Touching Hydrogen Future. Tour around the globe

Jules Verne Style' stories on the role of Hydrogen in 2030s and 2040s.

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FULL AUTHORS' LIST INSIDE

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Contents

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Foreword

Author: Andris Piebalgs

Following the ebb and flow of hydrogen hypes in recent history, there is a growing consensus that the current groundswell of momentum will see renewable and low-carbon hydrogen carve out a critical role in the transformation to a carbon-neutral economy. This has is being borne out by the breadth and depth of hydrogen strategies and roadmaps that have emerged around the world in recent years, including those to be explored in this book.

The goals for a new clean hydrogen sector extend well beyond decarbonisation. This sector raises the opportunity to develop new supply chains, jobs and innovation, and to fundamentally redraw the global economics and geopolitics that shape the wider energy sector. For countries without fossil fuel resources, hydrogen could reduce their dependence on imports or even turn them into energy exporters. Fossil fuel rich countries may be able to leverage hydrogen as part of a just transition to a more sustainable future. Hydrogen could help reduce the volatility of global energy markets and alleviate energy poverty by democratising the means of production, anchored in cheap and abundant renewable electricity.

The International Renewable Energy Agency (IRENA) estimates hydrogen could cover up to 12 percent of global energy use by 2050, with strong demand development in the mid-2030s.[1] There are immense opportunities for the global community in clean hydrogen development, with production potential far exceeding estimated global demand.

Nevertheless, we must take pause and acknowledge the difference between what we can envisage and what we know and see. I can personally attest to this difference. In 2004, during my mandate in office, I stood in front of the European Parliament during the Energy Commissioner's hearings and confirmed the importance of advancing hydrogen as a clean energy carrier. Subsequently, hydrogen was prioritised in the European Strategic Energy Technology Plan (SET-Plan) to accelerate the development and deployment of cost-effective low carbon technologies in Europe, leading to the creation of the European Hydrogen and Fuel Cell Technology Platform. Yet almost 20 years later clean hydrogen production remains incredibly scarce. This needs to change — and it will. Many countries and companies around the globe are taking the initiative with new pioneering projects emerging all the time.

'Touching Hydrogen Future - tour across the globe', drafted and edited by Erik Rakhou and Rosa Puentes, together with more than 20 authors from every corner of the world, provides a well-crafted and informative picture of the sector's trajectory. Starting with the Netherlands and moving westwards, the reader is taken on a true tour of the 'hydrogen world', discovering the ambitions and key projects of different countries. It is done in a way that makes this journey accessible and enjoyable for energy professionals as well as anyone curious and looking to learn more.

The reader learns from local experts about the moves of policymakers and industry, as well as significant technological breakthroughs that will help deliver real action on hydrogen. The book allows us to understand the gravity and complexity of the task in hand, with each country bringing its own opportunities, constraints, and positions. Although the transition will be far from simple, requiring unprecedented efforts from governments, industry, and citizens, the tour shows the reader the truly exciting opportunities hydrogen offers for all nations. It is not just a replacement of one type of fuel with another, it is a paradigm shift in the way we look at energy systems, with benefits across a number of the United Nations' Sustainable Development Goals for 2030.

Acknowledgment

Molecules flow. Electrons bump. Life flows and bumps in much the same way. So did a series of events that lead us to write this book in collaboration with so many great people. My co-author Rosa and I are blessed with many friends, great families, and loving parents and are not ashamed to ask for help and to collaborate. We approached many of you, and apologies if we do not list you all in this acknowledgment.

The idea for this book, in hindsight, may have started in 2017 in London, during an event on the role of natural gas. I was with over 30 energy executives from around Europe for a discussion on decarbonising gas markets under the Chatham House Rule. One idea was address the question 'What about hydrogen?'

Then in Amsterdam in 2019, a banking friend gave a wonderful presentation titled Hydrogen or Hype, which concluded that it could be both. The same event looked the potential for deep-sea cross-continent interconnections and concluded, why not? It was clear that the world was longing for urgent solutions to the energy transition.

Shortly after the event, a contact working on deep-sea interconnections asked me if I knew anyone in the hydrogen industry in Germany. I did not – but it made me think again about the interconnections between hydrogen and electrification (another vogue of these times).

Nowadays, the impacts of the Covid-19 on society have shown

us that virtual collaboration and trust can work. Through the pandemic, I also observed a growing interest from clients and contacts in the hydrogen economy. The work in this space took off, and I learned by being part of it.

Then, on a dark but cosy afternoon in Groningen at a conference titled Wind Meets Gas in 2021, I spoke to the CEO of an energy utility. Against the background of an ancient church, she shared her fear that we won't find enough people to build the energy transition. We need to teach new talent soon.

As Covid persisted through October 2021, the idea came – why not write a book that educates and enthuses on the lesser-known part of the energy transition: the future of hydrogen. With the potential to quickly become a decarbonised substitute for oil, coal and gas, the hydrogen economy can be the beacon that can draw new people to the energy industry.

Then, magically – as sometimes good ideas need a little coincidence - I received a message from Rosa 27 October 2021. 'I love the idea and could help.' Well, we wrote the first article as test on LinkedIn and drew happy as well as angry responses. But negative attention is still attention, and we knew then that this was the right time.

Once we published the article, it was natural to find great, smart and energy-savvy collaborators to write specific chapters on countries considering a hydrogen economy. Their names, in alphabetical order, are: **Amira Korayem, Andrey Bondar, Anne-Sophie Corbeau, Argun Karacay, Ben Egbe, Carlo Degli, Catherine Banet, Dan Shulman, Daniel Cortez Cazas, David Sheipourri, Eric Ehrhardt, Felipe San Gil, Gerhard Human, Giuseppe Grimaldi, Irina Gaida, Jens Mosselmans, Joachim von Scheele, John Baldwin, Katerina Sardi, Konstantin Lenz, Kwang Tae Lee, Lavinia Tanase, Luiz Piauhylino Filho, Maria**

Eduarda Piauhylino, Miguel Ballesteros, Nesma Aboshanab, Oghosa Erhahon, Pablo Ferragut, Petar Sofev, Robin Macpherson, Robin Mills, Rocío Salas, Sigrid Colnerud, Thomas Querrioux, Tom Baldwin, Dr. Venera N. Anderson.

We want to thank those who sometimes, after weeks of thinking, let me know that they disapproved of the rationale for a hydrogen economy rise in their country, and hence could not write about it. One country we do not cover is South Korea, a promising market with many manufacturer-savvy players and ambitions to lead the global rise. But it is heavily state-funded and driving to its own energy security. Perhaps, in the 2nd edition, we will find a writer to delve into its potential.

Thank you to our first reader, **Andris Piebalgs**, who wrote an insightful foreword.

Thank you to the **Luther Pendragon** team for supporting the media attention around this book's first release.

Finally, thank you in advance to you, the readers, for any of your feedback to this book. Please let us know via LinkedIn, both positives and negatives.

Hydrogen is currently a seen as a popular part of the energy transition toolbox. This book will show how some of it could possibly becoming a reality, while other parts could be delayed or fail.

One thing is certain: in 2031, it would be our honour for us to host at least an online event to bring all the authors together to assess the extent to which the hype, hope and realism turned reality. Maybe we will just realise that the whole idea aged very badly. Will you join us?

We have a dream that this book lands in the library of every educational centre worldwide in print. To help us achieve this, please contact us.

Our goal has always been to inspire people around the world to learn about hydrogen, and challenge it when needed. As humans beings, we are born to learn, think and even innovate.

'Knowledge is power, ignorance is bliss. But curiosity, even if it had killed the cat, is king', an American writer once said. We hope this book is the starting point of a journey that will encourage you to be more curious about the energy transition and the changes to come, and more fearless of the future. Hopefully, it will also help you realise that the energy transition is not only about switching fuels, but about human changes, too. That is what will make the real difference.

#TouchingHydrogenFuture

Erik and Rosa.

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38 people contributed to this book. In order of appearance:

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Singapore

Felipe San Gil

The beginning

All good things come from a start. In 1874, French science fiction writer Jules Verne envisioned a hydrogen dream in his book *The Mysterious Island*:

> "A world where water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable."[2]

The same Jules Verne loved to picture global travel and helped to show how one could cross the world in 80 days. Yet, since Verne published A*round the World in 80 Days* in 1872, the world has become far more energy dependent. The affordable, clean, and secure delivery of energy has become a societal cornerstone. Hydrogen, if scaled up, will hold part of the global answer to that need. Countries across the globe have started to recognise this.

The world has moved from prioritising fossil fuel industries over the last century to admiring the investors who understand the risks posed by climate change and are acting on them. This will give rise to a new, respectable, super-cool job in the the late

2020s and 2030s: the hydrogen professional. Enter any room in the world as a professional who is developing and promoting hydrogen, and you'll be treated as the star of the birthday party. This book will help you as a reader decide if you want in on that new job - if you want to take part in building a future based on hydrogen.

How would that hydrogen future feel to live in? We combine Jules Verne's ideas about hydrogen's promise and travelling as proof. Join us on a rapid tour around the globe in the 2030s and 2040s, covering more than 100 locations. We visit 27 countries with hydrogen ambitions, turning the PowerPoints of the 2020s into reality in 2030 and 2040. Through the eyes of today's *passionados*, we show you how the hydrogen world will feel and invite you to join in building it.

Imagining the future is delivering it.

Let's go!

I

Part One

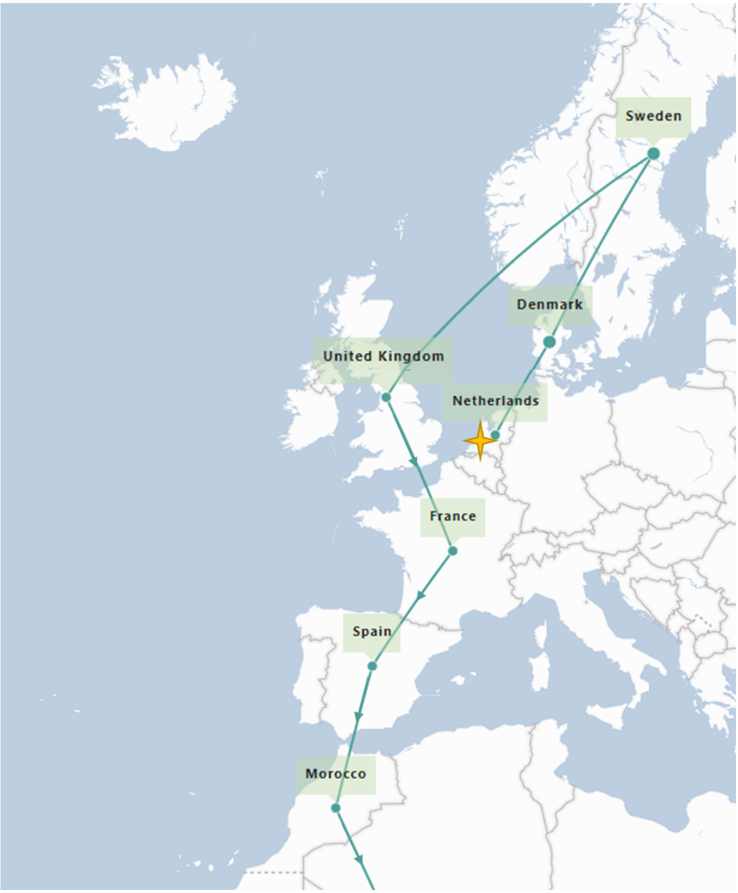
Part I. The journey on the map

We will visit 27 countries across all the continents of the world.

Starting in the Netherlands and finishing in Germany, we visit countries following a specific and deliberated order that allows the reader (i.e., the traveler) to take a round-the-world tour as she or he would do in real life, without interruptions.

Illustration of countries visited along the book. Source: Google and editors

The journey starts in the Netherlands and continues by visiting Denmark and Sweden, followed by UK, France, and Spain.



Map visualising part of the journey. Source: Google and editors

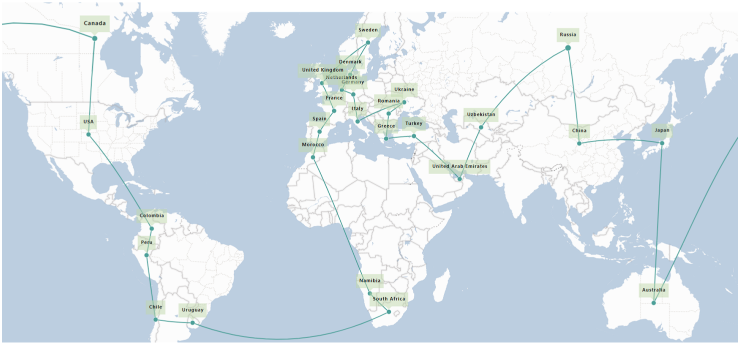
From Spain to Africa: From Morocco, down to Namibia and South Africa. We then move to South America to visit Uruguay, Chile, Peru and Colombia, and then head over to the USA and Canada in North America.

Map visualising part of the journey. Source: Google and editors

The journey continues by connecting Canada and Australia, then onwards to Japan, China and Russia. From Russia we move to Uzbekistan, the United Arab Emirates, Turkey and into Eastern Europe. We end with Greece, Romania, Ukraine, Italy and, finally, Germany.

Map visualising part of the journey. Source: Google and editors

See the complete journey below:



Map illustrating the whole journey. Source: Google and editors

For an interactive experience, visit https://www.mapcustomizer.com/map/touching-hydrogen-future-the-book

Note: The maps included herein are without prejudice to the status of or sovereignty over any territory, to the delineation of international frontiers and boundaries and to the name of any territory, city or area. Locations are indicative.

The Netherlands, 2029

Author: Erik Rakhou

The red light on the wing was flickering as he slowly awoke, seeing the aeroplane descending towards one of the extended Dutch airports. It was 3 November, 2029. Eight years after the UN's COP26 climate summit in Glasgow. In a quick dream, he had vividly remembered a visit to a COP26 side events looking at the huge steps needed to curb global warming and the climate crisis. He had recalled the somewhat inefficient tornado of pledges to cut the price of green hydrogen to $1/kg by 2030 – down by around 80 percent from 2021. That Hydrogen Shot challenge had triggered the rapid coming of "clean hydrogen"[3], like "fossil oil" in the decades before.

The plane suddenly started rising again, taking a detour. The pilot announced: "*Dear passengers, apologies, we have to circle across the North Sea. A temporary local blackout, due to power grid problems, has caused a power cut in the airport terminal and made it inaccessible.*[4] *The good news is, this allows us to showcase how the hydrogen used by our airline is produced! We're about to fly over the energy island where SOUTHH_2,*[5] *the successor of NORTHH_2,*[6] *is turning windmill power to split water into hydrogen and oxygen.*"

The structure of the energy island was inspired by a Dutch architect who became world-renowned for designing the first 200 MW electrolyser factory in Rotterdam. Some of the architect's early work (pictured below), floated as a memory in front of his eyes.

Design of the first 200 MW electrolyser factory in Rotterdam. Source: [Kraauvanger]

Down below, the giant structure of the offshore green hydrogen factory flickered with green LED lights that signalled its "green hydrogen taxonomy"[7] label. He remembered reading that the €15 billion project had just recently been commissioned[8] and included a small modular nuclear reactor, enabling it to keep using electrolysers when the wind dipped, thus lowering overall energy system costs. The project's artificial intelligence, provided by Spectrazon,[9] steered clean power towards the Dutch and other North Sea grids when they needed it over hydrogen to maintain stability and avoid now-common rolling, commercially-accepted blackouts. The hydrogen production had in part been sold on long-term contracts to various Dutch energy buyers – airlines, logistics providers, steel plants, and shipping fuel producers. Part of the production had been reserved for short term sales to allow new users to enter the market and ensure a transparent price evolution.

"*Blast,*" – his digital watch signalled the micro-hydrogen futures were pushing him for a small margin call. The futures, which he had bought for Rotterdam, were delivering clean hydrogen via HyExchange[10] to hedge his home use of hydrogen for his camping trailer. He asked a flight attendant for an "air vodka"[11] — now seen as an acceptable way to offset past emissions, and logically trendy as carbon had gone from being perceived as a burden in early 2020s to a recyclable resource for sustainable products.

The plane continued circling, and his mind wandered again. In the Netherlands, hydrogen use had been the norm since 2024. Rotterdam airport had shown that it could be done.[12] A good friend, who jumped out of planes as casually as drinking tea, now regularly checked with him on his views on the supply dynamics of the price of hydrogen because his flying club owned a hydrogen-fuelled plane. He had heard that Airbus was making good progress on the use of hydrogen-based fuels for long-haul flights too.[13]

Out the window he spotted a couple of huge Maersk ships starting to turn for the port of Rotterdam. Those ships operated on methanol,[14] a volume-efficient way of using hydrogen-based methanol[15] as fuel for shipping.

"*Blast*"— he remembered that in 2020 he had bet a case of Barolo wine against the CEO of a Benelux shipping firm that the region would be done with nuclear energy by 2030. Who could have thought in 2020 that nuclear energy, as a source of stable hydrogen production at scale for global shipping, would have made a renaissance by 2030? Yet, it was true – he remembered attending a meeting in the London Royal Automobile club chaired by Amber Rudd that proved to be prophetic with the release of a study paving the way to the marriage of nuclear energy and hydrogen in a policy debate.[16]

His watch bleeped again – his hydrogen-fuelled next-generation Toyota taxi, called the Dutch HYPE after a few successful Paris projects[17], reported that it was wait for him at the airport. How things had moved on since his debate with a Tesla taxi driver in Amsterdam in the early 2020s, who happened to be an expert on the pros and cons of electric vehicles versus hydrogen cars and trucks.

Me: "*So what do you think about the use of hydrogen in cars and trucks?*"

Tesla taxi driver: "*It's feasible but not sensible. It can't compete with battery electric and uses too much energy. The distribution of hydrogen is almost prohibitively expensive, and they're struggling to get rid of grey hydrogen in sectors like fertilisers and refining.*[18] *Hydrogen is a problem we've just started to solve. It's not a solution that justifies expanding the market for it. We're better off putting the effort into finding ways to make it competitive in sectors where hydrogen is already used. I'm all for green hydrogen for ammonia in the fertiliser industry, and methanol production. That's about it.*"

Me: "*Hmm... but I do see some industrial scale-ups for hydrogen trucks - Hyzon,*[19] *Nikola,*[20] *Daimler, Quantron,*[21] *Hyundai,*[22] *Tevva,*[23] *Gaussin & Plug Power*[24]*...*"

Taxi driver: "*It does not make it right, just because strong and innovative players are doing it. Most of the world's hydrogen is made from methane and coal in a dirty energy consuming process.*

Any expansion of that market shouldn't be allowed today. I can put it into perspective. Do you like maths? Here are some quick numbers for you. The current wind generation in this country is, say, 1x. Converting the trucks and car fleets from diesel to green hydrogen would require another 1.5x in comparison with 0.5x for the fully electric conversion of fleets. There are ball park figures based on Volkswagen research, which show huge conversion losses from renewable energy down to using hydrogen in fuel cells in comparison to the direct use of renewable power [25]*. Feel free to challenge me, I know this assumes the current state of technology. But there is no reason to even attempt to do that. It would benefit only the current fossil industry – using tax payers' money, probably. It would be insanely expensive, and still not solve the current decarbonisation problem.*"

Me: "*If we were only looking at building 100 percent renewable energy just here in Europe, I would agree. But there are global trade value chains emerging where hydrogen helps to bring stranded renewable power to end-users on different continents.*[26] *And what about other factors in the decision? In your experience, are your solutions for cars and trucks able to cover, say the 800 km between Rotterdam and Munich?*"

Taxi driver: "*I don't drive trucks, so it's a mental exercise. But if you are suggesting that hydrogen is superior to battery electric in terms of range, you're wrong. Range is similar in my view. The limitation for hydrogen is weight and volume, with emphasis on volume. The limitation for battery electric is also weight and volume with emphasis on weight. In reality there is no real difference at present. I'm aware of the dreams of storing the hydrogen in liquid form in trucks, which is possible, and will provide over 1,000 km in range, but paying for that kind of hydrogen distribution is foolish. The only benefit for hydrogen trucks over battery is filling time,* *which is a perceived benefit rather than a real one. There is no problem charging a 44-tonne truck with 400 km of range in well under an hour. 400 km is roughly what's required to cover the allowed time for driving intervals under European rules for taking breaks. That's more or less all you need to know to realise that hydrogen for cars and trucks is a dead end. Unfortunately, because it would be good for business. Plus, hydrogen refuelling stations would face challenges equal to electrical charge stations of requiring huge grid expansions.*"

Me: "*If range is indeed manageable at 400 km, in Europe hydrogen in trucks will face strong electric competition. It will come down to who manages the supply of hydrogen and storage versus electrons and storage better. The Nikola and Shell-Daimler concept, which appears to copy Tesla's approach of fuel-plus-vehicle, is a good one. If the same is offered in electric, hydrogen trucks will face competition indeed. The electric storage is not trivial – assuming now that current fuel stations get depleted every second day, one needs by analogue to hold a day or two's worth of power. Battery solutions, don't yet match the required duration, so one needs grid power. Grids may be slow to ramp up. But as the hydrogen value chain develops for other industries, then its supply chain could be reused for cars and trucks with hydrogen fuel cells, just in time to compete with electric cars and trucks ...?*"

Taxi driver: "*All those things matter, but in the end three main arguments should put a stop to any tax money being poured into subsidising hydrogen for vehicle use:*

1) It's still a monumental task to get rid of the existing grey hydrogen, which accounts for most of today's hydrogen production. Expanding the market to trucks will only be an expensive distraction in that effort until grey hydrogen is greened first.

2) Hydrogen trucks and cars need two to three times' more energy *as input due to energy conversion losses versus electric solutions - why would taxpayers want to pay for that fuel production?*

3) We are talking about the fruits hanging highest in the tree for CO_2 *reduction in transport. All efforts of transport decarbonisation should be focused on the lowest hanging fruits where electrification is another no-brainer. I'm sure there will be shipping industry or aviation industry firms that struggle for alternatives to decarbonise and will be more than happy to pay top dollar for fuels derived from green hydrogen, and pay for their special properties as molecules – hence there's no reason to waste green hydrogen in trucks or cars, just yet.*"

Finally, he added, "*Well, thanks for the conversation, we've arrived.*"

* * *

His mind circled back to today, in 2029. That taxi driver was quite right, aviation and shipping came first. But the use of hydrogen in cars and trucks came second, simply because power grid operators, including visionary firms like TenneT, realised that power grids alone would not deliver the energy transition quickly enough for carbon to become a non-issue.[27]

The plane finally started its descent. His dreams stretched farther, on a global tour of the green hydrogen-fuelled future.

Denmark, 2030

Author: Petar Sofev

31 December, 2030. What a fantastic year that was.

Introduction

When a year comes to an end, I like to sit in quiet and reflect on it. 2030 was perhaps the most eventful since I came to Denmark in 2015, as the first step in my career change. What attracted me then as a student and still attracts me today is the country's green ambitions and social system, and its high rank in the good country index[28] - to name a few things. It was not always a smooth voyage, but I've witnessed an immense green transformation across Denmark and the rest of the world in that time, and hope to have contributed even a little bit to it.

Many, but not all, of the 2030 pledges have now been reached. We sometimes waited until the very last minute to meet this crucial deadline. I am only thankful that climate change proved more patient than anticipated, and that we have somehow managed to avoid the worst of it — so far.

Winter 2030

It was a cold January morning and I was on my way to the Danish island of Bornholm[29] in the Baltic Sea, which in the past came under the spotlight for being one the planned routes for the Nord Stream 1 and Nord Stream 2 gas pipelines[30]. But today, Bornholm is one of Denmark's two major energy islands. It started with a planned 2 GW[31] of offshore wind power capacity from the Baltic Sea and now has 5 GW and is connected to the power grids of Denmark, Sweden, Germany, and Poland.[32] But on this trip I was more interested in the hydrogen production from the island's port of Roenne, which had been supplying more than 60,000 passing ships with liquid hydrogen and ammonia from as early as 2025[33].

I live in a suburban town only 20 km from Copenhagen but far enough that I rely on regional trains to get to the main train station or airport. Today, I was looking forward to flying for the very first time on a hybrid-electric plane that would complete the trip from Copenhagen to Bornholm in less than 40 minutes. I cannot get my head around the speed at which Denmark met its goal to make all domestic flights zero-emission by 2030[34]. Copenhagen airport has fully developed the IPCEI[35] project, Green Fuels for Denmark, announced in 2020. Today it produces more than 250,000 tonnes of sustainable fuels for transport, including e-kerosene for aviation[36], from its 1.3 GW of electrolysers. Most of the electricity comes from Bornholm's wind but the electrolysers are in the Copenhagen area. Most flights in Scandinavia are now close to zero emissions, too.

Planes are fast, but of all forms of transport, I like trains the most. Especially these days they are very comfortable and mostly reliable. I say mostly with a bit of bitterness as today, of all days, there were severe train delays. I hesitate over whether I should hope for the best, wait for a train and run the risk of further delays, or grab a taxi. I didn't want to miss my first hybrid-electric flight or the meetings in Bornholm, so I grabbed a taxi. I was treated to a brand new and somewhat luxurious Toyota Mirai cab — one of 500 hydrogen taxis roaming the streets of Copenhagen as part of a partnership that in retrospect proved essential for developing the refuelling infrastructure for hydrogen vehicles in the capital region[37].

Twenty minutes later I arrived at Copenhagen Airport with little time to spare. After a swift trip through the terminal, steadily running to the gate, I boarded a short-haul hybrid-electric plane. According to the brochure in the front seat, it can carry 80 passengers in comfort, mostly relying on solid-state batteries and a small e-kerosene generator, which for today's short flight would serve only as a back-up[38].

The flight was surprisingly silent and relaxing, but I was perhaps too excited to enjoy its intended benefit. I was also excited to once again visit Bornholm. I had a few meetings in the port of Roenne to discuss the port's role as an energy hub and its outlook for the future. My fascination with Bornholm as the first energy island, I believe in the world, went back to late 2021 when together with some students we visited the Technical University of Denmark Power Lab[39], where they had a small model of the island and, more impressively, a control room that is a physical duplicate and fully connected to the island's control room. It looked like something out of NASA.

Spring 2030

In the early spring some colleagues and I visited the second Danish energy island, located in the North Sea. This artificial island, 80 km from the small Danish coastal town of Thorsminde, took nine years to develop and continues to expand[40]. It now harnesses 3 GW of offshore wind and is on track to expand to 10 GW of capacity[41]. These days, almost everything that gets in the headlines is on the GW scale. It looks like and seems to operate just like a small industrial port. In addition, it has a power-to-x (P2X) - or hydrogen - production and storage facility, warehouses, accommodation, and a decent restaurant. Back in the day you probably would have needed special permission to get to the island, but now it is as simple as taking a ferry. The island also hosts an information centre with lecture and exhibition halls. A lot of students and foreign visitors come here to learn more about the cool concept and operations of an artificial energy island.

Snapshot from the visualisation of the VindØ project, credit the VindØ consortium

Summer 2030

In June, I visited relatives in neighbouring Norway and couldn't think of a better way to get there than with a fairly new hydrogen-powered ferry that replaced the old sister cruise ferries connecting Copenhagen and Oslo[42]. Stepping onto the top deck I had a *déjà vu* from the first time I took the overnight ferry. The only difference is that there were no exhaust chimneys here. Even with very low sulphur fuel used back then, they still stunk the place up. There were also no engine vibrations, making it more comfortable for passengers although reducing the drama of riding a big ship that some people nostalgically remember (myself included).

