply throughout the year.

One relevant consideration relates to differences in relative energy transport costs. If transport costs per unit of energy are relatively low, then it is easier to organise a market that spans a larger geography.[10] If the assumption is that the transport cost per unit of energy is lower for gasses than for electricity –a case that is often made, especially with regard to the capacities of already existing legacy gas infrastructure that can be converted for hydrogen use– then a hydrogen market in Northwest Europe (and beyond) can more easily have uniform pricing (or strongly correlated prices) across the region. If electricity bidding zones were to be expanded in a similar fashion, this could prove to be more problematic. Although Transmission System Operators (TSOs) can facilitate transport, they carry the costs of making expanded

9 Natural gas infrastructure has historically played an important role in dealing with the seasonality of energy demand in the region and in the Netherlands in particular. In the future, periods of low availability of both wind energy and solar energy can coincide with a cold spell that leads to high demand for heating for prolonged periods of time. Consider Figure 2 in Chapter 2 of the CIEP publication 'The Transition of the Residential Heating System,' showing the seasonal pattern in historical gas demand, which must be overcome.

10 In fact, historically, this is one major reason that markets for crude oil became more easily integrated globally than markets for natural gas. Transport costs for crude oil per unit of energy are relatively low. Only when the liquified natural gas supply case became more competitive did the gas market start to become more global.

market areas work. Such costs are ultimately borne by energy consumers, especially when substantial grid reinforcements and expansions are required.[11]

Once realised, a future hydrogen backbone will supplement, if not underpin, electricity infrastructure. In Europe's liberalised energy markets, price signals largely coordinate the behaviour of rational economic actors, elegantly shaping an interplay between the hydrogen backbone and electricity grids that would be difficult for central planners to realise. Once again, this is how the European liberalised energy markets function and how the coordination of (short-term) daily operations takes place. For (long-term) investments in the associated infrastructures, such signals may be more muted due to the large role of government policies in the sector, a distinction that is crucial to stress and to not be forgotten when discussing Europe's liberalised energy markets.

11 In the short run, electricity TSOs may intervene in the market through 'redispatching' electricity production, basically overturning the earlier production plans established through the market. In the long run, they will be forced to make expansions to electricity grids, even if other solutions are a better deal for society but do not fall within their mandate; these range from batteries to demand-side responses to transporting energies through other infrastructures, such as pipelines.

CONCLUDING WORDS

This paper demonstrates how energy flows in a future electricity-hydrogen backbone could seamlessly interact, in the spirit of the EU internal energy market. Through two examples –one of a future day in May and one of a future day in November– the paper illustrates this point.

The examples seek to illustrate how the internal energy market can be perfected further, through an intelligent integration of future hydrogen and electricity infrastructures. In this integrated system, electrolysers act as gateways between the hydrogen and electricity backbones, transforming electricity into hydrogen, while (converted) power plants act in a similar but reverse way, transforming hydrogen fuel into electricity. Arbitrage opportunities between the hydrogen and electricity markets incentivise commercial actors to invest in hybrid technologies and conversion capacities. The mere existence of the markets, the trade that is possible in such markets, the price information that is available to a great range of actors, and –crucially– the physical hardware underpinning these markets can all contribute greatly to a clean, reliable, and affordable energy service to consumers in EU member states.

It must be highlighted that the road to the market structure presented in the scenarios is still long. The EU's and member states' policies and regulations must acknowledge that an immature hydrogen market, beyond today's hydrogen market in the petrochemical industry, cannot be treated in the same way as the fully developed hydrogen market imagined in this paper. This understanding was at the heart of the CIEP paper 'From an Invisible to a more Visible Hand? Hydrogen and Electricity: Towards a New Energy System Backbone.'[12]

On a final note, it must also be stressed that the two examples were structured around perfect weather conditions for demonstrating how electricity and hydrogen infrastructures could interact. What they do not show, however, is that more-challenging weather conditions happen regularly. One area of particular concern stems from periods of low wind conditions in Northern Europe's winter season. In

12 CIEP (2019), Van Onzichtbare naar meer zichtbare hand? Waterstof en Elektriciteit: naar een nieuwe ruggengraat van het energiesysteem; and the translation into English, CIEP (2019), From an Invisible to a more Visible Hand? Hydrogen and Electricity: Towards a New Energy System Backbone.

this season, low availability of solar energy is also guaranteed in the region. Then, especially in cold conditions, when energy demand for heating is high, supplemental energy supplies are essential for the regional energy system to function, for many years to come. Natural gas has historically played an important, if not central, role in overcoming energy demand in the winter period, and this will surely continue to be so in the short to medium term. Electrification by itself will not change this, as the electricity system is dependent on gas-fired power plants for the times when solar and wind plants do not deliver. Given the complicated future for nuclear and coal-fired power plants in the region, as well as the problematic public support for the expanded use of biofuels, the dependence on gas infrastructure remains. It is, therefore, the absolute conviction here that investments in the decarbonisation of the gas supply chain through carbon capture and storage infrastructure (supporting 'blue' hydrogen) can contribute to the reduction of greenhouse gas emissions during the transition towards a system that is largely build on electricity and 'green' hydrogen from solar and wind. Without accepting a role for carbon capture and storage infrastructure (and 'blue' hydrogen) in the region, the unabated use of natural gas is the likely backstop outcome whenever electricity and hydrogen from solar and wind have run out.

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