The two new ferries have a similar capacity as their predecessors – 1,800 passengers, 120 trucks, or 380 passenger cars. They use compressed hydrogen in a 23 MW PEM fuel cell system[43] — a real technical feat when they first set sails back in 2027. If you're travelling with your car, camper or motorcycle, it will be fully recharged for free during the trip, whether it's hydrogen or battery electric. That's correct — there are 380 hybrid charging points in the car decks plus a few dozen for electric bicycles. We now take them for granted, but it took a long time to sort out the technical standards.

Despite my best hopes, I was treated to another rough sea voyage to Oslo. Trying to ease my seasickness I headed to the outside decks as early as the first sun rays were emerging on the horizon. "*There could be no better occasion to check on the latest hydrogen-related news,*" I said to myself. We were halfway through 2030, and taking stock of the climate, energy and hydrogen projects would probably take me the remainder of the journey to Oslo.

Before the summer holidays, Denmark announced it had reached its goal to cut emissions by at least 70 percent (compared to 1990), and that as planned, wind energy and P2X[44] had played a significant role in achieving this[45]. In 2030, Denmark has around 10 GW of P2X facilities in operation. The green hydrogen hub between the towns of Hobro and Vibor has doubled its 2025 capacity to a 700 MW electrolyser plant and 400,000 MWh of underground hydrogen storage.[46] The HySynergy project is another IPCEI that has expanded to 1 GW of electrolyser capacity to produce green hydrogen for heavy road transport in Fredericia[47]. Green CCU Hub Aalborg produces 20 million litres of e-methanol, half of which is used as a petrol additive for passenger cars[48]. A large portion is also used as a marine fuel[49].

I am probably missing something, there are so many projects in the country…

Autumn 2030

Autumn is perhaps not the best time to visit a port, especially in what is considered one of the windiest cities in Denmark (and therefore the world). But after the gloomy morning, that Thursday afternoon provided us with nothing but sunshine and a gentle breeze. We were visiting Esbjerg in South Denmark, where a number of projects were underway.[50] The city has been through several transformations so it can today call itself an Energy Metropolis.

Most of the offshore power and hydrogen flow through the port of Esbjerg, which is today a major energy hub in the North Sea. The hydrogen pipeline connecting Denmark and Germany starts from Esbjerg, and its green gas flows through Hamburg into the German gas grid. At full capacity, the pipeline can meet up to 25 percent of Germany's hydrogen demand. I think today it is only around 8 percent.[51]

The port of Esbjerg uses renewable energy and hydrogen for its own uses and has provided 100 percent green shore power to ships since 2022[52,53]. A 1 GW electrolyser[54] has been operating in the port since 2025. Due to high demand and expanding offshore wind capacity, it has recently doubled its capacity. The produced hydrogen is used for heavy road traffic such as trucks that refuel directly at the port and for several regional train routes. A pipeline connecting the port and the train station.

Esbjerg is also the home of one of the first large-scale ammonia production facilities in the world, the Høst project. With an electrolyser capacity of 1 GW, the plant has been supplying ammonia to the agricultural industry and to ships calling at the port of Esbjerg since 2027[55]. Large quantities of liquefied ammonia are shipped to Hamburg and other European ports via Esbjeg. In addition, a by-product of the Haber-Bosch process is large quantities of water with a temperature of 70°C, which is perfect for heating people's radiators at home. With its large capacity, the plant can supply half the city of Esbjerg with zero-emission district heating.

Hydrogen projects in Esbjerg are now a strong part of the local economy and community and directly employ more than 500 people in the region[56]. However, the two larger projects were delayed by more than a year each. It took a really, really long time to win public acceptance for hydrogen and ammonia. Today we see them as no riskier than natural gas, but back in the day, we were hesitant about having them in our backyard. We knew this could be an issue but still underestimated its impact. Back in 2021, I asked a room full of P2X *aficionados* how many would be happy to have an ammonia plant in their neighbourhood. No one raised their hand, including myself.

After this reflection, it seems that we in Denmark are truly very lucky to have so many world-class, and sometimes world's first, projects that are so easily accessible. It seems to me that Denmark more than ever wants to share its know-how with the world. After all, this is what true green leadership is all about.

Sweden, 2048

Author: Sigrid Granström

6 June, 2048

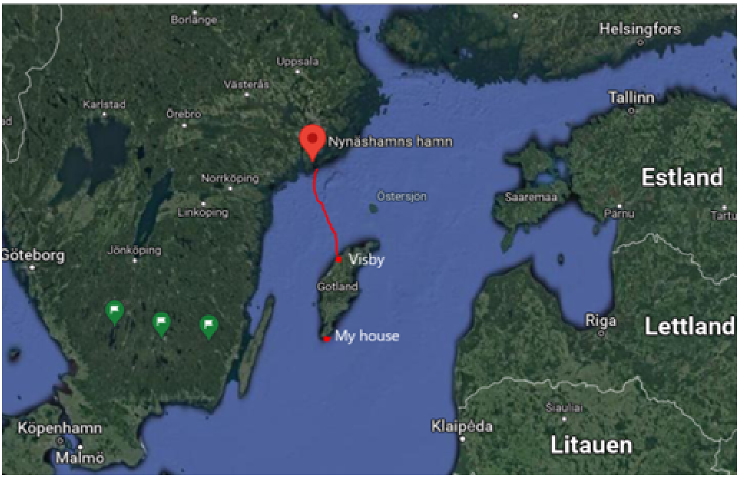
I find myself waiting for the ferry to Gotland[57], an island in the Baltic Sea where I have my own little paradise. It's a large stone house right by the sea on the southernmost tip of the island. It's been in the family for decades and we've been gently renovating it step by step. We're pretty much self-sufficient most of the year, with solar panels on the roof of the big barn even providing enough power to charge EVs for us and our neighbours. I don't have a car this time, but that's no longer a problem.

As I stand by the port waiting, I look at the old large natural gas tanks. Not too long ago, this was the main cargo port for gas imports. Gas arrived on diesel-motored ships and was stored until further transport by fossil fuel-powered trucks[58]. Today, two of the tanks have been transformed into a super-cool futuristic hotel with a seaside restaurant, a stage hosting theatre shows and concerts with a roof that's removed on warm summer nights, and a climbing centre[59]. The other tanks have been refurbished to store liquid hydrogen. Nowadays ships at this harbour are fuelled only by hydrogen, obviously.

Sweden set a goal some 25 years ago, in the 2020s, to have at least 84 TWh equivalent of electricity coming from electrolyser capacity[60]. At the time some said it was optimistic rather than realistic; others that it was naïve and imbecile. But here we are, producing far more hydrogen than we use. We're one of Europe's leading exporters. As a result, national emissions have dropped by more than 40 percent[61].

The cargo port remains, but with a new purpose, as a hub for carbon capture and storage. As the seabed around Gotland is mostly limestone, it's suitable for storing captured carbon dioxide. There is also a site for carbon capture and use, where the CO_2 is used as a raw material for the production of electro fuels such as e-methanol.

But here comes the ferry – let's go onboard!



Overview route to Gotland island. Source: Google maps augmented with author's indications.

Visby, the medieval (and only) city on Gotland

Leaving the ferry by foot, I appreciate the missing sound of car engines embarking the ferry. The city has been fossil fuel-free for a few years, meaning that all fossil fuelled vehicles are banned — no exemptions. You either have to drive an electric vehicle, or leave your fossil fuelled beast parked in the harbour. You're still allowed to use a non-EV outside the city, but petrol stations are already scarce, and everyone will know you're not a local.

Gotland. Source: Lonely Planet

Gotland was the first large-scale off-grid community in Sweden. With only one cable connecting the island and mainland, it's always been a vulnerable spot on the transmission network. It all started back in 2019 when the decision was taken to turn

Gotland into a pilot for a sustainable and fossil fuel-free energy system. Then it became part of the EU Initiative Clean Energy for EU Islands[62]. The pilot succeeded, and Gotland became the role model for the rest of the country. Looking back, it's strange to think we actually used to manage our energy system in such a short-term and unsustainable manner!

Nowadays there are windmills all over the place. Onshore is mostly on pastureland for sheep. Solar panels sit in fields with corn, buckwheat, and other crops, as they has been shown to actually increase harvest. Shade from the solar panels does more good than harm, as as the sun burns harder and rain is less reliable[63]. A vast majority of windmills, however, are offshore. They're beautiful, like immense Nordic flamingos out in the ocean. The installed capacity just around the island is an impressive 30 GW, with material production. That's three times more than the entire country had just 25 years ago. But it's unfair to compare output now and then, as the technical development and efficiency of each windmill have grown faster than Road Runner (for those who remember the old cartoon by Chuck Jones)[64].

When there's a regional net production surplus, the excess power is used for hydrogen production. That way, the volatile power production from wind can be stored. There are large subterranean hydrogen storage facilities, just like the above-land hydropower dams in northern Sweden. Sceptics said large-scale hydrogen production would be unlikely due to the lack of fossil fuel-free electricity, as the process is energy intensive. They were wrong. The electrolyser's efficiency can still be improved, but compared to an efficiency level of about 65 percent in 2020[65], it has improved. The excess heat that comes out of the process is taken care of and used, for example, to heat green houses during cold seasons and prolong growth and harvest.

Combined with emission-free electricity production and hydrogen storage facilities, there's a need for user flexibility. With regional decentralised solutions in Gotland combined with centralised national and European solutions, this works. At the European level, there are still some bumpy roads to be travelled. Nevertheless, those three components — emission-free electricity production, energy storage and user flexibility — are the core for our long-term sustainable security of supply. We have, in a short period of time, developed an integrated energy system in which fossil fuel-free hydrogen is included, and where different energy sources, energy carriers, types of infrastructure and kinds of users interact – i.e. in integrated value chains rather than multiple ones with Chinese walls.

Anyway, I'm still on my way home. As I walk through the city, I pass the new campus. It's a beautiful building in wood and natural stone. There are flower beds on the roof to help pollinators. All the windows are solar panels. It's what we call a plus-energy house, meaning that it produces more energy than it consumes. It has several energy efficiency components and is constantly self-sufficient on energy, hot water, heating, and cooling. Don't you just love that this is more or less standard for new public buildings nowadays? The fact that this one was even built is due to the 2019 energy pilot and the fast hydrogen development. There was simply a lack of knowledge and competence on how to plan, build, maintain, integrate, develop appropriate frameworks and regulations, get public acceptance, maintaining biodiversity, etc. I love the fact that students come from all over to study here. We essentially import thoughts and ideas from outside our own box and export thematic competence – win-win.

As I reach the bus station, the sun is high and it's warm. I drink from one of the public water fountains. Sweden's still on the top list of best tap water quality in Europe, together with our Nordic neighbours and countries around the Alps. I get on the bus while it's still charging. Not that full-charge is necessary. The long-haul buses going south more or less follow one of the two main roads. These have been e-roads for the last 10 years, meaning that buses, trucks and agricultural machinery can charge while driving. Super-efficient! It saves time and the vehicles don't need to carry loads of heavy batteries.

There's no bus stop right by our house, but the driver is usually nice and lets me off there anyway. I've been here all my life. I know this place better than my own pocket: this house, this garden with its fruit trees, roses, and the lavender alley that leads to the front door of the main house, the birch wood, the sheep dotting the pasture and, of course, the sea. Nevertheless, every time I've been away for some time, it strikes me how lucky I am and how much I love it. And yes, hydrogen is a vector and part of economy now, even in Gotland's paradise, used particularly for storing intermittent energy.

The 'little paradise' house. Source: Author's photo collection

United Kingdom, 2035

Authors: Tom Baldwin, with inputs from John Baldwin

From the hydrogen landscape, to net-zero, to Liverpool victory

April 2035

Liverpool Football Club are on course for their fifth straight league title under the stewardship of Steven Gerard, who has done a remarkable job since replacing Jurgen Klopp in 2029. Jurgen, who is entering his second term in the German government, has just announced a substantial investment (via government grants) in a green hydrogen pipeline from Algeria. It will be Europe's second from North Africa, parallel to the Moroccan pipeline commissioned in the early 2030s. The second pipeline is deemed necessary to diversify the EU's energy supply away from natural gas supplies, which pose issues. The economics of wind and solar energy generated in the Sahara Desert, with the vast scale and high combined electrolyser load factors, are expected to deliver less than €1/kg hydrogen to the no-regret industrial clusters and beyond[66] across Central Europe.[67] The hydrogen backbone is loading.

Klopp celebrating the new deal with a pint of his favourite beer (so say the ads). Source: Author

I sip my orange can of Brewdog as I approach Liverpool Lime Street on High-Speed Rail 3 (HS3)[68]. The new canned beer, creatively named *Dutch IPA*, is not made with fizz, because the price of carbon is so high that the beer is left flat in the production process. The carbon price in 2035 has exceeded £400/t CO_2[69]. The idea is marketed as a means of reducing the carbon emissions of the final beer product[70], although it is rumoured that the economics no longer stack up and fizzy beer no longer makes economic sense compared with nearby carbon export opportunities. These high carbon prices have resulted in the highly complex and innovative coupling of industries intertwined by the delivery and off take of CO_2 in regional grids in the north west and north east of England. For example, CO_2 produced in the fermentation process is at a large biomass facility, X, in the north of England. Gasification of biomass produces hydrogen, which is then blended with brewery CO_2 to make renewable methanol. That's then burnt to generate electricity to operate a direct air capture plant[71]. It's possibly not the most efficient of processes, but it's an innovative one. However, it should not be confused with its close cousin known as "liquid wind", where hydrogen is supplied via an electrolyser connected to offshore wind generation[72]. This what you get from drinking too much flat beer.

On a related and unexpected note, 2035 is tipped to see the full decarbonisation of the UK electricity grid, meeting the 2021 target, which rose from the fog of the 2021 retail crisis[73]. Backup generation is provided by gas generation with carbon capture and storage (CCS), and at smaller sites with green certificate-supplied gas generation (both hydrogen and biogas), which helps explain both the rise in carbon prices and the cost of green gas certificates. The caveat, of course applied to a decarbonised power grid, is an average wind year. Unfortunately, the same positive result of full decarbonisation cannot be said of the gas grid and domestic heating. Yet, huge investment in offshore wind and distributed generation assets in the past 15 years have led to significant periods of low prices in the UK. Thus, it's incentivising over 1 GW of grid-connected electrolyser capacity and raising the percentage of the grid supplied by low-carbon gases to 5 percent. And it's thanks to a great contribution from biogas with over 1,000 biomethane-to-grid plants now in operation in the country. Alas, dedicated domestic hydrogen feels dead in the water. The Health and Safety Executive is down to the last seven evidence gaps before it can decide if it is safe to burn hydrogen in the home, but it doesn't matter as the handful of welders left in the country are focused on industrial clusters and finishing the Hinkley Point C nuclear power plant. It's not all doom and gloom — heat pumps are truly starting to take off. The heat pump I ordered in 2025 has finally been installed; I can almost hear Ronald Reagan patting himself on the back that his anti-Soviet joke about new cars and plumbing is still applicable, 50 years later in 2035 in Europe[74].

I don't know why Russia is at the forefront of my mind at the time of writing this diary entry, but I can't help it, and it reminds me of the beautiful cruise I have just booked to celebrate my retirement. I will set sail from Plymouth tomorrow and will arrive in four weeks in St Petersburg. The ship will be a first-of-its-kind — entirely fuelled by hydrogen, with refuelling at the Port of Amsterdam, Hamburg, Copenhagen, Riga and Tallinn. From there I will return to the UK in an electric plane via Rome, where I will watch Liverpool win the Champions League final[75]. The inclusion of shipping and aviation in the reformed Emissions Trading System has been revolutionary and will allow me to retire and travel at ease, without the use of suspiciously cheap offset schemes on the Ryanair checkout page[76]. Not all offsets are bad though, well audited schemes run by NGOs are widespread. Ethiopia and other nations have ramped up their rates of tree planting[77], raking in a heaps of carbon cash as they do.

What the hydrogen cruise ship may look like arriving at St Petersburg. Source: Author

Final thoughts: A glorious day

I leave Lime Street Station and jump into an autonomous electric vehicle to arrive at the stadium. Unfortunately the charging infrastructure is not quite there, and we queue for 45 minutes as the car auto-charges itself and pumps its own tires at a self-service garage. It's not usually this bad, but it's a match day. Electric vehicles have dominated UK roads for a while now. At the ground, I try the cricket stew, part of the *Go Grasshopper*[78] campaign launched by an environmental group of conservative backbenchers – not delicious I must say, but land-use change and eating habits are firmly on the political agenda in 2035, finally. Every premier league club has now followed in the footsteps of "Game Zero" between Spurs and Chelsea in November 2021[79], with net-zero carbon emissions (yes, offsets play their part).

It's been a glorious day — the hottest April day ever in Liverpool, exceeding 30°C. Liverpool neatly dispatch newly promoted Manchester United 3-0. It's a great day to be a Liverpool fan. It is here that I reflect on my career working in energy. I have turned 40 and will therefore be retiring, as is typical these days, with universal basic income kicking in. This is the done thing, so that we free up our position in the ever-shrinking workplace for younger generations. I will be hanging up my PowerPoints, solid in the knowledge that it will be difficult, if not impossible, to slow the momentum behind net-zero emissions, as we reach the halfway point of the journey from 2021's COP26 UN climate summit in Glasgow, to 2050.

Liverpool 3-0 Manchester United, Anfield, April 2035. Source: Author

France, 2040

Author: Thomas Querrioux

14 May, 2040: A self-driving car trip across countryside

The beach

The smell of freshly ground coffee beans hits my nostrils as soon as I approach the cafe. I sit outside and order my favourite - medium-roast Ethiopian Yirgacheffe green coffee beans. Soon, the waiter leaves a comfortingly fuming cup on the table. I stretch my legs, ready for the sunrise. I take a sip - as always, pleasantly surprised by the outburst of floral aromas.

At 6:42 am the sky turns red and his majesty appears on the horizon, igniting the ocean. That's the sun, always on time.

Nearby, I hear a burst of laughter. People clap. The city is already busy. A few decades back it would have been quieter at this time, but people have adapted to the global increase in temperature. Our days start early and we avoid the afternoons. The spring morning is already warm and beautiful. Down the cliff in front of me, I can see surfers playing with waves. This is a religion in Biarritz, where surfing first appeared in Europe.

I recall this old documentary, *Biarritz Surf Gang*. The coastline looked very different back then and the Grande Plage, once a surfer's favourite, is now below sea level.

A ringtone pulls me out of my daydream. It is time to catch my car. From the app, I see it is parked a few streets away at the nearest dropping point.

The car could not reach me as I was in a pedestrian zone. At first, it looks very normal. So much for the 1980s pop-culture dream of flying cars. Yet there are a few twists. The car greets me as I approach. "*Good morning, sir, welcome aboard.*" It's the voice of Arthur, my dedicated virtual assistant, addressing me with the same tone (which I preselected for the perfect blend between obedience and sarcasm) he would use to fix a dentist appointment or to play music. The door opens and I step in.

And there is no steering wheel, just a comfortable working space, as I ordered. The door shuts. The car starts moving. "*Our trip will last two hours,"* Arthur says. *"The outside temperature is currently 23°C, no clouds, and light wind conditions.*" I dock my phone into the terminal at the centre of the working table.

"*Arthur?*" I say.

"*Yes, sir?*"

"*Can you give me this car's specs?*"

"*Yes, sir, you mean, the car that you <u>specifically</u> ordered?*"

I do not reply.

After a pause, the sarcastic robot proceeds, "*You are onboard the Peugeot 300000009, hybrid edition. This car is the most recent iteration of the series. It was released six month ago. The propulsion is ensured thanks to a fuel cell motorisation, allowing the car to develop a power of ...*"

I interrupt, smiling. "*Tell me more about fuel cell electric vehicles.*"

"*Please,*" Arthur replies.

"*What?*"

"*...Tell me more, please.*"

Damn, I have to remember to tone down the disrespect a notch. "*Please, Arthur.*"

The programme catches the impatience in my voice and proceeds swiftly. "*Proof-of-concept fuel cell electric vehicles where developed in the early 1960s, however by 2020 very few manufacturers were interested in producing FCEVs on a large scale*[80]*. One of the main challenges in the energy transition was decarbonising transport. This was especially true in France, where the energy mix, largely reliant on nuclear power, saw one-third of the national* CO_2 *emissions generated by trucks. Electric cars were a partial solution, as there were still some issues with the production of batteries and with the relatively limited range before electric cars needed to be recharged.*"

Back in the 2010s, France was at the crossroad of Europe, with road transport pollution becoming a heated public debate. Civil protests broke out when the government suggested raising taxes on fuel. The energy mix has since become more environment-friendly, but it has taken a few technological breakthroughs to make it economically acceptable to all, especially in rural areas with longer commuting distances. The concept is simple: use the surplus of electricity when demand is low to produce and store hydrogen. But it's taken great industrial efforts and creativity to get there.

This adventure is the focus of my investigation today.

The salt cavern

I like wine. (What a surprise). I am now heading to the delicious Jurançon region. But I'm thinking about salt, rather than wine – salt caverns. The car stops in the car park of an underground hydrogen storage facility. Amused, I notice that Arthur followed the reverse parking rule that remains the security norm on industrial sites, even though cars are now driven by artificial intelligence.

Paul is waiting for me to give me a tour. As I step out of the car, the heat is striking. I shake Paul's hand and we swiftly proceed to the main building, a discrete structure in the middle of cornfields.

"*How was the drive?*" Paul enquires, politely.

"*Very smooth, I must say. The car is definitely worth trying.*"

"*I was thinking about a trip to the coast this weekend, I will try to book one of these. Now, let me first talk you through our security rules...*"

I listen carefully to the main risks and rules to prevent an accident. These concerns have always been at the core of the culture of industrials dealing with natural gas first, then hydrogen. It starts on the parking lot and becomes second nature. Employees always use handrails on the stairs, always wear a helmet on the site and know where to walk and what to do. I am told about emergency rules, before being given a green helmet.

"*Now let's go,*" Paul says with a smile. We get out in the sun. We walk in defined corridors through what looks like a scree field. Paul points out installations and gives me titbits of information. "*What you see is all the 'plumbing' needed to inject and withdraw hydrogen in our caverns.*" He points to a few green tubes going in and out of the ground. After a few steps, I see, in the distance, what looks like a few oversized containers. "*This is a key element of the station: our compressors, which allow for injecting at very high pressure and extracting at a lower pressure the hydrogen we have stored,*" Paul says. He smiles, reading the mild expression on my face. "*All of this is pretty underwhelming, isn't it? Well, we do not mind keeping it that way... You see, everything happens underground.*"

While we walk back to the main building, Paul continues, "*We have stored natural gas in the region since the late 1950s, in aquifers and salt caverns. In 2020, researchers started to investigate the possibility of using salt caverns to store hydrogen*[81]*. Aquifers have a certain inertia and were good to meet seasonal variations of demand, but salt caverns are reactive and flexible enough to provide the flexibility needed in the hydrogen production to consumption chain. When electricity production exceeds demand, the surplus is stored in the form of hydrogen and not wasted. Hydrogen can then be used as a primary fuel for transport, as in your car, or to meet peak electricity demand, once extracted.*"

"*How does the hydrogen come and go?*" I ask, a bit naïvely. Paul shows me a dashboard behind him. It is a map of France, representing what looks like highways associated with parameters. There is no "*you are here*" icon, but I am sure that the circle at the lower left-hand corner is where I am standing right now.

"*Have you heard about the hydrogen backbone?*" he asks.

I shake my head.

"*Over the past 20 years, European system operators have strived to develop a dedicated infrastructure to connect supply and demand. Two-thirds of this infrastructure comes from a repurposing of infrastructure previously dedicated to natural gas*"[82]. After a short pause, he continues. "*You see, in France, the structure is close* *to our highway system, which allows a delivery close to hydrogen stations for long-distance transport.*" He points to the dashboard, "*Also here, and here, you see that the network reaches so-called industrial clusters. This particular one is one of our nuclear power plants… for an efficient synergy.*"

I process the information in silence before asking, "*It all seems so simple… What's the catch? Why wasn't hydrogen used before?*"

Paul smiles. "*I will limit my answer to my area of expertise. When it comes to infrastructure, the strong push came first from the EU's Fit for 55*[83] *policy package in the early 2020s, setting a programme for the energy transition. It took account of the EU hydrogen strategy set in 2020*[84]*. Previously, hydrogen was caught in a chicken-and-egg conundrum - what should come first, infrastructure or users? Fit for 55 set, hand-in-hand, goals for the heavy duty road transport industry and the infrastructure. As a result, by 2030, more than 60,000 fuel cell hydrogen trucks were benefiting from refuelling stations every 150 km along the main roads I showed on the dashboard. This was key to bringing economies of scale into the production of hydrogen, driving prices below €6 per kg of hydrogen and reaching prices below €2 per kg today.*"

* * *

As Arthur is driving me out of the car park of the storage site, I observe that having gathered elements on the use and transport of hydrogen, I am still missing some on its production. I feel, however, that these are just a quick nap away…

The nuclear power plant

I wake up when my seat vibrates gently. "*This is the next stop on your extremely active day,*" Arthur says. I raise my eyebrows. I was expecting a massive concrete structure, like in the old movies, but while the industrial structures hidden behind greenery are imposing, they are nothing like my preconceived idea of a nuclear power plant. We pass what appears to be the main facility to reach a surprisingly even more modest alignment of hangars and pipelines.

Aurélie welcomes me with a smile."U*nderwhelmed, aren't you? Well, we don't mind keeping it that way. What you've just passed is a Generation IV nuclear reactor. It solved some of the issues of its predecessors, more resistant to aggressions and more environmentally friendly, and blends better into its surroundings.*"

There's an awkward pause - nuclear is a tricky topic. But Aurélie, trained in public relations, knows how to defuse criticisms swiftly. "*Let's be clear, nuclear is not green, and that's not what I am saying here. I do recall the old debates triggered over the role of nuclear power in the decarbonisation of Europe*[85]*. But the topic of the day is hydrogen, right? Then, let's proceed with the visit!*"

She gives me a white helmet and smiles enthusiastically, while we enter the site. "O*K, you've heard about the hydrogen backbone?*" I nod. "*Well, with nearly 23,000 km of pipelines filled with hydrogen, you have to wonder, where the hydrogen comes from...*"

"*It probably did not happen in a day?*" I say.

She laughs politely enough for me not to be hurt by the fact that I did not intend my question as a joke. "*Indeed, over the course of nearly 20 years, the amount of hydrogen carried in the pipelines increased progressively. Initially, up to 10 percent of* *hydrogen was blended with natural gas; within a decade, it went up to 20 percent*[86]*. That was already a lot of hydrogen to produce! When this endeavour started in the early 2020s, most hydrogen was made by steam reforming of natural gas or coal gasification.*[87] *Both processes emitted carbon dioxide. Experts back then categorised processes according to their carbon impact, using all the colours of the rainbow and more. The conclusion was clear: only green hydrogen, produced from renewables, and yellow, from nuclear, are reliably zero-carbon.*"

We now enter one of the hangars. "*France has the second-largest nuclear fleet in the world, after the United States. It now generates 50 percent of its electricity based on nuclear power, but it used to be up to 70 percent. It's always been part of the picture. It seemed wise to use off-peak capacity, and perform electrolysis using the heat and electricity from the nuclear reactors.*"

I object. "*But why not use electricity directly? You must be consuming quite a lot of energy in the process.*"

Aurélie nods. "*It is a fair comment. Let me make a few observations. First, some of the uses for hydrogen precede the energy transition, and today the chemical and steel production represent 40 percent of the hydrogen consumption. Then, converting the unused electricity from wind and solar sources into hydrogen simplifies the management of intermittency within the electrical grid. The conversion of the natural gas grid allowed avoiding some investment in the electricity grid. Finally, the overall process efficiency improved greatly, from 25 percent with low-temperature electrolysis to 50 percent*[88]*, as we mastered the high-temperature thermochemical production of hydrogen, using nuclear heat to perform a sulphur-iodine cycle.*"

A pause, an awkward silence. "*You see, I majored in political science,*" I say.

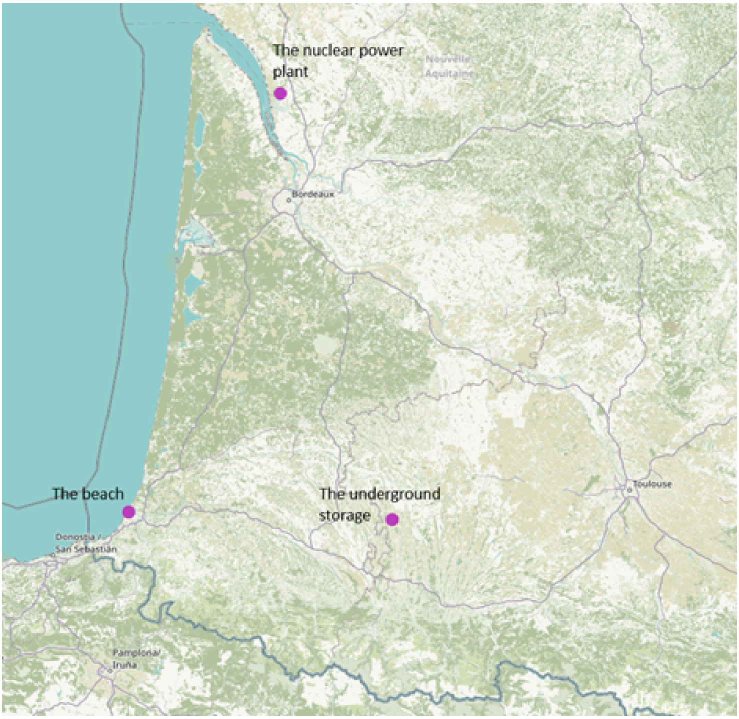
She rephrases, without hesitation or judgment (that I could perceive). "*We feed water into the process. We split it in two steps, using both electrolysis and a thermochemical reaction. We get hydrogen and, as a by-product, oxygen — which also has a market value, by the way.*" She points to the pipelines behind me. "*We produce it and feed it into the network directly. Zero-carbon.*"

I must admit I am impressed. "*And this is sufficient to produce all the hydrogen we need?*"

"*Unfortunately not. We currently produce about 60 percent of the hydrogen consumed this way. The rest is produced combining fossil fuels with carbon capture and storage.*"

I look disappointed.

She continues, "*I understand. You have been piling up numbers all day, and you were expecting hydrogen to be a miracle solution. Take a side step: hydrogen is one element of a complex system. The use of hydrogen in the electricity chain allows us to avoid certain network investments and provides flexibility, for example when demand and the availability of solar and wind energy do not match.*"



Source: Openstreetmap.org

* * *

"*Arthur, let's go home.*" The car leaves the car park in silence, leaving me lost in my thoughts. In the early 2020s, challenges posed by hydrogen were as great as opportunities. I think about these times of uncertainty. Hydrogen did not prove to be the answer to life, the universe and everything else. But it was an important piece of the puzzle. To this day, it contributes to the energy transition as a clean energy source as well as a tool to manage an electricity grid based on variable renewable generation. Assessing the benefits of hydrogen requires assessing the value of the service rendered to the system, and not only pure technical performances of this energy source.

"*Arthur, let's make a stop in Landiras.*"

"*To the Chateau de Leyre, I presume?*" I am too tired to be offended by the cheeky tone. "*You presume well, Stanley.*" Well, as I said, I like wine. The Chateau produces a Graves, an excellent red wine of the Bordeaux region. This will be the perfect conclusion to a lovely day. *Santé!*

Spain, 2035

Author: Rosa Puentes Fernández

July 2035: From Jaén to Madrid

It is time to leave. During the two minutes left for the bus to refuel[89] I have time to say a last goodbye and find a seat next to the window. The bus door closes and the trip begins.

The sun is shining bright, as it usually does at this time of the year in Andalusia, yet the heat is no longer unbearable. I remember those days in the summer of 2021 at 46°C. You could barely breathe, the pavement was almost on fire, and we were all lying on the sofa covered in sweat because electricity prices were too high to turn on the air conditioning.

I keep looking through the window. Surprisingly, even after all these years, I am glad to see that the views from the bus still resemble Machado's [90] poems: green hills "combed" by the sun, centenary olive trees "dusty and thirsty" under the clear light of the day[91].

Jaén. Source: Shutterstock, ABB Photo

In less than 30 minutes, the bus stops at Linares-Baeza train station. As I descend, I notice that birds are singing while resting under the shadow of the solar panels on the roof of the station. With my eyes staring at the horizon, I get a glimpse of the lithium-ion batteries[92] and the electrolyser of the hydrogen refuelling station. The integration within the natural landscape of the site is such that, unless you are specifically looking for them, you would not notice their existence. This was not achieved by accident; it was a pre-requisite for the regional government's permit for construction. Without a doubt, the centenary olive trees on the site are grateful for that choice.

On my way to catch the train, I meet Juan, the station manager, who accompanies me to the platform where the brand-new Talgo Vittal-One[93] is expected to arrive. Even in 2035, Jaén has no airport, and the medium-distance train is still the single fastest and most sustainable public transport mean connecting

Jaén to Madrid and other parts of Spain. Interestingly, the trip usually takes longer than going by car, and the train ticket keeps getting more expensive every year. But that is another story.

Juan has spent the last 30 years working at this station. When I first met him, he knew nothing about hydrogen or solar energy. I remember that day, already more than a decade ago, when he joined the first promotion of H_2 Safety Risk Training Academy[94]. He knew major changes were coming, as all sectors were transitioning to a climate-friendly version of themselves. He knew that sooner rather than later he would need to learn new skills to stay in the job market. *"Deciding to learn something totally different was a real game-changer. Some people told me I was too old for all that new and fancy stuff, but the truth is that the only time it is too late to make a change is when you're dead,"* he told me once. I could not agree more with him.

While I am waiting for the train to arrive, Juan briefly informs me about his plans to move to Córdoba. The e-methanol[95] plant is looking for a new plant manager and he was contacted for the position[96].

"How exciting!"

"*Well, changes are as exciting as challenging. It is not going to be easy, but if I don't take the chance now, there might not be another big one for me. I am getting old, you know. The world keeps changing fast and I feel this is my last opportunity to ...*"

Juan's sentence is interrupted by the beep from the station speakers followed by the announcement requesting all passengers with a ticket to board the train. The voice behind the speakers reminds us that we must use the underground access to switch between platforms, since it is forbidden to cross the railways. Before closing the microphone, the voice gives a last warning: "*We would like to remind you that those without a ticket* *cannot board the train. You can say goodbye from the platform.*"

When the train stops, there are literally 40 seconds left to board, so I can barely say a few words to Juan before the door closes. I realise that the next time I will visit, Juan will most likely not be here. Yet, my nostalgic thoughts are interrupted by a nervous voice shouting "*Hey, don't leave!"*A man is hitting the glass door. *"I need to get out! I am not travelling!*"

"*Here we go again,*" I think, wondering whether it is part of human nature to ignore instructions. So much progress and we are still incapable of following simple rules. "*Well, life has a funny way of teaching us lessons,*" I say inaudibly while looking for my seat along the narrow corridor of the train.

Already in Castilla-La Mancha, I start thinking about how the lives of millions of people have changed over recent years in order to accommodate the transition towards a net-zero-emissions economy. Although a lot has been achieved, more is needed to avoid a climate disaster[97]. Yet, shifting to a sustainable economy is not simply about switching energy sources. It's about making people's behaviour and lifestyle more sustainable. Great efforts were needed to make people understand the importance of this transition and their role in making the world a better place to live in. As always, there were and still are people around the world who could not accept that the rising sea levels, the unbearable high temperatures and skyrocketing CO_2 emissions were not acceptable for the planet or for all of us. Yet, much has been accomplished in the past decade and our lives have been directly impacted by decarbonisation.

The introduction of hydrogen in different sectors has been one of the greatest changes so far. As it always happens with new technology, it all started with the promises that hydrogen was the single technology needed to achieve climate neutrality.

Hence, the hype around hydrogen in the early 2020s surpassed all expectations. On the other hand, it soon became clear that hydrogen was not the silver bullet and renewables and efficiency alone were not going to meet the ambitious climate goals and sustainability objectives. But they were both a good and necessary starting point.

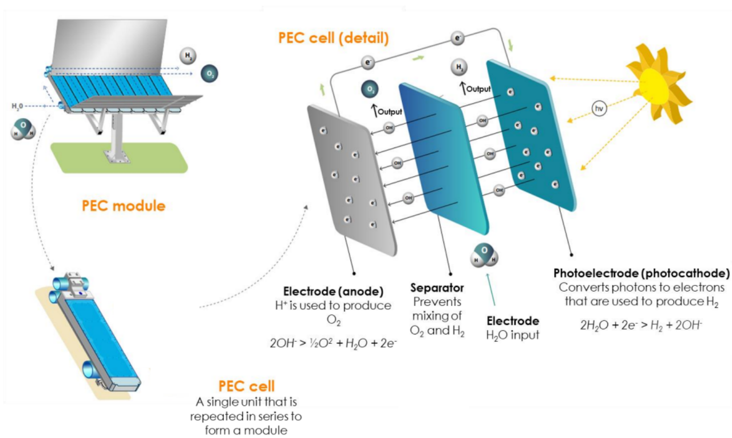
More than a decade after the publication of the European Hydrogen Strategy[98] and the Domino effect it triggered — including the publication of national hydrogen strategies in more than 15 member states[99] and announcements of hundreds of projects around the continent — we can already see the results from what became the implementation era.

In Spain, local industrial clusters started to emerge in around the country. Now more than 25 percent of the hydrogen consumed at the industrial level — mainly in refineries and chemical and steel plants — is green. It represents approximately 10 percent of total EU hydrogen consumption. More than 4 GW of electrolysis capacity has been installed. In 2020, natural gas was the primary source for the production of approximately 500,000 tonnes of hydrogen consumed yearly in Spain[100]. This shift was key to Spain's emission reduction of 4.6 million tonnes of CO_2 equivalent[101] between 2020 and 2030.

In 2026, Spain became one of the first countries in the world to produce green hydrogen cheaper than blue hydrogen[102]. The best is yet to come, as Spain will soon start producing the world's cheapest green hydrogen[103].

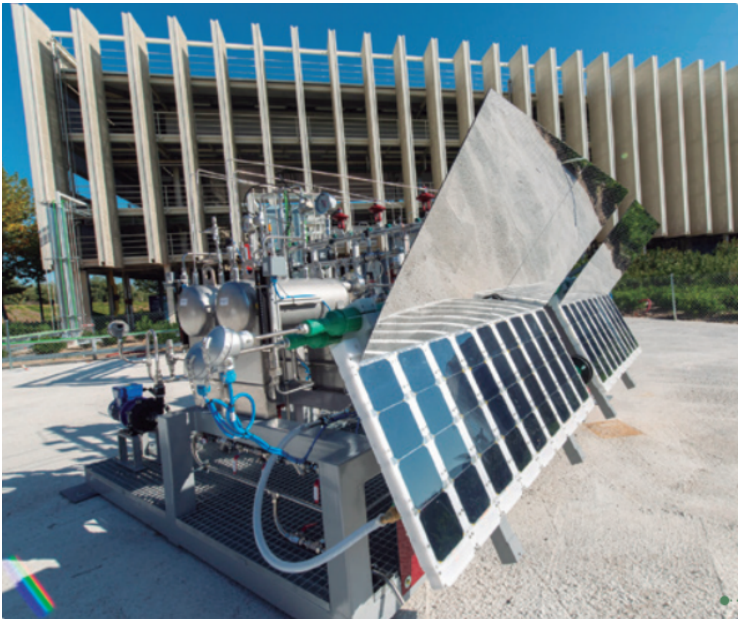
The rapid development of the hydrogen economy in Spain was favoured by numerous private and public investments over the past decade. In 2021, the Spanish government identified hydrogen as a key priority and allocated €1.55 billion of public investments for its development, with additional €2.8 billion of private money[104]. Those investments enabled the development of technology, knowledge, industrial capacities, the integration of hydrogen in all major economic sectors, and the development of new business models to reinforce Spain's leadership position in the energy transition process.

The introduction of Spanish hydrogen technology in the market proved to be a game changer for the sector. One of the key additions designed and made in Spain was the photo electrocatalytic (PEC) technology to produce green hydrogen from the sun's energy via a direct transformation process (without electricity input)[105].



SUN2HY project: Technology Overview. Source: Enagás

Globally there have been many and different approaches to this technology, mainly in Europe, the US, and Japan. But in 2020 these developments had very low levels of technological maturity. The SUN2HY project scaled up the technology by developing PEC modules at real scale, which was later validated experimentally in a pilot plant located at the Repsol Technology Lab facilities in Madrid's Móstoles municipality. The results have shown that this technology can simultaneously meet three requirements: high efficiency (over 14 percent), photoelectrode stability, and low costs due to the use of cheap and abundant materials[106]. Technological maturity was reached in 2028, and since 2030 it has been exported around the world for utility-scale projects.

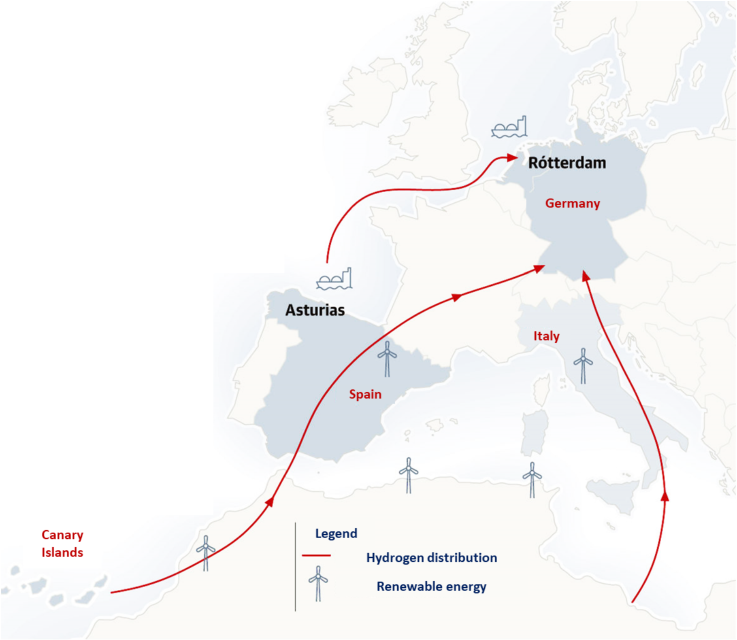


SUN2HY pilot. Source: FuturEnergy Dec.21 - Jan. 22 issue

At the beginning of the decade the use of hydrogen was no longer restricted to industrial processes, thanks to lower costs, targeted investments and new incentives for the market uptake of different technologies. Hydrogen was also used in sectors such as heavy-road vehicles, maritime and rail transport, power generation, and domestic heating in some areas.

The train starts to slow down as we reach Atocha train station in Madrid. One can clearly enjoy the view of the city from the window. The pollution in Madrid's city centre has decreased tremendously since traffic was restricted. In 2021, the Spanish capital was leading the European ranking for the number of premature deaths linked to nitrogen dioxide pollution[107]. The traffic restrictions combined with other measures in recent years — like the replacement of 1,000 diesel[108] taxis with fuel cell vehicles[109] — helped bring fresh air back to the capital's historic neighbourhoods and streets.

My thoughts are interrupted by the image of a large, long-legged and long-necked bird in the distance. I am not good at distinguishing types of birds, but something clicks in my mind: it's a Green Crane.[110] This project started in 2019 with the aim of paving the way for south-to-north green hydrogen flows in Europe and later turned out to be one of the most-used corridors for the export of green hydrogen to the rest of Europe[111].



'Green Crane' illustration. Source: El Comercio (translated by the author)

Along the same line, the HyDeal Ambition project, which in 2021 was the largest announced green hydrogen project in the world[112], has been delivering more than 3.6 million tonnes of green hydrogen per year since 2030 to users in the energy, industry and mobility sectors along the gas transmission network from Spain to France and Germany.

With such low costs for green hydrogen production, Spain soon became a hydrogen net exporter to other European countries. Hydrogen was exported as either a gas through pipelines, liquefied, or as part of ammonia[113]. Ports became important pieces of the hydrogen value chain as they facilitated the trade of hydrogen. The port of Valencia, for example, started using hydrogen to power heavy-duty port equipment[114] and has become one of the most important hydrogen hubs in Spain.

Port of Valencia. Source: [Valencia Port website]

* * *

"Hey! Where are you going? Didn't you see me?" A soft hand touches my shoulder as I'm about to get into a brand new autonomous Tesla taxi. "*Do not tell me you forgot I was going to pick you up!"* Marta stares at me smiling.

"*Oh, yes. Sorry!"* I close the taxi door, click twice on my right earphone, and say "*Alexa, cancel the taxi."*

We both head towards the car par. *"So, how was the trip?"* Marta asks.

"*Well, I was thinking about all the changes that have happened* *in the last decade. Especially about hydrogen and...”*

I am interrupted by Marta’s sigh. “*Oh, no. Here we go! Look, I tell you as a friend: if you keep talking about this hydrogen whatever to every person you meet, they are going to think you’ve gone mad! I know it’s your job and you really like it, but for a layperson like me, this is just another political movement that only makes consumers pay more. So please, let’s not start again...”*

I take a deep breath. I could respond with good arguments explaining why the rise of electricity prices is not a consequence of the introduction of hydrogen, and that her taxes have not been used to sustain the so-called hydrogen economy. But this is not the first time we’re having this conversation, so I decide not to answer. Still, it always makes me wonder whether we may have failed to make the general public understand the urgency of transitioning to a more sustainable system, and the impact it could have in their lives. Now we have to face the consequences which, obviously, come with criticism.

My thoughts are suddenly interrupted. *“So, let’s focus on the important things: where do we go for lunch? I will let you decide this time, since you will definitely miss the Mediterranean flavours when you’re back in Belgium.”*

Morocco, 2029

Author: Nesma Aboshanab

First day on the hydrogen job

The dream: A night in 2029

It was massive and indescribable, as if the earth was roaring violently. At first the sea was receded rapidly. People on Mehdia beach crowded the naked seabed, recording the disaster with their cameras. Then, suddenly, a fast-rising wall of water started to chase them.

I was standing there. I wanted to run but I couldn't. The tsunami was way faster than my legs; within seconds it hit the shore, swallowing everything in its path - including myself.

I felt like I was being sucked around a washing machine. It battered my body, driving me down again and again. I remembered my family, not knowing anything about them at this exact moment. I remembered our past summers here on Mehdia beach in in Kenitra.

Mehdia Beach in Kenitra, Morocco. Source: SanaaFariat

The faces of my family and friends appeared. I wanted to fight the waves, the rushing water, and the destructed wood and bricks. But I couldn't even call out for help .[115]

Alarm rings

5 November, 2029. Internship in Benguerir's green hydrogen cluster

I woke up suddenly, sweating and shaking, my heart pounding. It's the same nightmare again and again. I checked my room and everything was in place. I stopped the alarm. It was 7:30 am. I sighed and laid back on my bed.

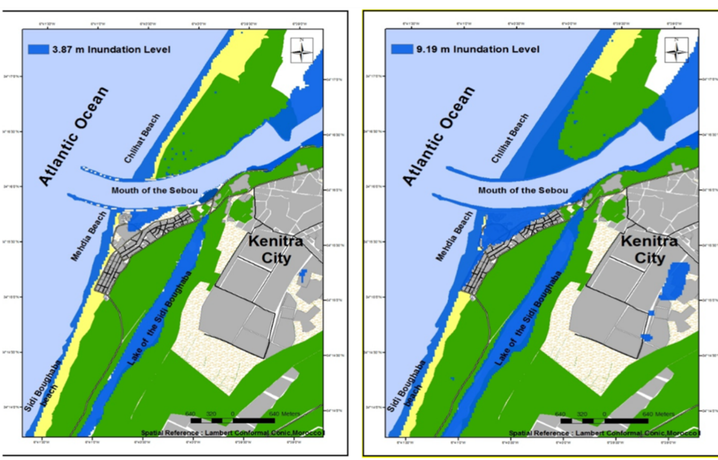
Then I remembered: it was Monday, 5 November, 2029.

I jumped out of bed excitedly. It's the first day of my internship. Two weeks ago I was thrilled to have been accepted as an intern in the green hydrogen cluster in Benguerir. The GreenH_2 was launched in May 2021 by the Research Institute for Solar Energy and New Energies (IRESEN) to connect stakeholders in the hydrogen industry including researchers, public authorities, and industry and boost the hydrogen economy in Morocco[116].

I was ready in 20 minutes. Although my hostel is only 3 km from the green city of Benguerir, I gave myself extra time to explore before my introductory meeting in the GreenH_2 cluster.

Ben Guerir. Source: Googlemaps

On my way to Benguerir I checked the news – nothing about any tsunamis hitting the kingdom of Morocco or even North African shores. Phew. My mind wandered. I've been having this nightmare for nearly 10 years. It all started one day in 2021 with three successive events: the COP26 climate summit in Glasgow, a Google search, and a movie night. My mother is an engineer and an environmental enthusiast, and she was keen on following the COP26. Although I had no interest, I managed to catch snippets from the talks, including about the hydrogen economy, global warming, decarbonisation, energy exports, and the colour green. Out of curiosity, I started researching Morocco using these keywords. It was interesting yet complicated to me, as a 13-year-old. That's when I accidentally learned about the effect of global warming on the sea level rise. I can still remember the figure showing land areas vulnerable to flooding including Mehdia beach and Chlihat beach.



Coastal land area vulnerable to flooding in Kenitra city in 2025[117]

I read about the threat of strong tidal waves and mini tsunamis, which I had read about in school books but couldn't picture until then[118]. Later that day, by chance, my friend invited me to see a movie. It was *The Impossible*, based on the 2004 tsunami in Asia. That's how my 13-year-old imagination caught on to the consequences of global warming, with a big tsunami marking ending the world. It's also when I decided to do my best to help change this, taking part in facing global warming. But the dreams continued to haunt me.

My mind wandered back to today, 2029. On my early arrival, I took a bike tour around the city. I was astonished by its urban planning, with various means of mobility, renewables everywhere, with everything digitalised and electrified. Benguerir was a mining town that had undergone a magnificent transformation.

Green and Smart Building Park in Benguerir, Morocco. ***Source***

I arrived at the GreenH_2 cluster in time, where I was welcomed by Mr. Saber and other interns. Mr. Saber has been working as a researcher in the green hydrogen cluster since the beginning.

"We are days away from the year 2030," he began. *"Ten years ago the news headlines were highlighting Morocco's effective in the area, describing it as one of Europe's leading strategic partners thanks to its green hydrogen potential. Today the installed capacity of renewable energy in Morocco exceeds 52 percent, as pledged in the country's Nationally Determined Contribution to the Paris Climate Agreement. With such a ramp-up in renewable energy, we are able to capture nearly 4 percent of the green hydrogen global demand of 600 TWh"*[119].

He proceeded to to talk about current developments in Morocco's green hydrogen industry, including the local use of green hydrogen as a raw material in the production of green ammonia, and how the countries is achieving its emission reduction targets by using green hydrogen to produce various products and export them.

Then he asked, *"Can anyone tell us about one of our developed pilot projects?"*

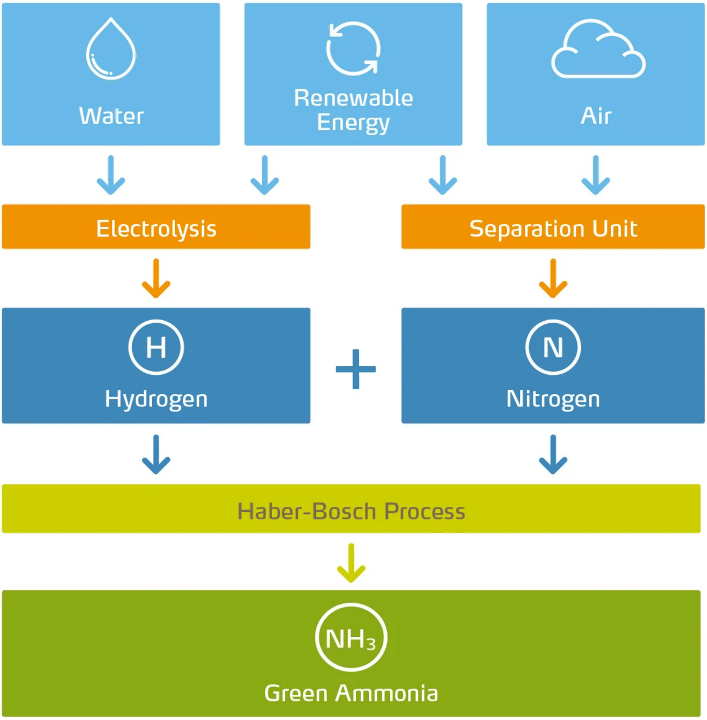
I raised my hand. I knew them by heart, as I had been following the developments through my mother and my own developed interests, passions and curiosity since 2021. Mr. Sabri called on me. *"Actually I know both pilot projects. In June 2020, Morocco and Germany agreed to form a 100 MW renewable energy plant to produce green hydrogen in Morocco through electrolysis with Masen. It now produces green ammonia and is being financed by the German government. It's part of the execution of the memorandum of understanding between the Kingdom and Germany."*

I continued, *"This is the large-scale project. There is another small-scale project to produce green ammonia with OCP Group, IRESEN, Fraunhofer Institute, and Université Mohammed VI Polytechnique. It aims to mainstream green hydrogen and green ammonia for the fertiliser industry"*[120].

"Perfect! So, anyone can explain how green hydrogen is used in producing green ammonia," said Mr. Sabri.

I excitedly answered, *"Through the Haber-Bosch process!"*

A girl from behind commented, *"But this is not what makes the ammonia green, the Haber-Bosch process is also used in producing grey and blue ammonia. Green hydrogen is produced through the electrolysis of water using renewable energies like solar or wind energy. Then the green hydrogen and nitrogen separated from the air react to each other at high temperatures and pressures to produce ammonia. Also, the production of hydrogen in the ammonia industry can account for nearly 90 percent of the carbon dioxide produced through the whole process."*



Green ammonia production. Source: Atfarm

"Well said, Rania!" Mr. Sabri said.

Rania's answer was confident and knowledgeable. I didn't know about the impact of the hydrogen production method on the carbon footprint of the ammonia industry. Considering that Morocco is one of the biggest importers of ammonia in the world, producing green ammonia for local use and for exports is a great move for decarbonisation.

After discussing the week's schedule, Mr. Sabri ended the session with a question. *"So what do you think are the major* *current challenges for green hydrogen and the development of the Moroccan hydrogen economy within the global sector? And what are we longing for in the next 10 years?"*

Although I had an answer, I was interested in hearing Rania's thoughts. She answered, *"Currently the cost of green hydrogen products is still higher than conventional alternatives. I think this is the main challenge, as well as the 2040 goal to reduce the costs of these products and establish environmental regulations to incentivise the use of green alternatives. Also, I think Morocco is longing to expand the use of green hydrogen as a carrier for energy storage in the power sector and as a fuel in transportation"*[121].

Good answer, I thought. I agreed that the main challenge is the cost. I wanted to mention challenges like the scaling up of projects and the development of users, such as transport. There were the likes of Alstom's hydrogen-powered trains, some of which have a dual mode that includes onboard electricity production and connection to electrified railway lines. But it was only the first day and there is still so much to learn and share, so I decided to research more and keep quiet for now.

At the end of the day, I felt enriched by the knowledge I had already gained and being given the space to share what I knew already. I convinced myself that today I had done something good for the world, and hoped that tonight I would sleep tight without any global warming nightmares.

Namibia, 2030

Author: Oghosa Erhahon

Namibia: The Energy Port of Africa

"Welcome to the Energy Port of Africa," a bold billboard states as we drive into the city from Hosea Kutako International Airport. Aina, who is originally from Namibia but works as communication strategist in Europe, remarks on how incredible it is that over 10 years Namibia took centre stage globally. Unlike the last time she was in the country, when the diamond markets consumed the nation's attention.

Aina and I had met in Europe a few months ago, at an energy congress. I said I had been living in Windhoek since the completion of the first green hydrogen production plant in Southern Africa in 2025.

The weather is cold in July across Namibia. Coming from the subtle European summer, Aina had to pull out the coat she had in her backpack. We boarded the newly built fuel cell train[122] to Luderitz along the coastline - the once sleepy seaside town now turned into a buzzing city.

"*I almost forgot that Namibia experienced winter and summer at opposite times as Europe and North America. How do experts and* *foreigners cope when they first arrive?*" Aina asks.

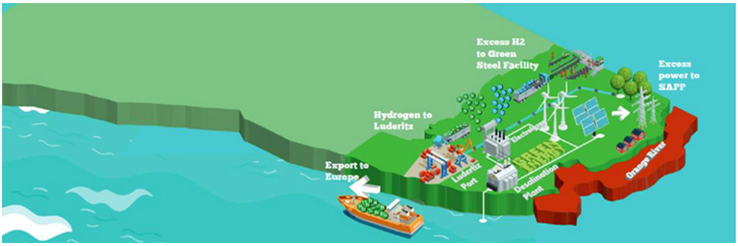
"I think most of them actually do not mind it," I replied. *"On average for the next few winter months, the average minimum temperature is around 7°C but can fall to below freezing at night in the deserts and higher areas. This usually lasts between July and August, although it's hard to predict the climate after all these years.*"

"*Some things never stay the same do they? Well, after the last elections, I was very concerned about the turnout of investors in Namibia. How does an African country important to the energy transition not drift with a change in government?*" Aina asked.

"*Namibia has one of the strongest governments in Africa, regardless of changes in government. It's a powerhouse, and it remains committed to the economic and development interest of the nation. The Harambee Prosperity Plan II (HPP II), which was introduced by H.E. Dr Hage G. Geingob, reached fruition, and the politics never lost focus of where Namibia could potentially get to.*"

"*I have heard a lot about the Harambee Prosperity Plan, but could you explain it in a nutshell?*"

"The plan was introduced in 2021 to maximise national benefits[123]*. It was a published document that included pathways towards building the now, Namibia's hydrogen sector*," I said. I pulled out my phone to show Aina few photos of the pilot project in Lüderitz.



Southern Corridor development initiative (Karas Region). Source: Green Hydrogen Namibia

Wind turbine outside Lüderitz. Source: Alexandra Wexler, The Wall Street Journal

I added, "*These activities meant financing, because the vision saw that hydrogen development would include green, blue and transition bonds and carbon credits as innovative financing tools.*

Since then, the other banks including Bank Windhoek[124] *have become commercial banks part of the Nasdaq Sustainable Bond Network. With Namibia's government support, the HPP II has worked impeccably at developing key activities, engaging advisory for the strategy plan as well as putting in the right regulatory framework and enabling environment."*

"*How did Namibia secure the largest hydrogen projects in Africa, with the sand dunes and the nation known for the least amount of rainfall in Sub-Saharan Africa? Doesn't green hydrogen require a significant amount of water?*"

"It's interesting — this is a nation where the ocean meets the dunes. It shares borders with Zambia and Angola to the north, Botswana to the east and South Africa to the south and east, and the Atlantic Ocean on the west. Namibians enjoy about 300 days of sunshine per year. That's reliable solar energy, plus strong capacity for wind farms," I explain. "*This 'Land of the Brave', as the nation is often referred to, developed a deep water port through public-private partnerships*[125]*. This was used as a benchmark for so many water port developments and financing across the region. There have also been new water authorities set up across communities, and the green hydrogen process involving electrolysis has improved the water situation in rural areas through introduced seawater desalination techniques. The initial green hydrogen production pilot projects received €40 million in funding from Germany, which was used on feasibility studies*[126]*.*"

The evening train grew busy with chatter about the elections and distant speakers playing music by the national icon, King Elegant.

The next day, after reading a couple of magazines and newspapers she picked up the airport, Aina made a few other observations on Namibia's economic and energy position. One of articles read: *"Namibia, the Energy Port of Africa is no longer dependent on electricity imports. Instead, it's on its way to becoming the first African nation to electrify 100 percent of its communities and cities, with 100 percent renewable energy."*

Aina said, "*It makes a lot more sense now, the traffic jams, busy trains and booked out hotels in the city. The population increased. Did you know that, according to the UN, Namibia had 2.5 million people in 2020, whereas now there are over 500,000 people working across the hydrogen supply chain alone? How incredible is that?!"*

"*That's very true. The influx of financing for green hydrogen projects meant increased supply of renewable energy to neighbouring countries,"* I said. *"And with electrification came new industries, too, like textile manufacturers. African and international businesses have found Namibia to be a good location to build industries – so more people in the job market!*"

"*And we no longer import electricity either?*"

"*Nope. Built on electricity access – Namibia for decades depended on the electricity imports from the South Africa Development Community region. Pathways for export to African countries like South Africa are being set up to encourage decarbonisation in those regions.*"

"*That's fantastic!"* Aina said. *"The GDP has also increased, and according to my family here, the standard of living is almost unimaginable compared to what it was.*"

"*Yes, completely. The government introduced the energy transition into a lot of the school curriculum as well as sustainability and conservation areas. So now, post-graduate students are specialising to join e-mobility manufacturing plants, financing institutions, circular economy and low-carbon emissions research and many other programmes. So many international students from across Africa now study here, gaining professional courses every year."*

"*I'm so proud and happy to be back home, Namibia's strategic positioning as an attractive investment destination in Africa has really paid off. Those highlights from Bloomberg, as an emerging market economy*[127] *in Africa had no doubts either.*"

"*It sure did, positioning itself as a leader in the emerging market for another hot resource: green hydrogen*[128]*,*" I said. *"A joint communiqué signed in August 2021*[129] *gave birth to a series of continental and international and bilateral partnerships on the production of green hydrogen. In 2021, a report by the Hydrogen Council, with McKinsey & Company, identified 228 large-scale hydrogen projects across the value chain that had been announced*[130]*. There are obviously a lot more now."*

"*This is such an eye-opener for me,"* Aina said. *"In 2021, there was no need to downplay the challenges of hydrogen emerging as a global fuel. The cost was daunting, I recall a time when a supply chain could barely be established."*

"T*he Namibian government saw and understood hydrogen to be an enabler for a renewable energy revolution, positioning itself in a space that is now inevitable. The Africa energy corridor has been rightly renamed as the Energy Port of Africa.* "

* * *

It was about time for Aina's first communication meeting. She would be working with the Namibian government on public relations and news from the Energy Port of Africa.

We waved our goodbyes and looked forward to attending the Africa Heydrogen Summit in Durban, South Africa, in the coming weeks.

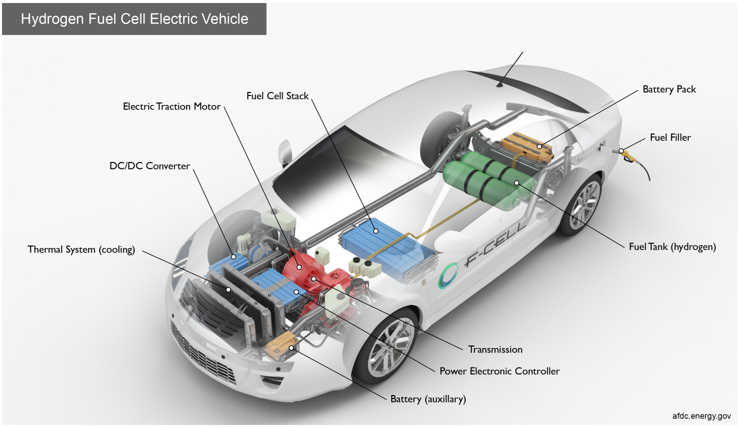
South Africa, 2044

Author: Gerhard Human

From Phalaborwa to Mokopane

It's 2044 and I'm on holiday in the Kruger National Park[131] with my wife and my son's family. We have spent the last three weeks staying in lodges, going on game drives, and staring at the stars next to campfires. My son lives in Johannesburg while my wife and I will be travelling back down to Cape Town. We'll be driving through the northern parts of the country to Johannesburg and then fly down to Cape Town.

This morning we pack my son's SUV and set off. Today's cars are an impressive display of how energy can be distributed between batteries, fuel cells and the electric engine[132]. It's fascinating.



H_2 fuel cell car functions. Source: US DOE

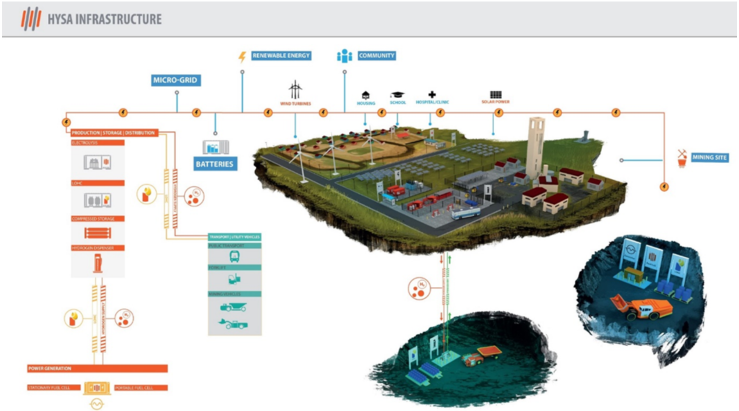
I often find myself staring at the screen and watching how the energy is consumed. Whenever I get into a car, I have the habit of staring and analysing the information on the screen. I am very much aware of our low fuel level. We've done almost 700 km since our last re-fill, and of course I make my son aware of this. Of course he says he knows, and that his car has already identified a station and booked a re-fuel. The computer shows we can only fill up to 50 percent fuel level. Although hydrogen is abundantly available in the country, remote places still have some infrastructure limitations. Half-full is sufficient to get us to a major filling station on the N1 highway, also pre-booked.

Our first re-fuel stop is in Phalaborwa[133]. It was a mining community near South Africa's most productive copper mind until the 2020s, when the mine reached the end of its production life. The mine became a decarbonisation leader even during its open-pit operations, before the term even existed, by employing a trolley-assist system for haul trucks coming out of the pit, to save on diesel[134].

Mokopane: The hydrogen hub

From Phalaborwa we drive to Johannesburg on the N1 highway past Mokopane[135], home of the famous Anglo American Mogalakwena Mine site, where the world's largest hydrogen fuel cell vehicle was first demonstrated back in 2022.

An example of hydrogen as part of the mining ecosystem:



Mining H_2 overview concept. Source: HySA Infrastructure

At the time, I was travelling regularly to the site where the electrolyser and fuelling station were being installed. It was a challenging site and time, with wind, dust and Covid-19 fears and restrictions causing more and more project delays. But the project was a big success. Today, the site hosts around 120 MW electrolysers powered by solar energy supplying green hydrogen for around 40 haul trucks and fuelling stations along the N1 and N3 highways all the way down to the South Coast.[136] As a result of this site, hydrogen is now abundantly available in the area. It resulted in the pioneering deployment of fuel cell buses, trucks and eventually cars in the country[137]. It took me a while to convince my son to get himself a hydrogen-fuelled vehicle. Now we can drive the more than 700 km from the lodge without having to stop too long — a major advantage since we don't have much time to stop if we want to catch our plane.

I hadn't visited this The Kruger area since moving down to Cape Town. What was once a rural and struggling region has flourished since becoming a hydrogen hub. If we'd had time, I would have loved to take my grandson to the nearby science centre, where all sorts of hydrogen technologies are showcased. Although they're probably not that impressive any more.

It's all a direct result of the Mogalakwena Mine truck project, which focused the world's attention on that one fuel cell truck. For my grandson, this hydrogen-fuelled car is just a car. He doesn't even understand the term "harmful emissions", as most of the energy he uses is powered by the sun. He is only 12 and grew up in a completely different world, where we had to choose between diesel and petrol. Today the choice is between refuelling hydrogen or charging batteries.

Lessons on hydrogen-fuelled mobility

As we drive, almost every third truck we pass is fuelled by hydrogen. Twenty years back not a single hydrogen vehicle would be spotted on any South African or even African road. Being excited by this, I tried to pull my grandson's attention away from his mindless videos.

"*What is powering your father's car and those trucks?*" I ask, pointing to H_2 decal.

"*The sun,*" my grandson answers, deadpan.

He thinks everything is powered by the sun, and he's 100 percent right. In his defence, his father is not technical, so when his son asks about energy sources he simply replies *"the sun"* — avoiding the complex process of harnessing solar power and using water to produce fuel. It's not wrong, but the kid is not learning anything. So, I take it upon myself and start telling him about fossil fuels and how countries like South Africa used to produce almost all their electricity and fuel from coal, oil, and gas. I then start explaining how cleaner energy and fuels emerged, but he quickly interrupts me.

"*That's the stuff you guys used to burn that caused pollution and damaged what's left of our environment.,*" my grandson says.

In fact, I want to stress, my generation helped drive the beginning of change.

"OK," he replies, deadpan, still staring at the screen.

I lose motivation and turn to his little sister, who has just woken up. She's only three and easy to impress.

Sasolburg-Prieska

My wife and I doze off in the car and wake up when we arrive at Johannesburg's Oliver Tambo International Airport. We board a plane back to Cape Town. Soon after take-off, I see in the distance what is likely to be the town of Sasolburg[138]. Tall chimneys like towers, characteristic of a chemical plant, can be seen in the distance. It is the site where South Africa first started producing fuels and chemicals 94 years ago[139]. At the start of the 2000s, the fuel and chemical industry in South Africa contributed more to CO_2 emissions than 100 small countries[140]. Today the situation is much better. In fact, 200 km away in Secunda[141], which used to be the highest CO_2-emitting single plant on the planet[142], the first sustainable aviation fuel was produced from green hydrogen and biomass being the carbon source[143].

Impressions of Secunda-based industry in 2020s. Source: Ecoloy & Evolution

Nowadays, approximately half of the site's 8,000 barrels per day is referred to as sustainable aviation fuel. It fuels this very plane we are in. When I booked our tickets, I made sure the flight was carbon-neutral, as is standard practice[144].

We fly southwest over two distinctive large pipelines emerging east-to-west from the plant. At this altitude they are still clearly visible. These pipelines transport hydrogen from the solar-abundant hydrogen hubs in the Northern Cape, to export ports at the coast and industrial users mainly in the Gauteng and Mpumalanga provinces. They remind me of pipelines I once saw carrying gas to Mozambique.

SASOL gas pipeline (Mozambique). Source: [wikimedia]

I fall asleep again and wake up again about halfway through our two-hour flight. We are almost directly over the town of Prieska in the Northern Cape. Prieska started producing green ammonia from renewable hydrogen 15 years ago. I look out through the small window and can make out the distinctive round crop circles along the notable twisting Orange River. Some square-shaped blue, greyish objects. These are undoubtedly large PV plants, or possibly concentrated solar power (CSP) plants[145]. Some of those are surely supplying solar power to the green ammonia plant's large electrolysers. Although it seems small by today's standards, more than 120,000 tonnes of green hydrogen is produced for the 70,000 tonnes of ammonia, which is exported though Boegoebaai and Saldanha ports. We fly past some of the great Karoo region. Once a dry, mostly unusable semi-desert mostly, it's now home to the country's biggest source of energy, made up of CSP, PV and gigawatt-scale wind farms, plus green hydrogen, ammonia, sustainable aviation fuel and e-methanol production plants for domestic use and exports. Ironically, years back it was hoped to be a source of natural gas.

Final thoughts

Although it started slowly, South Africa has evolved today be one of green hydrogen production hubs of the world. At the height of the fossil fuel era, South Africa's electricity was almost completely generated from coal. Today coal covers a quarter of power generation. Approximately 44 percent, or 40 GW, comes from wind and solar, with as much as 12 percent available from green imports[146]. These green imports, predominantly hydropower from East and West Africa, were a dream only 20 years ago. Today we boast the world's largest electricity network, connecting all of Africa and enabling green electricity trading[147]. The rest of our electricity comes from nuclear, hydro and biomass. An additional 47 GW of solar and 16 GW of wind power plants are dedicated to 28 GW of electrolysis. South Africa already surpassed its 2050 green hydrogen production targets and today exports almost 4 million tonnes of green hydrogen, as hydrogen, ammonia, methanol and sustainable fuels, through four major ports — Richards Bay, Coega, Saldanha and the newly completed dedicated hydrogen export port Boegoebaai. At one time we were home to the largest green ammonia plant in the world at Nelson Mandela Bay[148]. Today we export hydrogen for well below $1.2/kg. Our hydrogen economy has completely evolved and is still growing fast to meet demand from Europe and Asia[149].

* * *

My wife wakes me again. We've landed in Cape Town. After picking up our luggage we grab a cab home. At this point I am tired and just want to get home to a comfortable bed. Getting into our cab I notice it is a battery electric vehicle, as almost all cabs are. By habit, I check the information screen and notice sufficient charge for our trip. As we drive, I stare out the window and realise the number of hydrogen-fuelled transit buses we pass.

Today, almost all vehicles driving in and around our cities are battery electric, with most buses and trucks being hydrogen-fuelled. I remember the day I took my first trip on a hydrogen bus in Cape Town 19 years ago. Time has certainly not stood still, and luckily nor have technological advancements. South Africa, once struggling to take advantage of our immense renewable resources, today exports those renewable resources all over the world.

Uruguay, 2021 - 2031

Author: Pablo Ignacio Ferragut Varela

Talking hydrogen over coffee in 2021 and 2031

2021

Juan is on stage at a famous international conference, presenting the results of the successful energy transition in Uruguay to an enthusiastic audience.

"In the last three years, 98 percent of power in Uruguay was generated by renewable energy sources, being 55 percent hydro, 34 percent wind energy, 6 percent thermal-biomass, 3 percent solar PV, and only 2 percent thermal-fossil, used just for occasional backups[150]*,"* he says. *"Uruguay's wind energy is second in the world, only behind Denmark*[151]*, and is recognised for having made great progress in the energy transition. Not in vain, it is the best ranked Latin American country in the World Energy Council's Energy Trilemma Index*[152]*."*

Example of wind resources Uruguay. Source: earthisland.org

He pauses, and a long, loud applause invades the room. As he leaves the stage, people come to congratulate him, eager to exchange words as if he were a celebrity. He chats and thanks each of them. A bit overwhelmed after that, he quickly finds a quiet space for a breath and a coffee from the machine.

He takes a cup, a plate, and a sugar sachet and waits for his turn at the queue. A few people look at him, smiling approval at his presentation. He retrieves to a corner to drink his coffee in peace. But a shiver runs through his body when he sees a man with long thin fingers getting a coffee. He hears he hasn't heard in a long time, from a face that has terrified him in the past.

"You are wrong again!" the man says, approaching him.

Juan shakes and spills a bit of coffee

"Do you remember me?" the man continues. *"It has been a long time, I must congratulate you as many people are doing here. Or*

maybe you should congratulate me. I was right about more things than I could tell you last time. I told you that we would have a coffee again in 15 years, and a promise is a promise."

Before answering, Juan realises the man seems not to have aged even a minute since their last encounter. He's still lean, with an imposing presence, delicate features, and a peaceful but sharp way expression of a man who has seen everything.

"Of course, I remember, although I tried to forget," Juan replies, steadying himself. *" But I'm still wondering if that encounter was a real one."*

"How do you explain the two cups of coffee on your desk? In fact, I forgot to say 'thank you' back then. I apologise," the man said.

"But...who are you?"

"It doesn't matter. I only can tell you that I have seen the future, and it is magnificent, my friend," the man says with a smile.

Juan finds himself once again questioning whether he's actually speaking to someone, or imagining it. He starts to edge away, but the man gets closer.

"You are wrong again," the man says. *"You, in Uruguay, have transformed the power generation matrix and reduced and stabilised the cost of supply. This is a great achievement, and for sure these are the foundations to continue building.* However, *40 percent of your energy matrix still comes imported hydrocarbons, mostly for transportation*[153]*. As I told you last time, you should take a look at domestic resources."*

Juan takes the bait, answering with some apathy.

"We were not successful with the oil and gas offshore exploration campaign, despite our hopes," Juan replies.

"No, no, no. I am not talking about that, I am talking about green hydrogen potential," he man replies, raising his voice. *"Listen to me. Uruguay has 180,000 square km of land, low population density,*

and an incredible complementarity between wind and solar PV energy that together can reach a load factors around 60 percent[154]*. This would allow a high utilisation level of the electrolysers*[155]*."*

"I think that you are daydreaming," Juan says. *"I have heard that the cost of production of green hydrogen is about $3-8/kg* H_2[156]*."*

The man smiles. *"I think you reasoned similarly last time. You said the levelised cost of solar PV energy was around $500/MWh, and more than $100/MWh for onshore wind energy*[157]*. You said the only possible solution was to increase thermal-fossil fuel power capacity, or even opt for nuclear energy. You're making me laugh — again! Look at what happened with your predictions, and your presentation today."*

He pauses for effect. *"Electricity is by far the main cost of green hydrogen, and as you can see, things have changed dramatically fast in the last 15 years. They're going to change even faster in the next 15."*

Juan takes a breath. *"But you need lots of water, and the electrolysers are pretty costly too, or am I wrong again?"*

"Well, you don't need that much water," the man replies. *"This is a myth; you can travel almost 100 km in a hydrogen-fuelled car with just one bucket of water*[158]*, and there are huge amounts of water everywhere in Uruguay*[159]*. There will be so many green hydrogen projects around the world in the next few years, the cost of the electrolysers will fall drastically*[160]*."*

Juan is now lost for words, so the mysterious man continues. *"I will be very concrete: Under certain conditions, such as parallel global scaling of electrolysis*[161]*, if you install 2 GW of electrolysing capacity, powered by a combined 2 GW of onshore wind power and 2 GW of solar PV, you will be able to produce 200,000 tonnes of hydrogen per year and reach the magical competitive benchmark of $1.5/kg*$H_2$ *by 2030*[162]*."*

Juan, still lost for words and feeling touched in this intellectual fencing combat, comes back with a challenge. *"Well, this is a lot of energy, but who would consume so much hydrogen in Uruguay anyway?"*

"You are right on that," the man replies. The potential domestic demand for the transport sector by 2025 is about 150,000 tonnes of H_2[163]."

Before giving him time to reply, he continues. *"It needs to be developed for exports. That will create space for the development of an internal market in Uruguay and niche use cases for hydrogen, mainly in transport and industry and more traditional areas such as ammonia for fertilisers. Is the agricultural sector no the main exporter in your country?"*

"But … do you think there will be so much demand worldwide?"

"Well, you are committing the same mistake you committed last time," the man said. *"The past is a great school to learn from, but please don't project it into the future. The future of energy will look very different. decarbonisation is one of the most relevant topics on the European political agenda today; they will be hungry for hydrogen. You should look at the largest European ports – Rotterdam or Hamburg. Sure there will be lots of investors and off-takers looking for opportunities, looking towards countries like Uruguay."*

The man continued enthusiastically, without losing his thoughtful tone. *"Do you realise that Uruguay has many advantages? It's a reliable and stable country with a strong institutional framework. The transition of its power sector has created incredible opportunities. It's become a great place to invest, as exemplified by offshore oil exploration here. Some of the largest companies in the world came to an unknown province of Uruguay; the same companies that are now committed to net-zero emissions and are now investing in renewables and carbon capture and storage.*

The same areas that were tendered for offshore exploration could be now offered for offshore wind farms and hydrogen islands."

"*Well, but then one needs to develop offshore wind infrastructure, and ..."* Juan trailed off.

The man jumped in. *"Please, do not stress about the cost of developing offshore wind. It's true that the average can be around $80/MWh today*[164]*, but these costs will fall rapidly, and you can have load factors over 55 percent in your offshore wind platforms*[165]."

Both were silence for a moment.

"So if I understand correctly, you're saying that Uruguay has the right conditions to attract massive investments to produce green hydrogen at a competitive cost," Juan says. *"Hydrogen that could replace most of the imported hydrocarbons in the heavy transport sector, which represents only 4 percent of all the motorised vehicles but 36 percent of greenhouse gas emissions*[166]*, while creating quality jobs for our people?"*

"Local investments of at least $3.2–6.2 billion in the next 20 years are easily feasible[167]*,"* the man says, as Juan nods. *"It's good to see you finally understand. Imagine what the future could hold — adding up the potential to produce fertilisers, methanol for bunkering ships, or even synfuels for aviation."*

"Well, you told me that you have seen the future," Juan says. *"So how does it look exactly?"*

The man looks uncomfortable but also accustomed to the question.

"I cannot tell you that," he replies. *"I will lose my (mental) power to jump through time if I do so. I can only tell you that as has happened in past energy transitions; the sources and technologies that solve the problems of their time are the ones that finally dominate. The big problem of your time is decarbonisation. Don't you think that hydrogen has enough attributes to help us solve*

this problem? Don't you think Uruguay has a great opportunity to position itself in this new technological global wave?"

Silence.

The man continues. "*You will need to move fast; there are too many horses running this race. I'm sorry I cannot tell you more, but we are going to have another coffee together in 10 years.*"

Juan turned away to rest the empty coffee cup on the table. When he turned back, the man had vanished. Recovering from shock, Juan spotted a high-level government official looking at him in astonishment.

When he realises why, Juan points to the dirty cup the man left on the table. But the official still looked confused. Juan, without leaving room to be interrogated about the episode, rapidly said to the official, *"You know? We need to continue working on an ambitious green hydrogen strategy*[168]*,"* and gave him a long explanation that the official could barely follow.

December 2031

Juan is giving a presentation to a European delegation visiting a conference titled 'Global Hydrogen: Latin American edition'. He explains how Uruguay implemented its national hydrogen strategy back in 2020s.

It started with the H_2U project[169], which was supported by the government and state-owned energy companies. This helped to test the technology and create knowledge and capabilities to scale up future developments. The pilot project was in itself quite small, producing green hydrogen for around 10 heavy buses and road trucks with an electrolysing capacity of 1.5 MW. The project was awarded to a private company in a competitive auction, with more than 60 companies showing interest.

This is how Uruguay's hydrogen future took hold.

Juan also ran through the National Oil Company's initiative early in the 2020s to attract investment for the development of offshore wind farms dedicated to hydrogen production. The development was built in areas that decades before had been used for oil and gas exploration, taking advantage of the knowledge acquired about the climate, sea and seabed conditions during the exploration campaigns[170]. He mentions a few other initiatives developed, including the green hydrogen exports to the European mainland through the Port of Rotterdam[171].

Finally, he closed the presentation exultantly. *"Uruguay has grown into a large green hydrogen exporter while advancing the decarbonisation of transport and industry and solving a 100-year problem of costly oil imports. Green hydrogen is no longer a dream, but a reality that is helping drive jobs and opportunities in our country."*

Soon after, he notices a tall, lean man sitting at the meeting table, initiating the applause. He eagerly to his seat, ready to talk again with the man who hadn't changed about over the last 10 years. But when he looked again, the man had already vanished, leaving only dirty cup of coffee on the table.

Chile, 2030 - 2040

Author: Eric Ehrhardt

Over the next few pages, I'm going to take you across the extremely diverse and beautiful 4430 km of Chile. All the way from the northern red-rock deserts to the lush southern valleys full of lakes and glaciers. We'll make sure to stop by the bustling capital of Santiago with the Andes on one side and the Pacific on the other.

Chile is at a time of transition; it's reaching for energy independence through clean energy. The new policies and strategies are shaping up to be some of the most forward-thinking in the world concerning the environment and the role energy plays. We'll be looking at how hydrogen could develop in Chile over the coming years.

Different locations of the story. Source: Google Earth

Have you ever wondered what a country that runs completely on clean energy might look like? Chile in 10 years just might be one of the first. Let's travel to that time in the Atacama desert. Then we'll jump through time twice more, to Santiago and Patagonia, to give you a feel of the possibilities of hydrogen in Chile. Through the stories, we'll look at hydrogen through the lens of locals across the country. Let's go.

2030. Atacama Desert

Atacama Desert. Source: Google Earth

The distinct red sands of Chile's largest desert battered my helmet's visor as I sped up and down the dunes. My hydrogen-powered all-terrain vehicle (ATV) roared as I pushed it to its limits. It had already taken me most of the way on my 70 km rocky trip from the closest town of Calama. With the sun beating down you could tell that the most powerful solar radiation on the planet is found in Chile's north (>30-35 percent solar load)[172].

I was on my way to the recently expanded Cerro Dominador Solar Power Plant, which the Chilean government bought from a Spanish energy provider a few years ago. It was the country's first big step to energy independence. It's been my job to oversee all the green hydrogen plants that added to the growing solar fields. I'm typically working from the office, but every now and then I like to get out and see the plants for myself.

The goal to reach 25 GW of electrolysis capacity by 2030 was set after the National Hydrogen Strategy[173] . It keeps me busy. My mind started to drift thinking about how far we've come. But before I could indulge in memories too much, my partner Martin came in over the radio "*Alejandra, I see it, it's just over the ridge.*"

As I reached the top of the hill, there it was -the concentrating solar power (CSP) plant. It's beautiful in a way, it looks like a mosaic made up of thousands of solar panels all facing the central tower. Despite having visited the plant the previous year it looks like it has doubled in size. It's mesmerising. I wanted to pause there to take it all in, but Martin was already speeding down the dune.

Martin is my right-hand man, he's the technical specialist when it comes to anything hydrogen and has more energy than anyone I know. Good thing he does, because we have received new solar-to-hydrogen plant proposals every six months from developers. The progress is incredible, I just wish I had Martin's energy to keep up.

On our way to the hydrogen plant, we made sure to keep our distance from the panels so as not to cover them in sand. We passed the massive 1 GW electrolyser installations each capable of producing 0.15 million tonnes of hydrogen a year. That's equivalent to two coal-fired power plants or power for 750,000 homes[174].

We went inside. Mercifully the air conditioning was blasting - a perk of affordable energy. We were greeted by the plant manager, a former supervisor at the Ventanas coal plant down in the Valparaíso Region, which was phased out six years ago. Martin wasted no time, before the manager could say anything more than 'hello,' Martin asked, "*So how's the production start looking? Have we finalised installing the 5 GW? Have we started shipping hydrogen out to Antofagasta?*"

The manager, obviously a little overwhelmed, took a second to gather his thoughts. "*Yes, sir, everything has been running better than expected, the last installations were made last week and our electrolyser capacity is now just over 5 GW. The current batch of hydrogen supply is already flowing through the pipeline, we're also filling up some tankers headed to Mejillones with liquid hydrogen for exports*[175]."

My home town of Antofagasta is next to Mejillones, on the Chilean coast some 130 km from the plant. In the past few years, they've seen millions of dollars in investment, having become one of the main export shipping hubs for the hydrogen being produced.

"*That's great to hear,*" Martin replied. *"Could you give us a ride around the production plant, as our ATVs will to need a refill as well.*"

The plant manager nodded, and we set off. We couldn't stay long because we were planning to visit the Bolero solar plant some 75 km south. Martin was like a kid in a candy shop as we drove around the plant. He asked questions non-stop, from the electrolyser to the tanker loading area (which included liquefaction and compression installations for filling tankers, depending on the needs of clients), and back to the control rooms.

I had prepared a surprise I was sure would leave Martin at a loss for words. We walked through the solar field, and there it was: a state of the art hydrogen helicopter[176]. Martin was overcome with excitement, spouting facts to no one in particular. "D*id you know the hydrogen fuel system in this has four times the energy density of existing lithium-ion batteries*[177]*?!*" We made our way to the helicopter and boarded for the short trip to Bolero.

Up in the air, looking down at the mosaic of solar panels and the fields full of installed electrolyser installations, nicely blended into the surrounding nature, I thought back to where it had all comes from. It still blew me away how an element so simple could be harnessed to revolutionise a country's energy supply and uses.

Now we race forward in time and make our way south to the heart of Chile, Santiago.

2040: Santiago City Centre

As soon as I open the door to the apartment building, the sounds of the city flood in. I put my headphones on and step out into the bustling street, headed for the metro. Ever since Chile became a major green hydrogen exporter, Santiago has exploded with investment and people. I still can't believe the city is on track to reach 10 million inhabitants by the end of the year. I walk down the steps of the metro and can already hear the high-pitched whining of the trains as they rush past. I get down to the platform and glance at the updated metro map. Two new lines have been added in the last year. The steady hydrogen and renewable energy supply have fuelled the expansion of the metro in the past few years from 100 km of rail to 175 km[178]. Better yet, the government keeps dropping ticket prices because it's so affordable to run the trains, and it's helping to get cars off the street.

I step into the train and find a seat, they're much more comfortable than the older models. They had to switch out the older carriages to work with the new high-speed electric tracks. Now the metro accounts for 5 percent of the domestic energy usage[179].

The light in the carriage flickers, just a faulty bulb but it makes me think back to the daily power cuts we used to endure. Those days are behind Chile, thanks to the backup hydrogen cells. Whenever there is an excess of renewable power that isn't sold directly on a centralised power market or used, it is stored in hydrogen tanks[180]. With every building in Santiago being topped with solar panels that problem is more common than you'd think. I remember three years ago when we got hit by one of the biggest storms of the last decade, a significant portion of the renewables infrastructure was damaged, solar panels and wind turbines alike. The hydrogen reserves are what kept the country running during the rebuilding period.

I've been an energy trader for the past 10 years. The industry grew exponentially once Chile made strides on its hydrogen plans and became a net exporter of energy. I can barely keep up nowadays, with green hydrogen dropping close to $1/kg, as Chile has become one of the leading exporters of energy in the world. Chile and Santiago in particular are flourishing, but everyone in South America wants to repeat the success.

Today I have been invited, as a senior expert, to speak with Peru's energy minister. Peru has been looking to us, their neighbours in the south, and taken an interest in investing in a green hydrogen project on the border of our two nations. Being immersed in the world of energy, specifically hydrogen, it was my job to clear up any doubts they have about the project and green hydrogen as a whole.

The phone rings, it's the energy minister calling. "*Como estai minister, I've been looking forward to speaking with you.*"

"*I'm doing well Vicente,*" the minister replies. *"Let's get right into it, I have some questions for you.*"

"*Sounds good, I'm here to tell you why green hydrogen is the right direction for both our countries.*"

"*Alright then. Why should we pursue green hydrogen rather than any other energy vector, given the high energy and water requirements?*" the minister asks.

"*Valid question. Our two countries are in a unique position. We have an expansive renewable energy capacity and untapped potential. In Chile we've utilised the coasts and mountains for wind power with attractive load factors of over 70 percent, vast deserts for solar with attractive load factors over 30 percent, and the spanning rivers for hydropower. Few countries on Earth rival our ecological diversity, our load factors and thus renewable energies we have access to. So, for Chile, the problem hasn't been generating renewable energy, it has been utilising it and storing that energy efficiently and effectively. It is all well and good to have 25 GW of solar energy capacity, but that clean energy doesn't transfer by itself into lowering the emissions of our mining operations or dropping the carbon footprint of home heating. It doesn't even really help Chile become a net energy exporter. That is where hydrogen molecules came in and helped build the Chile we live in today.*"

"*Well that covers some of my 'why' concerns, but what about the water costs?*" the minister says. *"As I understand it, electrolysers require freshwater for green hydrogen and lots of it.*"

"*This is true*[181]*, and it was one of the main concerns Chile had when committing to green hydrogen,"* I say. *"However, research showed that desalination was the answer. With less than 1 percent of the world water being fresh we decided to keep the burden off the people's water supply. We found that the power required to run desalination plants was at most 0.13 percent of the energy required to run the electrolysers, so the choice was simple. Even from an economic perspective desalination added no more than $0.01/kg*[182] *to the cost of hydrogen production which enables us to stay below our $1.5/kg goal.*"

"*That's all very compelling Vincente, I have to think it over. If Peru did decide to partner with Chile on a project, what could we expect?*"

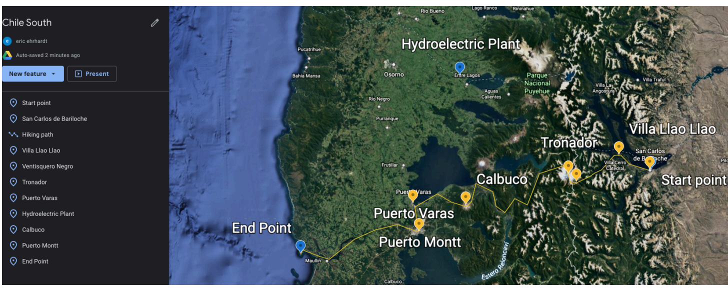
"*I'm not sure if you know this Minister, but green hydrogen can be used to create green ammonia. So the hydrogen we'd produce on our border doesn't have to necessarily go towards the energy grids. I know Peru has been trying to reduce its carbon footprint, and the green ammonia, which is used in the fertiliser industry, would go a long way in dropping the environmental impact of your large agriculture industry. Like my father used to say, 'Technology is mouldable'. Green hydrogen is no exception.*"

"T*hank you Vincente,"* the energy minister replied. *"I hadn't thought of that connection and am sure that'll factor into our decision. Thank you for the information, we'll talk again soon.*"

Moving on, we make our way further south to the beautiful Chilean Patagonia.

2030: Chilean Patagonia

I'm so glad I'm finally getting the chance to climb Volcán Calbuco, it's giving me time to clear my head and admire the countryside. The air is thinner up here at 2,000 metres, regardless the breeze feels like it goes right through my coat.



Chilean Patagonia. Source: Google Earth

Dotting the countryside below me are wind turbines, most of them supplying the power to the neighbouring green hydrogen plant. They're becoming more common, as I get closer to the coast where the bulk of them are, most feed the 4 GW green hydrogen production facility there. The towering 120-metre turbines cast a shadow across the valleys, where you can see the herds of Guanaco grazing on the picturesque landscape.

I'm six days into my 10-day hike, I'm on the back end of my 240 km from the Argentinean border to the Chilean coast. Cerro Tronador gave me some trouble, being 3,500 metres high, but Calbuco is a walk in the park in comparison. I reach the peak and look out over the valley; I just barely spot the hydroelectric dam in Pilmaiquén with my binoculars. It provides over 310 GWh a year[183] so it was one of the first to get a hydrogen production facility next to it.

I start making my way down the other side of the mountain, looking ahead, and plotting my way through the boulders. There's a clearing coming up, which turns out to be a decommissioned copper mine. Surprisingly the air feels crisp and clean in the quarry. With the rise of the energy export era in Chile, we could afford to scale back the mining operations. The drills, still active, have been switched over to electric or hydrogen cells limiting their environmental impact. The positive impact is easy to see in the recovery of the local wildlife.

Four days later

Lining the coast I can see not only the 120-metre offshore wind turbines, but also pipelines sending saltwater to the nearest desalination plant. Fifteen years ago, Chile wasn't even in the top 50 when it came to the percentage of energy consumption that came from renewable energy sources[184]. Now, Chile is in the top 15, in no small part, thanks to hydrogen. Through export profits being used to expand renewable energy infrastructure, Chile has preserved its environment and most importantly invested in the people, as the hydrogen economy brings jobs and opportunities.

Peru, 2032

Author: Rocío Salas

It's Friday, a normal summer day in Lima. January is known for being the best month in Peru to enjoy vacations with family. Marina, the most renowned researcher at the Glacier and Mountain Ecosystem Research Institute (INAIGEN)[185] is preparing to attend her last day of work before starting her vacation.

Today is special, she will be giving a speech to the Ministry of the Environment during the Commemoration Ceremony for the 10 years since the Supreme Decree No. 003-2022 MINAM was approved. The Decree declared a climate emergency in Peru and paved the way to urgently implement climate action measures in line with its Nationally Determined Contribution[186] to the Paris Agreement, which pledged to cut emissions by 40 percent by 2030 and reach carbon neutrality by 2050[187].

This was a milestone in the global fight against climate change. It also aligned Peru with the fulfilment of the UN's Sustainable Development Goals for 2030, the economic reactivation, the reduction of socioeconomic gaps, and the risks and vulnerabilities to the adverse effects of climate change. Among the national energy policy measures adopted, Peru's Ministry of Energy and Mines prioritised green hydrogen. Specifically, the *"design promotion programmes for the development of technologies, use and production of green hydrogen"*, and other measures promoting the use of renewable energy sources including *"the entry of electric vehicles, hybrids and [vehicles] powered by green hydrogen".*

The years following the Supreme Decree No. 003-2022 MINAM's approval saw the implementation of emblematic climate action projects in Peru and the accelerated development of the green hydrogen economy. To secure the commitment of all sectors in this crusade, researchers and scientists such as Marina presented the effects of climate change on Peruvian ecosystems. We got to where we are today thanks to the collaboration between the government, academia, private sector and civil society, who committed to developing the first pilot projects to integrate more renewable sources and reduce CO_2 emissions. This was particularly relevant for areas of protected nature reserves, with the goal of preserving beautiful Peruvian ecosystems such as the Amazon in the jungle; the Cordillera Blanca, with its system of mountains and lagoons; the highlands; and the hydro biological wealth of the Peruvian sea.

Such pilot projects will be replicated this decade, 2030-2040, in the main protected natural reserves of Peru, and will set the example for big economic sectors and cities.

* * *

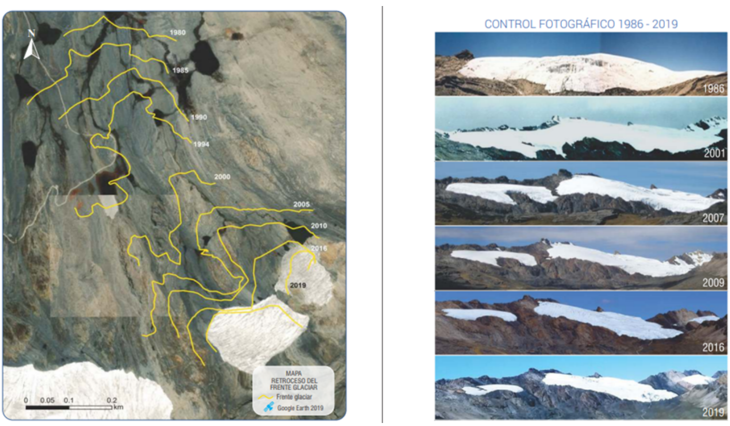
Marina's presentation begins with photos of the jungle, mountains and coast of Peru, and continues showing the conclusions of the publication *Pastoruri, 40 years of Glaciological Studies*[188] published in 2021. That marked the start of the Peruvian energy mix's entire transformation, which allowed Peru to achieve its Nationally Determined Contribution.

Landscape of MANU National Park located in Peruvian Jungle. Source: [peruincamagicadventure.com]

Landscape of Paracas National Reserve located in the coast of Peru. Source: [peruincamagicadventure.com]

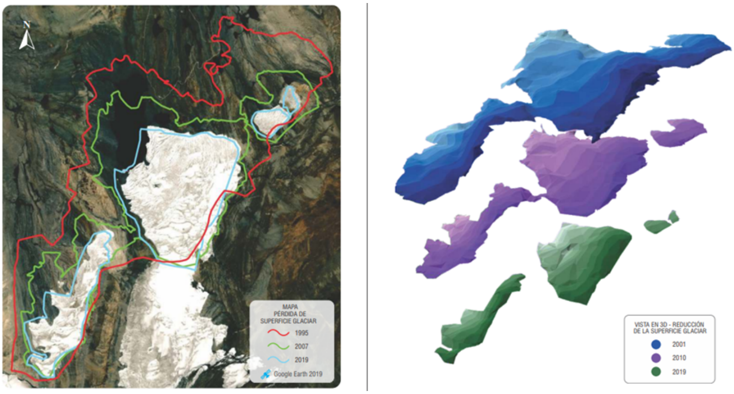
"*Pastoruri,*" Marina says, with a clear expression of nostalgia, "*used to be one of the most important tourist destinations in the Huascarán National Park. It later became a symbol for addressing the effects of climate change. International media such as National Geographic back in 2018 analysed this problem*[189]."

Front Retreat of the Pastoruri Glacier Peru, 1986 to 2019



Source: PASTORURI 40 years of glaciological studies/ National Water Authority. 1a. Ed. Huaraz: ANA, 2021

Reduction Area of the Pastoruri Glacier Peru, 1995 to 2019



Source: PASTORURI 40 years of glaciological studies/ National Water Authority. 1a. Ed. Huaraz: ANA, 2021

"*As can you see here, between 1980 and 2019 the glacier front receded by 651 metres,*" Marina continues. "*The average glacier retreat per year was 15 metres between 1980 and 1994. It increased to 23 metres per year between 2000 and 2019. Over 25 years, the Pastoruri mountain lost 70 percent of its glacial surface. This area gives Peru a natural competitive advantage and led us to become a leading producer of super foods that are highly valued around the world. So urgent action to preserve it became a priority. In this context, as well as the global energy transition towards net zero emissions, the 2022 Supreme Decree catalysed the changes we commemorate today.*"

The audience included distinguished academics who played key roles in advancing Peru's green hydrogen economy, including from the National University of Engineering. It's scientific research on the production and storage of green hydrogen and lithium batteries for electro-mobility has contributed significantly to Peru progress in the past decade. Dr. Arturo

Talledo Coronado, vice chancellor for research at the National University of Engineering, presented the university's plans and strategy with companies and Peruvian researchers in an interview with the Andean News Agency a decade ago[190]. Since then, Peruvian companies have approached the academy to form alliances to help them reduce emissions, contribute to the Sustainable Development Goals and help Peru meet its Nationally Determined Contribution.

Thus, in 2020s, the first pilot project was carried out in Pastoruri mountains in the Ancash Region, Marina noted. This promoted the use of green hydrogen in industrial processes, transportation, energy storage and mining for most activities in the area. One of the 10 largest mines in the world by production capacity is located in the Ancash Region, and was the most enthusiastic stakeholder to participate in the pilot project. The country's major steel producer and other representative industries in the region took part, too. In parallel, the public transport service and tourism buses incorporated electric and green hydrogen-fuelled vehicles into their fleets. Likewise, the minerals transport fleets, which mainly diesel, were replaced by green hydrogen vehicles. The generation of energy for mining operations was greened as well, in line with reaching carbon neutrality by 2040[191]. Providing thermal heating for homes in the Peruvian Andean highlands, where the temperature usually drops to below zero, was also a priority for the pilot projects, with strong support from the regional authority.

Other just transition initiatives were promoted to reduce the mortality of livestock as a result of climate change, such as raising vicuñas[192] and alpacas[193]. Vicuña fibre products are highly appreciated in the local market and abroad. The green hydrogen economy development was designed to ensure it did not affect water supplies or land use for traditional livestock activity.

Overall, the pilot projects' successful implementation in the Ancash Region proved it was possible to replicate the green hydrogen economy development in other protected natural areas that are highly sensitive to climate change. The sense of urgency that the approval of Supreme Decree No. 003-2022 MINAM provided allowed for the accelerated changes we commemorate today.

* * *

"*Peru was a pioneer in South America in the production of green hydrogen,"* Marina said, finishing off. *"The Cachimayo industries' ammonia plant, located in Cusco, has produced hydrogen using the electrolysis process since 1965, fed by a hydraulic power plant. Sixty-five years later, it's still going strong.*" Applause breaks out as she steps down.

Colombia, 2040

Author: Miguel Ballesteros

The following story will take you on a trip around Colombia, focusing on the Caribbean region in the north, which became the epicentre of the country's energy transition. Let us travel a couple of decades into the future and discover this place of abundant natural resources, with hydrogen as a nascent energy vector but aiming to become a mainstay for decades to come.

* * *

We left the apartment at 4:30 am on Friday, 13 January, 2040 to catch a 6 am flight from El Dorado airport in Bogotá, 2,500 metres above sea level. My family was excited to visit Cartagena, a magical city with a historical heritage and beautiful sunsets by the ocean. I like to teach my children about the places we visit, and had planned a special tour for them.

Julieta, our daughter, had recently turned six and liked to constantly ask questions about our surroundings. Luckily today not yet; she fell asleep in the taxi, warm despite it being 10°C outside. Arnold, however, looked out the window in surprise: "*Dad! We need to go back home, now!*"

"*Calm down champ, if we go back, we risk missing our flight. Did you forget something?*"

"*My iPad,*" he said despondently. *"I need it for my energy project, and it has important information I need while we visit the fields you promised me on this trip.*"

"*I brought mine, don't worry,*" I said. *"You can access your account and all the information will be there. That's why I always tell you to work in the SharePoint. Trust me, it will be alright.*"

"*Stop being so nerdy,*" grumbled Julieta, still half asleep.

At 5:30 am we were sitting on the plane, awaiting to take-off. I sat next to Arnold and Kathe, my wife, was in the row in front of us with Julieta.

I decided to help Arnold with his energy project.

"*Did you know that aviation, globally, is gradually becoming the mode of transport that emits the most* CO_2*? It's one of the greatest challenges remaining in reaching carbon neutrality by 2050. President Ivan Duque set that goal in 2021, alongside other countries at the UN's COP26 climate summit in Glasgow. Aviation is soon to become the most polluting mode of transport — not because it's getting worse, but because light passenger vehicles, trains and heavy trucks have been extensively decarbonised in the last couple of decades, thanks to alternatives such as fuel cell hydrogen electric vehicles. Traditional manufacturers like BMW and Toyota, as well as new entrants, have taken advantage of hydrogen costs around $4/kg. Coupled with its ability to last long-range, the fact that they are zero-emissions, and economies of scale, hydrogen has significantly reduced the purchase price for EVs*[194]*. That's why you can now see plenty of hydrogen refuelling stations in big cities, and why electric vehicle charging stations are now the norm. This was not really the case before you were born.*"

He watched me quietly, and I continued. *"Emissions from* *shipping and aviation have been more difficult to abate because clean fuel alternatives are less accessible. But hydrogen is a very versatile molecule. A few years ago, in Colombia, the first domestic commercial flight landed successfully using a sustainable fuel that combined hydrogen produced from renewable energy and sustainable carbon dioxide, captured from the air or from biomass emissions*[195]*. This is mixed with conventional kerosene to produce the synthetic kerosene that significantly reduces the carbon footprint. While sustainable aviation fuels are important, in other regions like Europe, hydrogen-powered flights have been deployed in the last decade, combining hydrogen combustion and fuel cells resulting in a highly-efficient hybrid-electric propulsion system for planes*[196]*. In the global mix, the aviation industry has tackled mostly medium-range aircraft. This is the segment that emits the most, so it helps to avoid hundreds of millions of tonnes of carbon dioxide using different types of hydrogen propulsion technologies, including a significant reduction in the mass of liquid hydrogen tanks*[197]*.*"

We were taking off as I paused, the sunrise shining across our seats. Arnold was already drafting the first part of his project.

"*Dear passengers, welcome to Cartagena, where the local temperature is 27°C and local time 7:30 am,*" the pilot announced.

We descended the plane and headed straight for a traditional breakfast of arepas and coffee to energise us. After unpacking and lathering up with sunscreen, we headed to the San Felipe Castle; a fortress erected during the Spanish colonial period in the 1500s. Before the arrival of Europeans, indigenous tribes in different parts of the country had a rich civilisation and culture, as evidenced by gold and clay relics now displayed in museums. They already used coal at the time to provide the heat required to mould materials and produce ceramics such as cooking utensils[198]. About five years ago, the way we use coal evolved to become a source of hydrogen production.

"*Are we going there on our trip?*" asked Arnold.

"*Yes, we will!*" I answered.

In the meantime, we looked out at the magnificent view Cartagena from the top of the castle. Towards the end of the day, full up on a lunch of fresh fish, we walked through the beautiful streets of the city, which was declared World Cultural Heritage Site[199] in 1984.

San Felipe de Barajas Castle. Source: Wikipedia

Cartagena. Source: unsplash.com

The next day we visited Barú and Rosario islands, with a spectacular show of dolphins and other marine life on the way. In Barú, we spent the day on the beach, Julieta covering her brother with sand until his face was barely visible. The colours of the sky turned reddish as the sunset approached and we hopped on the boat that took us back to Cartagena. Julieta was amazed with the immensity of the Atlantic Ocean.

"*That is why our geography teacher told us that Colombia is located in a blessed place with two oceans — the Atlantic and Pacific — and also many rivers that go through the Andes mountains!*" she said.

"*And that is very true,*" I answered. "*In fact, this is important for Arnold's energy project. Colombia has relied on its water resources for a very long time — 70 percent of its electricity was hydro-powered*[200] *in 2020. But that share has been largely replaced by wind and solar energy. That explains why we saw onshore wind turbines today and many buildings with solar panels. We'll also see enormous solar farms when we go to La Guajira.*"

* * *

The next day we prepared to go to Barranquilla.

"*Did you know that we are going to the city where Sofia Vergara was born?*" Kathe asked the kids, two blank stares looking back at her. They register more recognition when she adds that 62-year-old Shakira was born there too!

The bus to Barranquilla was one of around 4,000 hydrogen-fuelled heavy vehicles in the country. Since 2021, when Colombia's hydrogen roadmap[201] was launched, an increase of foreign investment and government support schemes allowed the country to meet its 2030 targets. It now boasts 2.5 GW of hydrogen capacity with electrolysers and a levelised cost of hydrogen (LCOE) of $1.7/kg, at least for the Caribbean region with the greatest renewable potential. The hydrogen used in this bus may have come from a green or blue hydrogen plant. Blue is considered low-carbon hydrogen, produced in a nearby Cartagena refinery using Steam Methane Reforming

— a process that makes hydrogen from natural gas paired with carbon capture, utilization and storage (CCUS). Two and a half hours later, we reached our destination.

We toured Barranquilla and visited Kathe's relatives. Preparations were underway for one of the major folkloric festivals in South America in a month. We visited the Bolivar Port[202] and had an interesting talk for Arnold's energy project. From this port, hundreds of millions of tonnes of coal have been exported overseas over the years. These resources have been essential to our economy, and we have reserves for 100 more years. But coal is the highest-emitting fossil fuel. So instead, the port recently started export hydrogen to China and Japan. Revenues from hydrogen are expected to eventually match the several billions of dollars from coal exports. Most of the new hydrogen demand is coming from Asia, but Europe will also be a significant importer, and this port will be critical for our economy. Julieta relished watching the ships, especially an enormous Newcastlemax vessel that would start its journey to Flushing in the Netherlands[203].

We spent one night in Barranquilla and left early the next morning for the coal mine *El Cerrejón*. To get there, we travelled around the Sierra Nevada de Santa Marta national park, characterised by the surprising proximity between the sea and snowy mountains. It was a long six-hour ride but the landscape was worth it. Kathe explained to the children that we were now close to the border with Venezuela; they were amused by the local accents.

"*Why is Colombia still producing coal?*" asked Arnold."*You said it's not good for the environment.*"

Production levels have decreased significantly in the last decade, but it remains a necessary energy source for energy security in some countries, especially those with a rapid population growth like Pakistan or India. And it still contributes to our GDP. Nevertheless, to reach carbon neutrality in 10 years, it is being significantly offset by CCUS technologies, in order to prevent CO_2 emissions.

"*You must remember I told you coal is now being used to produce hydrogen here with a gasification/conversion process where coal is heated to produce a syngas, rich in hydrogen but also CO and* CO_2*. That's why CCUS technologies*[204] [205] *are being employed, along with tax breaks*[206]*, for carbon dioxide sequestration to certify the exports as brown hydrogen,*" I answered. "*The storage potential from five suitable clusters of oil fields for enhanced oil recovery in the country is around 150 million tonnes of* CO_2[207]."

We explored the open pit mine, sweating under 38°C. The children were surprised by the dump tracks, dozers, excavators and other machinery. We also saw the unit trains that transport coal to the Bolivar port, where we were before, via a 200 km railway.

We then headed to Maicao for a rest after a long day. It was already evident from our few days here that the Caribbean region had become the epicentre of the energy transition in Colombia[208].

The next morning we left early and took a two and a half hour journey, looking out at wind and solar farms on the way, to Cabo de la Vela. It was a remote desert village with a world-class solar radiation and wind project, and a cultural hub for the indigenous Wayúu people. Most of the electricity supplying homes here comes from renewable energy. The first wind farm in the country was procured here in 2004, called Jepírachi, meaning "*winds from the Northeast*" in Wayúu dialect. No new projects were developed for almost two decades after that, but nowadays there are many more wind farms across the Caribbean region that account for a capacity of almost 2 GW. Combined with solar capacity, it amounts to several GWs of renewable power available for thousands of families, including those in rural areas that years ago did not have access to electricity.

"*How about the green hydrogen? Is it produced here to take advantage of all the renewable energy available in this region?*" asked Arnold.

"*That's correct - the country's cheapest green hydrogen is produced here! It provides international competitiveness for green hydrogen production, but still needs to scale up in order to meet the ambition of exporting it to many other countries. For instance, solar irradiance in the northern region of La Guajira*[209] *is around 2,000 kWh/m*^{2} *and the wind energy potential on the Atlantic coast alone is around 21 GW*[210]*. New technologies have emerged and now the electrolysis process, which separates oxygen and hydrogen with electricity coming from renewable energy, is much more cost-efficient.*"

"*I like hydrogen,*" said Julieta. "*It sounds like a very colourful molecule, like the rainbow over there,*" she continued, pointing at the beautiful rainbow that had appeared in front of us. It had started drizzling while we were talking, which was unusual since we were in the dry season and the Guajira region is generally very dry, with less than five days of rain per month during this season.

* * *

The competitiveness of hydrogen is allowing it to progressively dominate other applications such as shipping and other industries. So, Arnold and Julieta, you will witness much more progress as time goes by. It's satisfying to know that future generations will continue living sustainably and that global warming slowing, partially thanks to hydrogen.

This should be good for your energy project! In the meantime, let's continue enjoying our last few days in the Caribbean region. Our next adventure starts in the city of Santa Marta, where we will visit the Ciudad Perdida — or lost city. It's an old, remote city that some say existed before Machu Pichu and a magical place to discover after walking over four days through mountains and rivers. There is no phone signal or access to internet there, so this is the end for now!

United States, 2035

Author: Anne-Sophie Corbeau

Hydrogen in the United States, 2035

Flying in

I wake up with a start as the flight's steward announces we will arrive in New York City in 30 minutes. It is almost 5 pm. Unfortunately, that means it's 11 pm for the French frog, and I am starting to feel a bit jet-lagged. I should be used to it, it's been 14 years since I started regularly travelling between Paris where I live and the University of Columbia in New York.

I look out the window to find the offshore wind turbines[211]. The US East Coast has become a great resource for wind energy, with about 40 GW total[212]. The turbines are giants, towering 150 m high[213]. They provide clean power to New York City and the whole state, and produce green hydrogen.

I hear the noise of the engines preparing to land, and think that for all the things achieved over the past decade or so, we still don't have long-range hydrogen planes that can cross the Atlantic Ocean, despite some attempts from aeroplane manufacturers since the early 2020s[214] to develop the first zero-emission aircraft by 2035. It's too bad, I was a big fan of some of the concepts proposed. We have seen a handful of prototypes using hydrogen for short range travel[215] within Europe and within North America but the technology has not massively taken off so far for the general public.

I'm not surprised, aviation was always going to be one of hardest of the so-called hard-to-abate sectors to convince and to convert. For the moment, it seems that biofuels for aviation are still in the lead followed by synthetic fuels. It's a semi-victory, as these synthetic fuels are based on hydrogen: we are using power-to-liquid technology to produce green hydrogen and combine it with carbon dioxide, which has been captured. It's a bit expensive, but considering that today the price of carbon in Europe and North America is $260/tonne (about $200/tonne in 2022 dollars), what is expensive is all relative. It was only $100/tonne CO_2 at the end of 2021.

Loving trains, taxis and trucks

Checking my watch, I think about ordering a hydrogen taxi to get to my hotel downtown, but the traffic looks pretty congested. So I opt for my second favourite option – the hydrogen train[216] running from Jamaica Station to Penn Station. I have loved this train since the first day I took it; it was a few years ago but it seems ages ago. Replacing the old diesel trains on one of busiest commuter rails in North America with these brand hydrogen trains was ambitious, but it worked out and the public loves them. The design has not massively changed since those first models, they still have the hydrogen tanks on the rooftop. Not only are they quiet (a big difference from the previous ones), but also fast and clean. They only emit water vapour. They can also be refilled quickly, in about 15 minutes. Other train lines subsequently switched to hydrogen, not only in New York but across the country. California was one of the first to move, having been a prime mover in hydrogen development, including for trains, after years of consideration[217]. The use of hydrogen for trains provided a predictable but also substantial demand for hydrogen. That predictability and the fact that the first generation of trains had a range of over 1,000 km simplified the logistics of supplying hydrogen in the early days.

H_2 train. Source: Maxpixel

Tomorrow I will certainly hop into a hydrogen taxi to go to my meetings around the city. Even though the take-off of hydrogen in private cars has been modest due to the prevalence of electric vehicles and the lack of a widespread deployment of refuelling stations, hydrogen taxis have thrived. The shift to hydrogen taxis was easier, as companies could set up refuelling stations at a few strategic points around the city, such as airports.

I remember taking a hydrogen taxi for the first time in 2021, by coincidence when the rapid train in Paris was disrupted and and I had to switch to a taxi. To my delight, it was a Hype taxi based on a Toyota Mirai[218]. The driver was surprised I knew it was a fuel cell car. I was apparently the first person to ever tell him that. I had been pleasantly surprised by how quiet they were and still are. At that time, the cost of hydrogen in Paris was €12/kg. The tank on that first generation of Mirai could hold 4.6 kg, which would cost around €55 to refill[219]. Since then the cost has dropped significantly worldwide and refuelling infrastructure has spread. In New York, the number of hydrogen buses is also rising. They beat electric buses on one critical item: the charging time. Electric bus fleet operators need to operate larger fleets to compensate for the charging times, and charging depots occupy valuable space in a city as crowded as New York.

The other part of the transport sector that started using a lot of hydrogen in the United States is long-haul transport. As soon as a few trucks models started to appear[220], there had been buy in from a few key transport companies, eager to improve their green credentials. There was even a competition between drivers on who would have the funniest "*I drive a hydrogen truck*" logo. This adoption of trucks had contributed to bring their total cost of ownership (TCO) down to the level of diesel trucks before 2030, making the economic switch easier. Of course, these trucks needed to refill, despite their 800-mile operating range. Such a range is made possible by the use of liquid hydrogen, with the four tanks stored right behind the truck's cab. Meanwhile the refilling had been facilitated by the simultaneous development of hydrogen highways along specific corridors[221].

H_2 truck. Source: Wikimedia

Back to the future: Why the second hydrogen revolution succeeded

But I digress, as usual. I always tend to think about the transport sector first. After all, I did start my hydrogen career in 1999 by working for original equipment manufacturers (OEMs), and married a car engineer. This brings me back down memory lane. That was what people called "*the previous wave*" of hydrogen, which did not lead to a massive take-off of this energy vector. There was very little talk about electrolysis and its potential at that time. To be frank, I ran into hydrogen because I ran into fuel cells. People were talking more about fuel cells and how they could be used than about hydrogen. At that time, my job as a young engineer working for OEMs in Germany and then in France consisted of understanding the reforming process to produce hydrogen and trying to see whether we could have an on-board reforming system within a car. Looking back at my young self[222], it's crazy to think of all the options we were looking at that did not materialise.

Fortunately for the world, the situation changed course in the late 2010s and on the way to COP26 in Glasgow. When I look back at the past 13 years of our hydrogen journey, I can't help by marvel at the progress we have made collectively. In 2020, the United States was consuming just above 10 million tonnes of hydrogen and was one of the largest consumers of hydrogen in the world, only second to China. At that time, hydrogen was consumed mostly in refining and to produce ammonia or methanol. Besides, it was mostly grey hydrogen as we called it back then and therefore the source of CO_2 emissions. Around 80 percent of US hydrogen production was based on natural gas reforming. A lot was needed to convert that to renewable and low-carbon hydrogen.

The early 2020s was a period of euphoria quickly followed by constructive realism about what was needed to build a hydrogen economy and increase clean hydrogen production, not only in the United States but elsewhere in the world. Back in 2021, significant funding started to be allocated to hydrogen, both in countries that wanted to use the fuel as well as in potential producers and exporters.

In 2021, the US government launched the first Energy Earth-shot focusing on hydrogen. The target was to achieve a cost of clean hydrogen of $1/kg within a decade[223]. This has almost been achieved. Then the Bipartisan Infrastructure Law dedicated $9.5

billion to clean hydrogen, including $8 billion with the target to develop at least four hydrogen hubs. But one of the most essential actions was an agreement on the hydrogen production tax credits that would support the uptake of clean hydrogen. It was critical to spur investments. What I always liked about the US approach was that it was colour-blind. In Europe, the priority was clearly put on green hydrogen, and by green I mean supported by solar or wind. The US decided to focus on the carbon intensity, which gave blue hydrogen a chance while also boosting the development of green hydrogen by reducing the cost of electrolysers and renewable electricity.

I remember visiting Plug Power's green hydrogen project in Western New York[224] when it started. It was then one of the largest green hydrogen plants in the United States, with a 120 MW electrolyser powered by hydropower from Niagara Falls and producing 45 tonnes per day, or around 16,500 tonnes per year — a fraction of the hydrogen demand back then. It seems so ridiculously small now as electrolysers have grown to several GWs, but at that time it was tremendous progress.

A lot of work has been done to incentivise hydrogen demand as well. In the last decade we saw a lot of testing for different applications, various segments of the transport sector, high grade industrial heat, power generation to complement renewables and trials to blend hydrogen into the natural gas system. That has enabled a much faster development of hydrogen since 2030, as some anticipated[225].

Some American cities have been leading on both hydrogen and renewables since the very beginning. As New York state boosted renewables to 70 percent of its electricity in 2031 (just past the 2030 target, but nobody complained), some hydrogen was needed to provide flexibility to the grid. Using electrolysis, the renewable electricity was used to produce green hydrogen in order to manage the intermittency and store the high volumes of energy for when demand was high.

* * *

As I turned on my laptop to do some writing, my mind wandered to the hydrogen revolution in the 2030s.

Demand for hydrogen has picked up strongly across the United States since 2030, like in the rest the world. It's almost doubled since 2020. The country is using a majority of clean hydrogen powered by a mix of solar, wind and even biomass. A large part of hydrogen demand still comes from traditional sectors, such as ammonia production. But demand has expanded beyond these sectors to entirely new applications. What surprised me most was that the expansion to new uses was not easy, partly because it was detrimental to the fossil fuel industry.

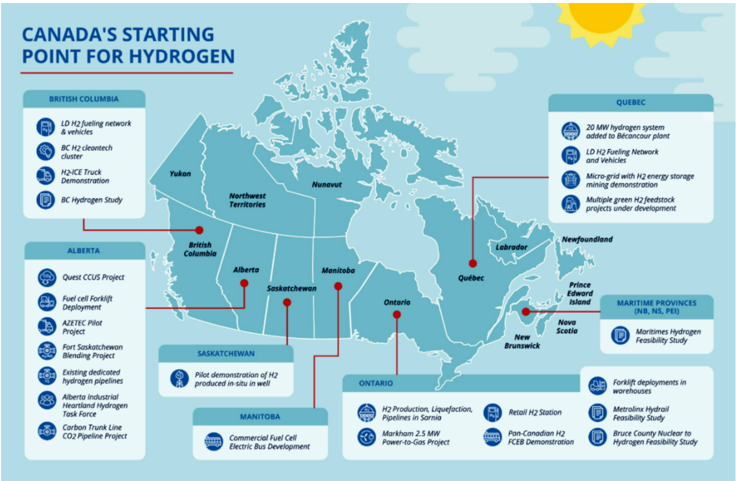
Nonetheless, I am confident that we are now on the right path to decarbonisation.

Canada, 2040

Author: Robin Macpherson

Breaking the vestiges of carbon economy in air

I generally don't do very well in lotteries, or at least that is the reason I normally give to myself for not entering them. But something about the prize – the opportunity to be a passenger on the maiden voyage of a hydrogen powered flight[226] from the east to west coast – piqued my interest. Partly because I love seeing the vast expanses of Canada from the air, but also because it seemed exciting to venture out on what could be a real hope to break one of the last vestiges of the old carbon economy. The flight wasn't just the usual Toronto to Vancouver shuttle that criss-crosses this enormous country multiple times each day. No, this was the Hydrogen Special Charter that would zigzag its way east to west, taking in all that enabled Canada to become the hydrogen powerhouse that it is by 2040.



Canada's 2020s hydrogen strategy. Source: Hydrogen Strategy for Canada[227]

After an unusually short taxi to the runway — presumably we were given preferential treatment by the control tower — the low hum of the engines powered by a mix of synthetic fuels[228] (one of them being a derivative of hydrogen) propels us forward. Soon we are airborne and leaving the big city lights of Toronto behind us, as we set course north-east for Quebec and the wilds of Atlantic Canada.

Quebec: Green hydrogen, sourced in hydropower, helping in hard-to-decarbonise sectors

An hour or so into the flight, we come across the first of several huge hydroelectric facilities in Quebec and Atlantic Canada which forms one of the backbones to the Canadian hydrogen story. Built originally as pure power generators that could serve the province but also send renewable energy to the power-hungry US east coast, the advent of green hydrogen has seen the power diverted instead to industrial scale electrolysers. Using water and clean electricity the electrolysers produce green hydrogen for energy intensive long-haul trucking and mining operations – both sectors feature in the hard-to-decarbonise category which has enabled notable reductions in Canada's carbon emissions. Before heading inland, our flight heads south, crossing over the St. Lawrence gateway to the Atlantic where plans are afoot to develop new port capacity to further use green hydrogen for export to the European, and Asian demand centres.

Ontario: Nuclear powered hydrogen powerhouse

Heading westbound we are soon back over Ontario. While the province may not quite be able to match neighbouring Quebec for hydroelectric output, it more than makes up for it with emission-free nuclear generating capacity. Ontario has seized on green hydrogen production as a means to effectively combine ample freshwater from the Great Lakes with the surplus baseload output from the nuclear fleet to develop a regional hydrogen hub. With close proximity to a number of demand centres both in Canada and the US, Ontario has developed infrastructure to move green hydrogen to meet the needs for a range of end uses. Perhaps most significant has been the expansion of green hydrogen as a heat source and feedstock to the heavy industry in southwest Ontario[229].

Trucks winning the hydrogen prize in Prairies

Having taken all this in, we leave behind the urban centres of Ontario and begin our journey across the vast open spaces of the Prairies. Even here though there is evidence of the hydrogen revolution that has taken place as we look down and spot the occasional 'fast-fill' facilities that have popped up to support the long-haul trucks which run on hydrogen fuel cells. While electric batteries have mostly won the day for the light-vehicle market, hydrogen has proved highly attractive for the high-energy consuming heavy-duty trucks where the alternative battery units proved too cumbersome. This, combined with faster fuelling times for hydrogen has seen an ever increasing number of long-haul trucks make the hydrogen conversion, supported by a rollout of fast-fill infrastructure to meet the demand.

Alberta: Home of blue hydrogen

As the aircraft slowly turns northwest, the resource-rich lands of Alberta come into sight and we begin to see the other side of the hydrogen revolution in Canada: blue hydrogen. Extensive natural gas reserves in the region meant that as soon as carbon capture and storage technology was proven[230], Alberta became an obvious place for blue hydrogen production. Favourable geology in the region provides good access to salt caverns for the carbon storage and hydrogen (in separate caverns), which drives down costs and further improves the competitiveness of locally produced blue hydrogen. Once produced, the legacy of the oil and gas in the region means there is existing pipeline infrastructure which can be leveraged for shipping blue hydrogen to the west coast export terminals and other end users.

Vancouver: Final thoughts on creating green economy from vestiges of carbon world

After taking in the splendour of the Rockies - which never fail to amaze, no matter how many times I see them – the captain announces that we will shortly begin our descent into Vancouver, and the end of our maiden long-haul hydrogen-powered flight. The sightseeing isn't entirely over though as we fly over several more hydroelectric facilities, now paired with electrolysers, which supply emissions-free public transport throughout the region.

As we touch down I am in a reflective mood on what has been achieved with low-carbon hydrogen. Perhaps the most striking thought is how it has leveraged existing and legacy infrastructure with new technology to make such a significant contribution to the transition to a low-carbon economy, creating green jobs out of vestiges of the carbon world.

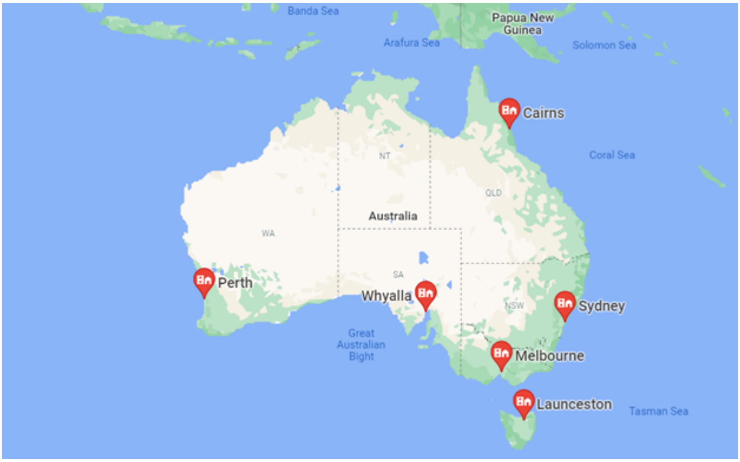
Australia, 2040

Author: David Sheipouri

Just a bit on Australia: The smallest continent; the sixth-largest country

Our journey takes us all the way to Australia – the land down under. A continent of harsh, arid plains and gentle, embracing coasts. A mysterious land of deep, ancient connections with Aboriginal ancestors dating back over 40,000 years. An ecosystem of unique wildlife, from hopping Kangaroos to semiaquatic, egg-laying, duck-billed, Platypus – not to mention, all the spiders and snakes!

At 7,692,024 km^2, Australia accounts for 5 percent of the world's land area, is the smallest of all continents, but also the largest of all islands and the 6th-largest country. Things are a little different when it comes to population though. Ranked 55th by population size, there are only three people per square km of land in Australia – that's Iceland's level of crowding. That said, much of the land is barren and 85 percent of all Australians live within 50 km of the coastline, which may explain those golden tans.



Overview of the 2040 journey. Source: google maps

The Australia-shaped souvenir clock of my grandfather

It's 2040, we're only 10 years away from our net-zero targets[231], and what a ride it has been. For some it was the best of times, and for others it was the worst of times. Much like *A Tale of Two Cities*, radical change and transformation was the only way anything could survive.

The Covid-19 era has become but a fleeting memory, taking with it policies and attitudes we would rather forget we held at all. No more hiding behind others when it came to global climate change forums.

Australia was a place I always heard stories about as a child, so much so I felt like I had lived there a million lifetimes ago. My grandfather was one of the early engineers heralded as the founders of Australia's gas exploration and export boom in the late 1980s. He would never shy away from a good story. As he sunk into his equally tired couch, his hands, equally scorched as the ground he once tread, would reach over and grasp the Australia-shaped souvenir clock sitting on the television cabinet.

"*I have a story for every hour on this clock,*" he would exclaim, life beaming from behind his magnificent green eyes. By the time I knew myself, I had all but felt the radiant beams of sun burning away at the back of my neck, all but surfed the most pristine of golden beaches, all but driven through the vast, red plains and all but bitten into the saltiest of Vegemite[232] sandwiches.

"*We made that place what it is today,*" his voice only prouder when talking about the sacrifices Grandma had made for the family while he was working. A quiet confidence would roll into his grin, "*World's largest exporter of LNG! All they knew was coal and iron ore, coal and iron ore, occasionally gold, but always coal and iron ore. Sometimes copper, but always, always, always, coal and iron ore*!" He wasn't wrong, even in 2020 iron ore accounted for over 21 percent of Australia's total exports at A$100 billion, coal over 11 percent at A$54 billion and LNG closely behind at 10 percent for A$47 billion[233].

The years passed, and the second-hand memories grew fonder, as I watched the hours on the clock turn to my 21st birthday. Mum had warned me that this year everyone pooled in some funds, and I only have one present to open. This had to be the first example of our family being able to agree on something, so I was equal parts excited and worried.

"*Open it, open it,*" the crowd chanted as Mum handed over the oddly shaped present. Is this what it feels like to be on a game show? As the first bead of nervous sweet formed on my forehead I locked eyes with what I could only describe as a child at Christmas inside the body of a pensioner. He's behind it, I know it. The familiar grin rolling up his creased face, now nodding with persuasion.

Carefully, I pried the tape from the paper, making sure not to ruin the only present I would see this year. It's the clock. It's the clock? It's Grandpa's Australia-shaped novelty souvenir clock, gifted to him by his Australian colleagues. OK, that's an honour, but I must be missing something, the clock means much more to him than it does me. Maybe the card will tell me more? Seems thick ... money? OK, money makes sense. Just as all the ideas on what I could spend the money on flicked through my mind like a slide show, out slipped the ticket. A ticket, on its own such a limp, lifeless product. No taste, no smell, no sound, and hardly a desirable texture. Australia! I'm going to Australia! I am going to, AUSTRALIA! Cheers broke out and the bead of sweat transformed into a welling up of my eyes, as if it had reabsorbed itself and found its rightful home.

A heavy hand rested on my shoulder, the grip – firm and familiar. "*I've made you a plan,*" in all the commotion I hadn't noticed Grandpa sneak up behind me. "*The clock, it will be your guide and with time, it will become the filling cabinet of your memories.*" We spent what felt like a few minutes, discussing all the amazing destinations scattered around the clock's face, it seemed to disagree with us, striking midnight as if to mark a turn of the page into a new chapter.

"*I've let everyone know my grandson is finally coming and to take good care of you,*" Grandpa said.

"*Everyone? Who's everyone?*"

"*My old oil and gas buddies, they're not all still in the same roles or* *in the same states but Australia has done well to use their knowledge – you might even learn something.*" Cue rolling grin.

OK, Grandpa was well-loved and well-connected. This should be interesting.

"*Just follow the clock and tell them Uncle Paul sent you, they'll take care of the rest. Lord knows I've saved a few nephews in my time,*" he continued.

With that the adventure starts, just follow the clock – let's go! Airbus? Boeing? I hadn't even noticed; all I knew was that I was finally on my way!

Far North Queensland, Cairns: From diesel to a weekly hydrogen truck

My first stop is in far north of Queensland, known more colloquially as The FNQ by the locals. Cairns airport is bustling with tourists, it seems that UNESCO's recommendations in protecting the Great Barrier Reef are paying their dividends[234]. Between all the tour bus drivers I see my name in big bold letters, BENJAMIN! Exhale. Sigh of relief, they didn't forget! A warm, friendly smile lights up his face. "*G'day mate! I'm Timmy, you must be Uncle Paulo's favourite grandson, Benny. Welcome to Cairns mate and watch out for the banana benders.*"

If all I had to go by was his bellowing laugh that followed, I knew I was in good hands. Timmy was overflowing with stories about the good old days, it seemed he had a special place in his heart for Grandpa and their time on major LNG projects.

"*That's all changed now, mate. We're all about green up here now – even the off-gridders have turned.*" He went on into colourful detail on how the coal-fired power stations wrapped up their operations in Queensland with all the wind and solar farms being installed. "*They never had a chance mate; it was only a matter of time – they held on for a while, I'd give 'em that,*" he said as he stared out into the horizon. "*Once they got electrolysers and hydrogen storage to the right price it was practically game over from there*[235]*.*"

It turned out Jimmy had never shaken the old days from his heart, which was perhaps why he held Grandpa to such high regard. With coal-fired power generation becoming too expensive to continue, the Australian government kept the industry alive with subsidies over the years[236]. This was only until energy storage reached a scale ready enough to take over. From there, any time the wind stopped blowing or the sun stopped shining, it was covered by hydrogen. Even remote communities switched the diesel delivery truck with a weekly hydrogen truck, turning up to top-up their hydrogen reserves until they had enough renewables and storage to be truly independent.

"*We're not getting outages any more and my clothes don't stink of diesel, so that's a win.*" His laugh this time forgot to bellow. Although Timmy was a huge asset to the transition away from fossil fuels and they consulted with him for decades, it seemed the familiarity of a bygone day was hard to shake.

I was taken by Timmy's experience, it seemed time and tide waited for no man and even something so astonishing as the transition in Queensland, took with it a silent casualty. It was time to follow the clock that also did not wait.

New South Wales, Sydney: Blending natural gas wealth with green hydrogen

Landing in Sydney I was welcomed by Michael, not as colourful this time. Michael was a financial manager on projects Grandpa worked on and it turned out they didn't always see eye-to-eye.

"*He was a larger-than-life character, occasionally even too large for his own boots,*" his tone unchanged throughout the entire monologue. "*Times change, Benjamin – everything has an expiry date, even you and me. It would only be an obscure act of wilful ignorance to think otherwise.*"

If I called him calculated it would have been an understatement. His stories broke down every step he took in navigating the energy transition his industry had faced with surgical precision. "*Yesterday I was presenting exploration figures to investors, promising them all the wealth the Earth concealed, today I'm presenting investors models to dilute that same wealth with green hydrogen.*"

For Michael it seemed increasingly obvious that his business of blending hydrogen was a matter of pure economics. When the renewables were producing more power than the consumers were using, his solar and wind farms would divert the energy into electrolysers. The electrolysers produced the hydrogen and instead of needing to store it at a central location, he would blend it into the natural gas pipelines. Helping save the environment was, for him, a side effect.

"*275 petajoules, peta – that's a trillion times kilo, 275 trillion kilojoules. That's how much natural gas storage is available on this great country. More than all the gas every house and business in Australia uses in an entire year*[237]." He went on to describe how he influenced an entire nation into accepting blended hydrogen into their household and into their appliances, made fortunes by balancing the electricity market whilst securing gas supply to Australia.

"*My next target is the aviation fuel industry. I'm going to blend them too. My hydrogen is worth far more per kg that way, and I will get paid to take the* CO_2 *from prehistoric businesses still handling fossil fuels. Once we create the aviation fuel from mixing my hydrogen and their* CO_2*, we can sell the responsible flying dream*[238]."

It was calculated, the details were colder than the first plunge into a swimming pool on a summer's day. But once your hair was wet it started to make some sense. Michael was an industrious man, where there was money to be made, he was there. For the sake of the environment, we were lucky that making money was a side effect. Time was ticking and we had to move.

Victoria, Melbourne: Home of hot fashion, fine coffee and converted oil and gas rigs

Now 2,950 km away following a hydrogen-fuelled plane flight, I emerged in Melbourne and immediately notice three differences: the weather was cooler, the fashion was hotter, and an intoxicating aroma of coffee seemed to swirl around me like the southern lights – Aurora Australis!

Abraham was at the gate, as promised. He'd arrived two hours before I was scheduled to land in case something happened. His build was slight and his stature strong, forged from the beating of a laborious life. "*Benjamin, finally mate, I was a minute away from calling your Grandpa!*"

Abe, as I was instructed to call him, was an astute man, alert as a fox at mealtime. All his years as a safety officer on major projects around the world had raised his resting vigilant level to Meerkat status.

"*He always knew what he was doing and had a funny way of getting anything done, regardless of the years he took off my life in the process,*" he said as a fondness relaxed the muscles in his neck. "*You wouldn't get away with half of what your Grandpa used to get away with, these days – that's all I'll say.*"

Ten minutes later he proved it wasn't all he would say, and the next three hours confirmed it. "*But that's all in the past, our systems are so protected now that you couldn't flush a toilet twice without an executive order from the UN General Assembly.*"

Abe found himself in an interesting position over the energy transition. His extensive experience on oil rigs and on renewable energy projects made him a shoo-in for his role. "*We took all the oil and gas assets that I worked long and hard making sure were built to the highest standards and converted them to be clean. Offshore oil production platforms turned into wind turbine platforms*[239]*, crude oil storage tanks now hold liquid organic hydrogen carriers*[240] *and gas compressor stations now refuel hydrogen cars, buses, trucks and boats.*"

Interestingly, Abe failed to mention was he was awarded a Medal of the Order of Australia for his service to the energy industry, both for building the original fossil fuel exports and transitioning it to where it stood now. Perhaps it had something to do with the A$75 billion he saved the government at the time in decommissioning liabilities[241].

From the world's largest island to the 26th largest, we are off to Tasmania!

Tasmania: The world hub for producing e-methanol as a game changer

Landing at Launcestone Airport I was surprised and a little confused by the amount of advertising space that energy companies had invested in. On every possible square centimetre was another company touting its latest project, in a rather polite and silent yelling match[242].

This time I was greeted by Franz, strong handshake, strong moustache, and strong appetite. "*Hello, welcome and good afternoon, Benjamin. It is remarkable to see you and fantastic you could make it all this way to visit. Please come with me in this way.*" His polite manner was oddly confident and disarming.

"*You have arrived in the world's most green energy and chemical hub ever created on the face of this wonderful planet. We take a lot of pride in our work and are working hard for the future of our great, great, great grandchildren.*" His unwavering facial expression underlined how serious he took his assignment. Franz was brilliant. If his aura didn't draw you in, his office decorated with awards and medals in chemistry would do.

"*Your grandfather is very much in my thoughts every day, without his belief in my work I would not have achieved half of this, even in two lifetimes. The old industry helped us understand, moved us out of the dark. Once we understood and could see, it would only be foolish to continue in the same way – for sure I am not washing my clothes by hand, this is the same. We must continue to use the tools we have now found in the light! Can you for even one moment imagine where this can take all of us? You could be Batman, Spiderman, Superman, whatever-man, Übermensch*[243]*, who knows – nobody, but it is our moral obligation and duty to light the candle for those who may follow, as those before us have lit for* *us.*"

It was rare that the man of so many words was also the man of many actions. Franz had pioneered the basis to commercial scale capture of carbon from the atmosphere[244]. Pairing his technology with green hydrogen produced by Tasmania's abundant hydro power meant they could produce a synthetic version of methanol without any fossil fuels - e-methanol. This not only changed the game, it also changed how the players played. Hydrogen was now transportable in the form of e-methanol. Ships now had an option to consume a green fuel in the form of e-methanol. Inks, solvents, resins, adhesives, and dyes had an option of using green raw materials in the form of e-methanol[245].

As it was built, so they came. Consumers no longer wanted products produced from fossil fuels, nor did they want their products shipped around the world on fossil fuel burning ships. This pulled the e-methanol and carbon capture industries into the market.

If I had stayed any longer in Franz's intoxicating company, I wouldn't have left – his passion, conviction and intentions meant his results would never amount in failure, but only varying levels of success. Our handshake on departure was as much a farewell as an early congratulations, and with that we fly back to the mainland and into South Australia.

South Australia, Whyalla: Hydrogen brought jobs and reduced risks of blackouts

Andrew waited by the gate in Whyalla; I could tell it was him from the alternation between confident overcompensation and nervous stammer in his voice on the phone the previous day. Stand up, sit down, check phone, re-check phone, sit down, bite nail, stand up, check flight information screen, check phone, drink of water, sit down – this was my guy.

"*Bennnnnjaminnnn, what took you so long, welcome, was the flight OK, the food is never good, I always eat before I fly, unless it's a short flight, then I would eat when I land in case I need to use the toilet and I don't have enough time because it's a short flight, even though I hate using the toilet on the plane, who knows who has sat on that seat, and that God-awful noise it makes feels like it's sucking the air out of the room. Anyway, are you hungry?*"

OK, I could tell I would be doing the listening on this trip.

Through all the noise, it turned out Andrew was in human resources and had worked with Grandpa in bringing the required talent to Australia in the early days while developing the local education curriculum to meet the industries' requirements.

"*I don't know how I always find myself in industries that are going through ridiculous amounts of change, it's like, can't you just sit still for a second? Are you trying to make my life difficult? I just want an easy life. Anyway, it pays the bills.*" Yep, more listening.

With all the changes in the energy industry, hydrogen had not only progressively become more available and more cost-effective than burning fossil fuels, consumer demand, much the same as the situation with e-methanol, had forced the industry to change its way. Hydrogen was now used to reduce the iron ore back to pure iron metal[246].

"*Our first step was to make sure everyone knew this didn't mean they would lose their jobs; it actually meant the plant would be upgraded and increase its output and there would be more jobs. Then we took all the people we had and offered them up-skilling, this meant that we had people who already knew the rest of the plant and only needed to be trained a little, delta-training. Most people went with that. The next step was to fill in any gaps of staff with local, national, and international employees.*

We're lucky the energy industry did a good job in influencing educational curriculums to meet their requirements. The effect was twofold, the more the hydrogen economy gained momentum the cheaper and more reliable our electricity also became. No more risks of blackouts! With the increase in our competitiveness, we then affected the manufacturing industries, and they love us to no-end now. It's a true win-win-wind-windsor-window-winter-wingardium levi ohhh saa. Anyway, everyone's happy."

Happy that everyone was happy, I took my happy self to the happy airport and on to the next happy destination. Final stop, Western Australia – The Wild West.

Western Australia: 'Go green or go home' is now a bumper sticker here

With a land area accounting for 32.9 percent of Australia[247], the state it would be ranked 11th in the world by size if it were its own country, and isn't so from lack of trying by the locals.

This time I was picked up by a limousine as my guide was too busy guiding his business. Chauffeur, complete with white gloves and black hat — I could get used to this. "*Any guest of Swiggy Norris is certainly a guest of ours,*" he calls out, as he watches for my response in the rear-view mirror and recognises the contemplative look on my face. "A*nd don't mind the coasters, Swiggy loves to put his face on everything.*"

Twenty minutes of enduring the driver's piercing looks and we arrive at what looked like an enormous cucumber protruding into the sky. "*Welcome to the big pickle.*" OK, I wasn't that far off.

I'm escorted into a high-speed elevator and whisked to what I imagine to be the stem of this magnificent vegetable, ears popping like corn kernels. The sliding doors give way to an open plan office with one long, long table, matching chairs and one man pacing back and forth on the serving end of a very robust telephone conversation. The longer it went on for the more air was sucked out of the room. No sooner was the call over that the grin I had come to memorise in the limousine was firmly back in its place.

"*Benjamin, welcome and please excuse the ramblings of an old man. Sometimes even our closest confidants mistake a garden path with a green one. Simple error happens to the best of us – just have to nip it in the bud.*"

Swiggy was a hospitable man, until he wasn't. I was lucky enough to be the grandson of the man who convinced him to enter the energy industry at precisely the right time, as it started to turn away from fossil fuels. "*I owe a lot to Paul, there's a man who can take a dressing down and understand it without taking it to heart. Everyone inside and outside this pickle is better off for it.*" Turns out Grandpa had his finger on a few pulses and knew the right people with enough courage and conviction. It also turns out that his final mark on this beautiful land was to instigate an evolution so great it revolutionised and eventually replaced the very industry he was heralded to have helped build.

"*Go green or go home – I'm having bumper stickers printed as we* *speak. I began by converting everything I own to run on hydrogen and its derivatives, and I have a lot of stuff – trust me, the diesel sales guys loved me. Mining trucks, converted. Power generation, converted. Bulk cargo trains, converted. Bulk carrier ships, converted. It wasn't enough though, we needed to get serious, we needed to scale it up, sell it overseas and reduce our costs per kg.*"

Swiggy did exactly what he set his mind to, he gave me a rundown of the last 20 years and how he persistently lobbied and inspired the change Australia needed. "*We went from exporting natural gas - your Grandpa's fault by the way - to exporting synthetic natural gas. All we did was combine hydrogen, green of course, and carbon we already had laying around, no ridiculous holes in the ground. That was fun, seeing the oil and gas codgers squirm in their seats. Then we combined hydrogen with nitrogen, plenty of it floating around, and made ammonia – no one asked for whom the bell tolls after that.*"

Harsh, but someone had to do it.

As the clock ran out of hours, it was time to bid this most amazing of lands and most brilliant of people a farewell. I would leave, owing the magical lands of the Northern Territory a well-deserved exploration at another time. I hadn't expected to learn as much I did, but it showed me that with every change there was an opportunity and no matter who you were or what you did, growth was an uncomfortable process.

As the plane's wheels lifted for the last time, so my mind wandered. "*For some, the opportunity of growth didn't start until it was more uncomfortable to stay still than to move. For others, growth was the only option and they knew to jump well before they were pushed. As for the politics of it all, let's just say that Australia went from being pushed to being the pusher.*"

Japan, 2030 - 2040

Author: Dan Shulman

Christmas reflections on the hydrogen economy of 2030s Japan

It was December 2040, and I was sitting by my small Christmas tree in Tokyo and reflecting on the progress of the hydrogen economy in Japan. It was warm and cosy in my beautiful but modestly sized lodgings.

Lodgings impression. Source: Author

Hydrogen in 2039 Japan

"From the beginning of the 2020s, soon after the Japanese government committed to carbon neutrality by 2050, it established hydrogen and ammonia as pillars of the new strategy to reach its environmental goals. The whole hydrogen supply chain was, however, close to non-existent and, despite numerous announcements, progress on this front has been slow. It is now 2039 and Japan is still slowly rolling out its hydrogen plan. By now, hydrogen is beginning to be used in co-firing in thermal plants, as well as in industrial processes such as the production of steel and fertilisers.

Most of the hydrogen is imported from Australia and the Middle East, with local production only in remote, sparsely populated areas.

From the beginning, the Ministry of Economy, Trade and Industry (METI) had planned to import most of the required hydrogen. In order to develop the supply chain, the environmental value of the hydrogen and ammonia was not the priority at first and grey hydrogen found its way into Japan. The Paris Climate Agreement's implementation and policymakers continued to influence the landscape, and you've seen for yourselves how things played out."

I still remember how Erik asked me to write something on the future of hydrogen, and I hesitated as I was slightly sceptical of how fast the hydrogen economy would really take root, and knowing how complex it is to design the correct incentives for industries to act, but I agreed nonetheless. My mind wandered again.

Back to 2021 and the original hydrogen strategy from METI

"METI had planned for hydrogen use to increase to 3 million tonnes per year by 2030, up 50 percent from 2 million tonnes at the time of the hydrogen strategy publication in 2021. This was followed by a 20 million tonne target for 2050.

The 2030 volume target was met, supported by generous subsidy programmes such as the $20 billion Green Innovation Fund (GIF)[248], which financed pilot hydrogen production and utilisation projects. By the end of 2021, the GIF had already allocated $3.4 billion to two major projects that will help create a large-scale hydrogen supply chain and develop hydrogen production through water electrolysis.

While volume was achieved, METI's hydrogen price targets proved more difficult. From 100 yen per normal cubic metre in 2021, METI expected the hydrogen price to fall by more than two thirds, to ¥30/Nm^3 in 2030 and further to ¥20/Nm^3 or less in 2050 – below *the natural gas cost forecast. It has been particularly difficult to achieve these numbers for CIF* (Cost, Insurance and Freight) *100 percent 'green' hydrogen.*

METI's plan also placed targets on the demand side of the supply chain with the development of 1,000 hydrogen stations for mobility in 2030; 800,000 fuel cell vehicles in use by 2030 and 2-3 million by 2040; 1,200 fuel cell buses by 2030; 10,000 fuel cell forklifts by 2030 and 5.3 million residential fuel cell units by the same year."

I reflected that, yes, incentives (grants and subsidies) do work to make the world move forward with plans. But still, markets have minds of their own. My mind wandered again – guided helpfully by my experience in business consulting - following the various sectors where the hydrogen economy was now touchable. My mind landed first on power generation.

Hydrogen and ammonia in the power generation industry

"Japan had traditionally been heavily dependent on coal and gas for baseload power, and 40 percent of its power still came from these fuels in 2030. Rather than replacing this capacity with non-despatchable renewable energy, Japan focused on reducing carbon emissions by mixing hydrogen and ammonia with gas and coal in its thermal plants. Companies like Mitsubishi Heavy Industries (MHI), Kawasaki Heavy Industries and IHI started developing co-firing turbines in the early 2020s.

For example, in January 2021, MHI jointly conducted an experiment with The National Institute of Advanced Industrial Science and Technology (AIST) and achieved stable combustion of hydrogen with a single-cylinder engine.

Momentum slowly built up, and in 2025 the first 30 percent *hydrogen co-firing turbine was commercialised. In 2030 large-scale 100 percent hydrogen-fired turbines were available. This technology was partly the result of the experience of Japanese industrial firms' involvement in foreign projects. MHI was involved in a project in the Netherlands to convert the LNG-fired Nuon Magnum Power Plant, with 440 MW in capacity, to a 100 percent hydrogen firing plant. In 2025, MHI had provided a turbine for an 840 MW gas plant co-firing 30 percent hydrogen in the USA.*

Nevertheless, the adoption of hydrogen and ammonia in the power generation sector was slow. By 2030, only 1 percent of the power mix came from these fuels. In the following years this number only slowly increased, with opposition to hydrogen from both politicians and the business world, which have questioned the environmental value of the technology. Green hydrogen is still not available in Japan at the price and scale that would be necessary to fully convert Japan's fossil fuel generation fleet and keep costs below ¥17/kWh (the original 2030 target from METI's plan). Many have argued that given the limited time and resources that Japan has to meet its environmental goals, other options might prove more efficient to decarbonise the energy mix whilst staying in the 3E+S framework[249] defined by METI."

The reflection of candles played in the windows; power generation was providing some light, and clean hydrogen was powering some of the turbines doing. Who could have imagined it?

Lighted city impression. Source: author's photo

My mind moved on to mobility.

Hydrogen and ammonia in the mobility industry

"Despite ambitious goals, individual fuel cell vehicles did not develop as expected. In 2021 there were 3,800 hydrogen cars in circulation in Japan and 162 fuel stations. The targets of 200,000 fuel cell vehicles by 2025 and 800,000 by 2030 were missed. The price premium to electric cars did not erode, and more importantly the lack of a supporting infrastructure did not favour hydrogen cars.

The incentives to push the adoption of electric vehicles, with their increasing role in the balancing of the grid and the emergence of new business models for vehicle-to-home and vehicle-to-grid after 2024, disrupted the adoption of hydrogen cars. The development of *hydrogen stations was slow from the beginning. By 2025 approximately 320 stations were developed and this number increased to 900 stations by 2030. The original plan was to stop government subsidies by the second half of the 2020s, but the lack of demand made this option unrealistic. The lack of scale did not allow for the cost reductions expected and the construction and operating costs failed to reach the ¥200 million and ¥15 million/year expected by 2025.*

However, while unsuccessful in the passenger vehicle market, hydrogen proved more successful in haulage and other long range, heavy vehicles, particularly in low density markets. In 2021 Tokyoites could already board one of the 104 hydrogen buses available in Japan. But today, it is places like Hokkaido that have really taken to the technology. The original 2030 target of 1,200 buses set by METI was met and the market has kept growing since. In these remote, low population density areas with few charging stations, the superior range of the hydrogen buses and trucks is a real advantage.

The cost of hydrogen buses decreased rapidly from about ¥105 million each in 2021 to ¥52.5 million by 2030, when government subsidies were stopped. Since then the market has grown steadily without subsidies."

A nice song in the background briefly caught my attention – Christmas radio was reaching its peak. I enjoyed taking the bus sometimes (and it was a hydrogen powered bus now). I didn't mind that my car was electric – heavy duty transport always looked to be a better option for hydrogen than personal vehicles. My mind wandered next to how we make things.

Hydrogen and ammonia in the steel and chemical industries

"In December 2021 METI released a technology roadmap for the chemical industry to reach carbon neutrality by 2050. On the whole, this has proved accurate, with the necessary R&D and pilot projects being financed by the Green Investment Fund in the 2020s as predicted, supported by study groups from major industry players such as Idemitsu, Iwatani, ENEOS, Nippon Steel, Mitsubishi Chemical, Air Liquid and others.

In the early 2030s, steam methane reforming was partially replaced with imported greener hydrogen. A few years later ammonia was used as fuel to power naphtha cracking furnaces.

Green hydrogen is also the basis for green methanol and other new low-carbon industrial applications. In steel making, hydrogen reduction is still in the early stage of application at Nippon Steel. Nippon Steel has spent several billion dollars in the past two decades to develop and apply this new technology and is now building the first equipment. It expects to spend several more tens of billions of dollars on CAPEX. The technology is an important element of its decarbonisation vision for 2050, published in 2021. Green imported ammonia is also now readily used in the production of fertilisers in Japan."

Christmas started banging on the door in the form of noise from my next-door neighbours' my home - lots of materials used, or consumed (e.g. in my fridge), were now in fact made with clean hydrogen behind them. What a hidden but interesting change. It was time to remember how the supply of all this greatness came about. My mind wandered once more.

Hydrogen and ammonia supply

"Looking back, it was clear from the initial green growth strategy and revised hydrogen strategy published by METI in 2021 that the Japanese government was relying on imports to cover the vast majority of its hydrogen needs.

Already in the 2020s several consortiums were developing pieces of the supply chain to bring hydrogen to Japan. Sumitomo, Chiyoda, Toyota and other members established a hydrogen import hub and distribution network in the Chubu area. ENEOS and Kawasaki city did the same for the Kawasaki waterfront area. Kawasaki Heavy Industry developed a liquid hydrogen carrier ship and joined forces with Iwatani Corporation, Shell Japan, and J-Power to pursue a liquid hydrogen supply chain.

Major Japanese players such as Iwatani and Mitsubishi Heavy Industries have been investing in brown and green hydrogen production projects in Australia since the 2020s and are now importing the fuel to Japan. The Kobe hydrogen terminal is one of the major hubs.

The Middle East is the other major partner in the Japanese hydrogen supply chain. By 2021, METI had signed a memorandum of cooperation with Adnoc to encourage cooperation in the field of fuel ammonia (both blue and green). The same year ENEOS signed a memorandum of understanding with Saudi Aramco to consider the development of a CO_2*-free hydrogen and ammonia supply chain. These partnerships have been key to building today's imports of hydrogen from these countries.*

Japan has also managed to develop some domestic hydrogen/ammonia production capacity. Companies like Asahi Kasei started to commercialise hydrogen production equipment back in 2025. The company scaled up operations and managed to drive production *costs down to ¥330/kg by 2030.*

There has also been progress in producing hydrogen in remote locations where local renewable power is available and transport costs make bringing in hydrogen expensive. In the 2020s the Green Innovation Fund financed R&D projects that supported local distributed generation capacity. It all started with pilot projects such as the one conducted by ENEOS and IHI who, in 2021, began development of hydrogen production in Fukuoka prefecture. The project made use of IHI's energy management system to control multiple renewable energy power sources simultaneously. It was conducted under a public-private partnership with the Ministry of Environment's supervision, and the involvement of the Fukuoka prefectural government and of several cities. Around the same time, Hokkaido EPCo and Nippon Steel Engineering began a similar project in Ishikari City, Hokkaido, with the aim of producing hydrogen from offshore wind (under NEDO subsidy). The task was daunting as initially green hydrogen production costs were more than three times higher than imported grey hydrogen. Today, after a cost reduction of over 50 percent for both CAPEX and OPEX and the optimisation of energy management systems to maximise the use of intermittent renewable power, the production of domestic hydrogen is competitive with imported alternatives."

As I emerged from my reverie, I tried to pull the thoughts together before departing for my neighbours' Christmas party. Today hydrogen is well integrated in the heavy industries and in remote areas with low population density. To reach this point in Japan the CIF price fell by almost 80 percent and strong political ties and joint investment with exporting countries was required, beginning in the early 2020s. Hydrogen has found its most victorious niche with buses and trucks in remote, low population density areas, not with personal cars. EVs have proven more attractive in most areas, due to cost advantages and a lack of hydrogen fuelling stations, as well as the integration and monetisation of electric cars in the power system.

I had to admit to myself that the CO_2 value ($CO_2e/kg\ H_2$) of the imported hydrogen is still an issue, and each source has a unique level. That affects the degree of decarbonisation at end use. For example, the co-firing of hydrogen at thermal power plants has made limited progress because of cost disadvantages and a lack of an effective carbon price until the mid-2030s.

Japanese green hydrogen production is cleaner and costs continue to fall, but until recently, it had remained at a relatively small-scale due to the limited availability of renewable energy. The latter did worry me as a citizen of the world and keen Paris Agreement fan. But since 2035, as the offshore wind sector has begun to grow in earnest, increasing volumes of surplus green wind power have provided a boost to Japan's green hydrogen sector, driving down power and hydrogen production costs at scale.

As the Christmas celebrations raucously continued, I felt hopeful for the hydrogen economy in its next decade – admittedly, racing much more slowly to its grand finale than many had anticipated in the 2020s.

China, 2030

Author: Joachim von Scheele

From biggest in grey to biggest in green

It is January 2030, and China is soon to become the world's largest economy and I am about to land in Beijing, and the skies are clear. I remember my Christmas prediction of 2021 that in China by 2030, green hydrogen capacity would reach about 5 million tonnes with a corresponding electrolyser capacity of about 80 GW. In particular it would service industry and heavy-duty transportation. And it's happening, according to my hydrogen community friends who invited me over for a professional seminar. My thoughts wander back to the winter of 2021-2022. I watch the screen of my laptop and my "hydrogen is going to be big in China" speech.

My 2021 speech. What role will hydrogen play in the transition?

"China is the world's largest emitter of CO_2, accounting for approximately 30 percent of global CO_2 emissions. Since 2000, more than 60 percent of the increase in global CO_2 emissions have taken place in China despite a 40 percent decrease in CO_2 intensity in the Chinese economy during that period. More than 80 percent of the CO_2 emissions in China are attributed to two key sectors, power generation and industry. The corresponding figure for the EU is 55 percent. In September 2020 President Xi announced a commitment to peak China's CO_2 emissions by 2030, at the latest, and become carbon neutral by 2060. This is of course an enormous challenge to fulfil, as President Xi noted. Will this even be possible to achieve? And what role will hydrogen play in this gigantic transition?"

My mind is briefly back in 2030 – yes, policy really mattered a lot.

And off again to nine years ago, on the laptop:

The policy framework

The 14th Five-Year Plan (14FYP) for 2021-2025 was launched in March 2021, clarifying the fundamental changes required to ensure that the Chinese energy system would rely on four key pillars:

1. *Improved energy-efficiency for both production and use*
2. *Electrified industry and transportation sectors, in conjunction with the decarbonisation of electricity supply*
3. *A greener energy supply with the increased use of renewables and natural gas and a significantly reduced use of coal*
4. *Strengthened research and innovation related to energy pro-*

duction and use.

In April 2021 President Xi said China would strictly limit the increase in coal consumption over the 14FYP and decrease it during the 15FYP. This implies an effort to peak coal consumption already in 2025.

To increase sustainability and reduce the carbon footprint, the following general hierarchical approach based on efficiency is principally applicable everywhere:

1. *Increase the life cycle of the products – a year longer in use saves a year of emissions from production*
2. *Increase the recycling rate – usually less impact compared to using virgin inputs*
3. *Electrify wherever it is viable to electrify*
4. *Increase the energy efficiency in processes that are not electrified*
5. *Replace a high-carbon containing fuel with a low-carbon containing fuel, and ultimately with hydrogen where that makes sense.*

Accordingly, it is important to note that the use of hydrogen is not the first action. We can clearly see much of China's laid out framework follows along this general approach.

There are several factors supporting a successful Chinese transition to carbon neutrality, for example:

- *The Chinese population is not growing much and will be contracting in the coming decades, probably already before 2030.*
- *Large investments in infrastructure made over recent years will not have to continue at the same pace, which will reduce the*

need for cement, steel, etc.

- *The focus on the domestic market rather than on exports, which began 15 years ago.*
- *The enormous increase in production of steel and other metals over the past 40 years, of which 80-90 percent has been based on virgin raw materials, can now to a continuously increasing extent be based on recycled materials. This will have a huge impact on reducing CO_2 emissions.*
- *The ongoing reduction of emissions from transportation, including the expansion of public transportation. The subway systems in Beijing and Shanghai are already the two largest in the world and the country is leading in the expansion of electric vehicle fleets and automotive assets utilisation (China is already number one in electric taxis).*
- *A massive expansion of nuclear power with almost 50 new reactors planned.*
- *Being world-leading in artificial intelligence and Big Data, which supports the creation of more efficient and optimised processes for production and uses.*
- *China is habituated to change; the Chinese people have huge experience in adapting to change, particularly over the past three to four decades."*

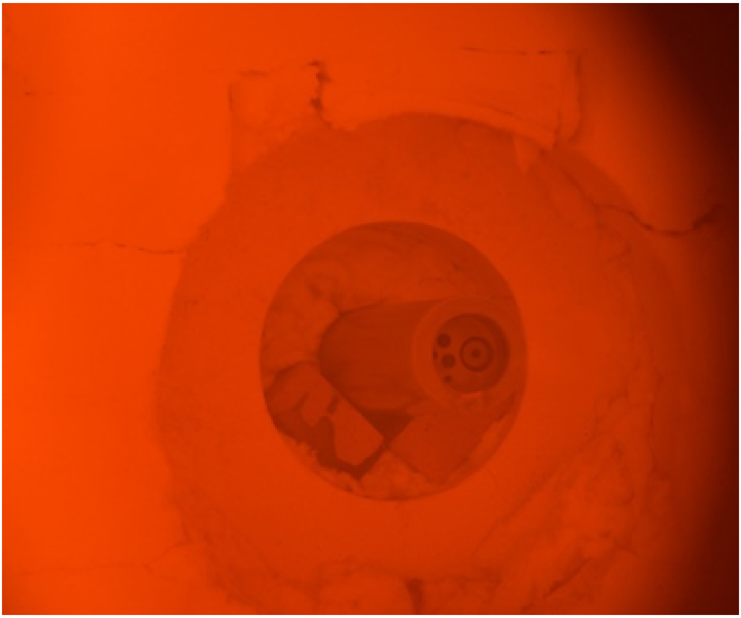
Again back in 2030, thoughts race to adaptability, ability to change which always has impressed me with China. This has been pronounced in the last decade with energy efficiency, dealing with volatile natural gas markets and electrification. Those three developments were the ecosystem success needed as a basis for hydrogen to become big in China. I jump back to my notes from nine years ago:

Decarbonisation will require energy efficiency, dealing with volatile natural gas markets and electrification

"It is of interest to compare China to the US and the EU. Two such parameters could be energy use per capita, and energy use compared to GDP (energy intensity). If we look at the per capita figures for 2020 the US is at 266 GJ/person, China at 104 and EU at 116. Accordingly, each US citizen is on average using about 2.5 times more energy than the average Chinese. But let us now also look at it from a GDP perspective in 2020. The US figure is about 4,200 GJ/$ while the corresponding Chinese figure is 9,900 and EU's 3,000. To be on the safe side, let us apply purchasing power parity on the Chinese figure – we then get about 6,000 GJ/$. Accordingly, in general terms we can then say that currently the US economy is at least about 50 percent more energy-efficient than the Chinese, and the EU is at least twice as energy-efficient as China's. In other words: clearly there is room for improvements of the Chinese energy-efficiency, even more than in many other industrialised countries.

Let us just make a quick back-of-the-envelope check of what could be possible. Assuming the Chinese economy will grow with a conservative compound annual growth rate (CAGR[250]) of 2.5 percent until 2060, its GDP will then be 2.5 times higher than what it is today. Reasonable efficiency improvements in China until 2060 could make it reach an energy-use compared to GDP (energy intensity) equal to the EU's today (3,000 GJ/$). That would mean that a richer China in 2060 would use 25 percent less energy than today. This is challenging, but doable!

In China there are more than 120,000 industrial furnaces in operation. The energy use in those furnaces accounts for more than 25 percent of the total energy use in China, and more than 60 percent of energy use in its industry. One of the proven ways to increase the *energy-efficiency here, is to modify the combustion system by using oxygen instead of air as the primary oxidiser, i.e., convert to so-called oxyfuel combustion. This would potentially result in a decrease of the fuel consumption and carbon footprint from those operations by 30 percent or more, and eventually with clean hydrogen as fuel eliminate it completely.*



Flameless oxyfuel can reduce fuel consumption massively in many furnaces and other processes using combustion, and it is ready to use hydrogen as fuel. Source: Author

Hebei province will screen out a total of 1,000 existing factories for replacement with less-polluting alternatives under the 14FYP, and *there are similar plans for each of China's 34 administrative areas. Under the 13FYP, concluded in 2020, Hebei reduced its installed cement production capacity by 12 Mt/year, which already has had a large positive impact as the cement industry is among the top three industrial emitters of CO_2. By comparison, this reduction in Hebei equals shutting down all of Canada's cement production.*

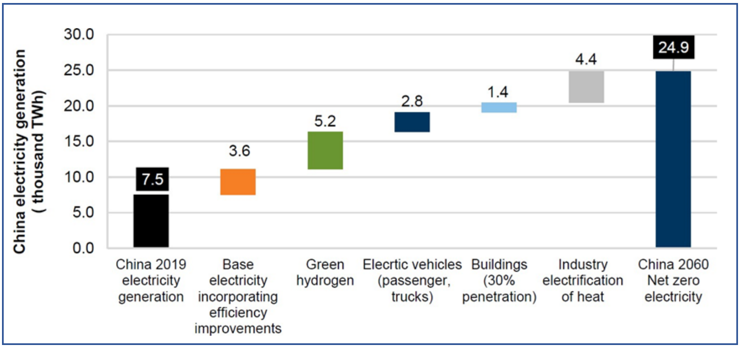
Another example is China's steel industry, today accounting for around 15 percent of the country's carbon emissions. There is now an ongoing expansion of China's electric arc furnace (EAF) steel-making capacity, allowing for the use of 100 percent recycled scrap as raw material, which will have a large positive impact on the carbon footprint. China plans to boost EAF steel production to account for 15–20 percent of its total crude steel output by 2025, which is a doubling compared to last year. Eventually, more than 50 percent of China's total crude steel capacity could come from EAFs. In 2021, China approved the construction of 43 new EAFs, with a total crude steel capacity of 30 Mt/year. To put this in perspective, a 30 Mt/year output equals that of the tenth largest steel producing country in the world.

Today less than 20 percent of China's steel production is based on scrap. The 2020 figure of 260 Mt of steel scrap used is aimed to increase to 320 Mt by 2025. Assuming a similar addition of scrap use going forward and that the Chinese steel production will stay at around 1 billion tonnes annually, around 70 percent will be based on scrap by 2060. This is a cautious estimate as it seems the domestic scrap supply could increase by 20 Mt//year every year from 2025 onwards. Now assuming that all the balance input would be supplied as Direct Reduced Iron (DRI) produced using hydrogen as reductant, those roughly 350 Mt of DRI would need 150 GW of electrolysers to produce the required 25 Mt of hydrogen. Adding 15 Mt to replace fossil fuel gases in combustion applications, we could then make

China's steel industry green using 40 Mt/year of hydrogen. This would require a power supply of 240 GW.

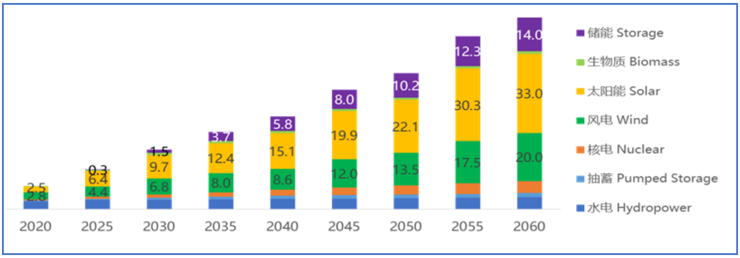
It seems we can assume a considerable part of China's decarbonisation might take place basically without changing fuels; mainly by increasing energy efficiency, reducing the use of coal-based processes, electrification, etc. Then, still before getting into hydrogen, there are two areas to touch upon: increased use of natural gas, and electrification. China has increased both its production and import of natural gas tremendously over the last years, and that trend seems to continue – now largely boosted by the decarbonisation agenda. The domestic natural gas production more than doubled from 2010 to 2020, reaching 192.5 billion cubic metres. 2020 imports reached 138.4 billion cubic metres, so altogether China used 331 billion cubic metres of natural gas in 2020. China's LNG import increased further to a new record in 2021.

Electrification will play a central role in China's pathway to carbon neutrality. Most forecasts indicate China's electricity consumption in 2050 could be doubled compared with the 2019 level, and even tripled by 2060, largely driven by transport, industrial sectors and applications of hydrogen produced from electricity.



A tripling of China's electricity generation estimated by 2060 (unit: 1000 TWh). Source: Author

An increased supply of non-fossil fuel electricity is important for both the electrification and production of clean hydrogen. From the 14FYP onwards, the use of new and green energy will increase to become the main energy sources. By 2030 the capacity of installed non-fossil fuel power is expected to reach 2,300 GW, accounting for over 60 percent of the total installed capacity. It will further increase to 6,500 GW, accounting for at least 80 percent (sometimes even 95 percent is suggested) of the total by 2060. To reach the goal of 1,200 GW of wind and solar capacity by 2030, as stated by President Xi at the UN Climate Ambition Summit in December 2020, it is estimated that as much as 5-20 percent in storage capacity needs to be developed at the local level, depending on local renewable resources. The current prioritisation can be seen from how China's finance ministry has set the 2022 renewable power subsidies: the allocated $607 million was distributed with 40 percent to wind turbines, 59 percent to solar power, and 1 percent to biomass power generators.



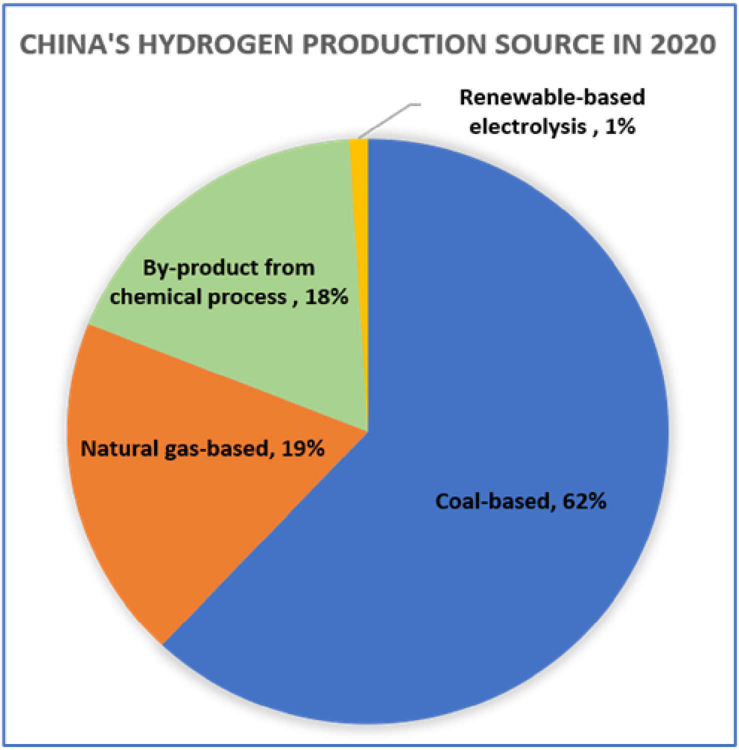
Forecast of non-fossil fuel power installed capacity 2020-2060 (unit 100 GW). Source: Author

Sinceyears, China has been at the centre of global supply and demand for renewable energy, accounting for about 40 percent of capacity growth from 2015 to 2020. Naturally, electrification through renewable power will be the technology that dominates the low-cost decarbonisation spectrum. It is believed it has the potential to support the decarbonisation of more than 45 percent of China's CO_2 emissions and, additionally, support the production of green hydrogen. Similar forecasts for clean hydrogen estimate this will drive 20 percent of the decarbonisation, playing a critical role in several industrial processes such as iron and steel and petrochemicals, and long-haul heavy transportation."

Back in the present, the pilot announces she wants to take another tour through the airport approach, as we are a bit early – this allows me to incidentally see some of the hydrogen economy in action. We are flying over a highway, where I notice some of the locally produced hydrogen-fuelled buses and trucks neatly traveling the road alongside electric personal cars. My mind wanders to my thoughts on hydrogen development in China back in those eventful early 2020s:

Hydrogen in China. By 2060, it may account for 130 million tonnes (about 20 percent of energy consumption)

"China is the largest hydrogen producing country in the world, with an annual production of roughly 30 million tonnes. In China, cheap supply of grey hydrogen is abundant from coal gasification, catalytic steam reforming of natural gas and as by-products of chemical processes, such as the partial oxidation of heavy oil. The production of blue hydrogen is still in an early developing stage, while the production of green hydrogen has been limited. Green hydrogen production based on electrolysis contributed only 1 percent of the total hydrogen supply in 2020. However, this is expected to increase to 15 percent by 2030. Hydrogen production as an independent component (non-syngas or in a mixture of gases) that meet industrial quality standards, normally referred to as merchant production, reached about 12.5 million tonnes.



The production of hydrogen in China by source in 2020. Source: Author

"China is keen to develop its natural gas infrastructure. The current pipeline network for hydrogen is limited. It is unlikely we will see a large parallel expansion of a pipeline network for hydrogen, but rather a blending of hydrogen with the natural gas in the increasing pipeline infrastructure.

The number of hydrogen fuel cell electric vehicles, mostly larger vehicles (buses and trucks) in China has grown rapidly since 2019, reaching over 7,000 by end of 2020. The number of fuel cell EVs *is expected to reach 1 million by 2035. When it comes to hydrogen refuelling stations, China today has about 100, however, Sinopec alone aims to add 1,000 during 14FYP. China's current vehicle fleet is about 300 million. Assuming it will increase to 500 million in 2060, 1 percent of fuel cell EVs would equal 5 million. China today has 300 million electric scooters, but it is unlikely fuel cell technology will compete much in that space.*

China's climate goals for 2030 and 2060, plus its ambition to accelerate its energy transition by increasing the total installed capacity of solar and wind to 1,200 GW by 2030, are the new policy drivers for green and high-quality hydrogen development. Specific targets for hydrogen development have been set up as an important component in China's short-term and long-term energy and climate transformation.

To realise the high ambition of green hydrogen development, a large amount of renewable electricity of high quality at a competitive price will be necessary, but also a key challenge. For instance, more than 70 percent of the cost of extracting hydrogen from water is electricity. It takes 50 kWh of electricity to produce 1 kg of hydrogen. Assuming over 5 million tonnes of green hydrogen in 2030, this means more than 260 TWh renewable electricity needs to be delivered. The critical factor is the electricity price, i.e., the scale-up of supply to meet all demands, not only for hydrogen.

Currently, average solar and wind on-grid prices are at $0.05-0.10/kWh in China. Estimates indicate renewable-to-hydrogen needs a renewable electricity price of $0.015/kWh to become competitive. The current production cost of green hydrogen in China is at $3/kg compared with just over $1/kg for hydrogen from coal.

As of 2020 the Chinese government had already invested more than $315 million in hydrogen energy and fuel cell R&D. In the 14FYP, increased financial funding will clearly target hydrogen *production and research and innovation. China's Ministry of Finance plans to appropriate $125 million for hydrogen R&D in four technical areas: green hydrogen production, safety storage system, energy efficiency upgrades, and 'hydrogen in to 10,000 homes' demonstration projects. In those four areas, 19 research and innovation programmes have already been launched in 2021.*

According to the China Hydrogen Alliance, in 2030 China's annual demand for hydrogen will reach 37 million tonnes, accounting for about 5 percent of the final energy consumption. By 2030, the green hydrogen would have reached about 5 million tonnes with a corresponding electrolysers capacity of about 80 GW. Under the carbon neutral scenario for 2060, China's annual demand for hydrogen would then have to be about 130 million tonnes, accounting for about 20 percent of the energy consumption. At least 100 million tonnes of that will be green hydrogen, and most of the balance will be blue hydrogen. Industrial use of hydrogen will still be the largest, accounting for 60 percent, while hydrogen in the transportation and building sectors will account for 30 percent."

The pilot now firmly asks us to fasten our seatbelts and prepare for landing. I'm thinking of what I will say at the seminar if they ask what I think of the role of hydrogen in China in last decade and going forward, as I will walk into the room full of students who are very critical and smart. I practise my response:

Hydrogen is a vector in the joint global village, not a sole or purely national solution

"Neither in China nor in most other countries of the world do we see hydrogen as a sole solution – today or in the coming decades.

Together with other ongoing sustainability trends – increased energy efficiency and electrification which play large and growing roles. As elsewhere in the world, the key to a viable supply of green hydrogen is a continuous and viable supply of green power (or at least non-fossil fuel power).

It appeared possible for China to make the enormous transition towards carbon neutrality, where hydrogen played and will play an essential role in that. This is despite China starting in the early 2020s from a position with comparatively low energy efficiency, 30 percent of the world's CO_2 emissions, and – despite being the largest hydrogen producing country – in a rather weak position for green hydrogen.

In the first 20-plus years of the century the world's wind power capacity has increased from 6 GW to 750 GW. A large part of this expansion had taken place in China, for example in 2021 having a capacity exceeding 300 GW. Looking towards the 2040s and the road ahead for green hydrogen, a similar development can be expected.

Please, remember how the journey with large-scale projects all started when Sinopec in the early 2020s announced a 20 kt/year electrolyser based on 300 MW of solar power to be commissioned in Xinjiang in 2023. Remember the forecasts saying that more than half of the world's electrolyser installations in the 2020s onwards would be taking place in China. Well you know how this played out.

Reducing the carbon footprint continues to be a task for our shared global village, where China and all other countries contribute to our common future. It seems China does and will do its part, with an *important and huge use of hydrogen across multiple sectors, and China will continue to transform from being the world's biggest producer of grey hydrogen to being the world's biggest producer of green hydrogen. Would you agree?"*

Yes, the projections have been fulfilled, and I felt happy to meet and discuss with the audience in the seminar. Indeed, t was going to be an inspiring and encouraging day in Beijing, jointly looking into a bright future.

* * *

Acknowledgement

The author is most thankful to Dr. Nannan Lundin and her colleagues at the Embassy of Sweden in Beijing and to Dr. Flora Kan and her colleagues at the EU-China Energy Cooperation Platform for their great support with input data.

Russia, 2040

Author: Irina Gaida

Russia: eight time zones of hydrogen and the Northern Sea Route

Life is good because one can travel

It's January 2040. I'm reading a quote on a poster in the train station, "*Life is good because one can travel,*" by a famous Russian traveller named Przevalsky[251]. I have just arrived by hydrogen powered high-speed train to St. Petersburg, a major hydrogen trading hub on the western border of Russia. Following oil, refined products and natural gas, spot and futures trade on hydrogen were introduced here as early as 2025 to facilitate both domestic and international hydrogen trading[252].

I arrived in St. Petersburg from Kaliningrad, also a hydrogen hub, where the first green hydrogen project was completed in 2024[253]. Later that day I will give a presentation reviewing how the hydrogen economy has developed in Russia in the last two decades.

I am reflecting on St. Petersburg's and Russia's current roles in the global hydrogen economy, and the eight time zones I've crossed on this hydrogen economy trip across Russia with a group of friends. The cruise from Murmansk to Vladivostok took 23 days and allowed us to see some of the other major hydrogen hubs such as Yamal, Norilsk, Kamchatka and Sakhalin. My mind wanders first through the story of St. Petersburg as a hydrogen hub, as I enjoy the fantastic views of Nevsky prospect[254].

St. Petersburg hub

"St Petersburg in the last two decades has become home to the first turquoise hydrogen production plant, based on Russian proprietary hydrogen technology of pyrolysis of methane in molten metals and plasma pyrolysis. These technologies are now licenced to the producers across the world to provide low-carbon hydrogen from natural gas or bio-methane[255]. Building on nuclear, airspace and manufacturing engineering centres, which were always abundant in the city, St. Petersburg is now home to a major educational, R&D and engineering cluster. More then 500 students from all over the word graduate annually from H2University in technical and business disciplines of hydrogen economy."

I remember boarding the hydrogen powered cruise ship in St. Petersburg that took us to Murmansk[256] – the first port on the Northern Sea Route. What a great invention, the Northern route. My mind reflects what a great economic boost that provided, and how the Murmansk hydrogen hub came about.

Northern route

"As a result of climate change, the duration of navigation season on the Northern Sea Route increased significantly and became the shortest and fastest sea route for the shipment of goods between

Asia and Europe.

The volume of goods (not hydrogen) transported through that corridor has grown to 130 million tonnes in 2035 and now exceeds 200 million tonnes. From the beginning of the active development in 2020, this corridor was supported as a low carbon transport route with LNG-powered vessels and nuclear ice-breakers. After the approval of a hydrogen development roadmap, a significant share of shipping vessels was converted by ammonia, hythane (a mixture of methane and hydrogen) and eventually pure hydrogen. Now the Northern route is a driver of major economic impetus for the Russian economy taking part in global trade."

Murmansk hydrogen hub

"Murmansk is the first hydrogen hub on the Northern Sea Route. It has two major production clusters – the nuclear-power based Kolsk hydrogen plant, operated by Rosatom and a joint venture between Enel and Rosnano combining a wind generation and green hydrogen production. The Kolsk project allows the export of surplus power available from nuclear plant through the sea route. Domestic demand for power was declining and power line construction was not a viable solution. Hydrogen exports to the EU market became a cost-effective alternative after the implementation of the EU's Fit for 55 package of policies and its gas decarbonisation package. While the Enel project was from the beginning targeted at export markets, the EU's introduction of a carbon border adjustment mechanism (CBAM) significantly increased domestic demand for the low-carbon power and hydrogen, and the project now primarily targets the needs of the local metals and mining industry[257]."

Murmansk. Open source

I continue to draft my notes for the presentation I am preparing, using my trip memories. Next stop, a harbour along Yamal Peninsula[258] – so far away, so vast. And so interesting to see how it transitioned from its carbon past to a low-carbon future.

Yamal hydrogen hub

"Yamal is now home to the Novatek hydrogen cluster. Novatek started experimenting with hydrogen to reduce the carbon footprint of its facilities as early as 2021. It was the first Russian company to install Siemens hydrogen-powered turbines for power supply to its LNG plants[259]. Novatek's strategy was to be the world's lowest carbon footprint gas supplier, and Yamal's hydrogen cluster was part of that plan. The hydrogen used was originally blue – produced

through steam methane reforming with carbon capture and storage in subsurface gas storage facility. Later, onshore wind projects and electrolysers were built to further reduce the carbon footprint."

From Yamal, the tour along the Northern route took us a to a nearby small harbour, connected to Norilsk[260], similarly to the Arctic city of Murmansk. As my mind looks back to the cruise experiences, I started drafting again, busily remembering how Norilsk became a hydrogen hub.

Norilsk hydrogen hub

"Norilsk nickel — the world's number one nickel and palladium producer, and number three global platinum producer — was one of the first companies to invest in a hydrogen R&D programme in Russia. It was the first programme agreed with the Russian Academy of Sciences, in 2003[261]. Since 2003, the company has put significant efforts in both decarbonising its own production assets and developing one of the world's largest clusters of hydrogen fuel cells manufacturing for heavy-duty vehicles and railroad applications, building on access to natural resources like palladium[262]. Large attention was also given to the development of innovative hydrogen storage solutions."

From Norilsk, back to the cruise ship, I remembered how the cruise boat arrived at Penzhin Bay[263], passing the Bering Strait[264], and then sailed farther onto one of the harbours on Sakhalin Island[265] where the trip finished. From there I flew home to Moscow. I started scribbling presentation notes again, both on Penzhin Bay and Sakhalin.

Kamchatka hydrogen hub – Penzhin Bay

"H_2 Clean Energy and RusHydro realised the Penzhin tidal power plant project, which was originally developed in the Soviet Union in 1980.

The tides in Penzhin Bay are 9 metres high and reach 12.9 metres in the case of spring tides, which is the highest magnitude for the Pacific Ocean. As the area of the bay basin is 20,530 km^2, it corresponds to diurnal discharge of 360–530 km^3. This water rate is 20–30 times higher than that of the world's biggest river, the Amazon River. At the time, there was no demand for large-scale power generation in the region and long distance power transmission to export markets was not feasible. As a result, the project was archived for over 40 years until the 2020s, when an export-oriented hydrogen strategy was adopted by the Ministry of Energy.

The rise of demand for green hydrogen in South Korea, Japan and China created an opportunity for electrolysis-based hydrogen production in Kamchatka. By 2040 a smaller project, the North site with a capacity of 21 GW of electrolysis, was launched and now bigger ones, with capacities of 87 GW electrolysis, are in construction."

Sakhalin hydrogen hub

"Sakhalin hub was the final stop of the trip – on the far eastern island of Sakhalin. In 2020, this was the first Russian region to declare a goal of carbon neutrality, which it achieved in 2025. It launched an ambitious export-oriented hydrogen production programme. Several hydrogen production projects were realised by consortiums of Russian and international players – SMR with CCS, Pyrolysis (Rosatom, Linde and Gazprom[266]), wind-based electrolysis (Air

Liquide, Rosatom, Copenhagen Infrastructure Partners), biogas conversion to hydrogen from city waste, forestry production and algae. It was also the first region to build a greenfield 'hydrogen city' – Ecopolis — where both transport and utilities are hydrogen based."[267]

Conclusions: How the carbon economy travelled to its decarbonisation through hydrogen

I was smiling. Life is good when you travel – albeit, it's even better if it's hydrogen-passion-fuelled travel (Przevalsky didn't think of this). It was going to be an interesting discussion at the workshop. I looked over my notes on Russia's hydrogen economy development, checking for omissions. Yes, it needed some final thoughts. I felt that the magic rule of having three key points could be appropriate here. My pen started moving, and conclusions emerged:

- *"Hydrogen was a major driver of economic growth for several regions, helping the just transition across the economy and supporting economic development.*
- *The development of the hydrogen cluster in Sakhalin occurred ahead of other regions due to the proximity to the key developing global hydrogen markets, which took a technology agnostic approach to hydrogen development (Japan, Korea, China), albeit later on pivoting more and more dominantly to low-carbon hydrogen opportunities.*
- *The Russian role in the hydrogen economy is not only supplying low-carbon fuel to the world but also supplying technology for low-carbon hydrogen production and components to hydrogen equipment (e. g. electrolysers and fuel cells) on par with other*

leading hydrogen economies of the world."

Uzbekistan, 2040

Author: Giuseppe Grimaldi

Pictures from Uzbekistan's hydrogen economy in 2040

It is 20 March, 2040, and we're in the Uzbekistan capital of Tashkent[268]. Colourful celebrations for Nowruz are underway at the National Research Institute of Renewable Energy Sources' main building[269]. Many students, researchers and experts from all the corners of the most populous country in Central Asia are celebrating. The institute is busy, as is the capital and the whole country. It gives a sense of mass gathering, since more than 40 million people[270] live together in Uzbekistan; almost 7 million more than in 2020[271].

Nowruz (Uzbek: Navro‘z / Наврўз) is a popular festivity in Uzbekistan - the day of the equinox[272], when day and night are equal. It marks the beginning of spring in the Northern Hemisphere and is widely celebrated across Central Asia, and in many places has acquired special features. When Uzbekistan was part of the Soviet Union, Nowruz celebrations were generally unofficial, and at times even prohibited. Despite the institute's frenetic activities, almost everyone paused to celebrate this holiday. Even a group of young students who are finalising their working group assignment for History of the Energy Transition class on their country's impressive transformation from old oil and gas assets to ultramodern hydrogen and renewables.

In this group sits Lola, a student in her 20s with a genuine passion for her country and somehow for the energy sector. She is originally from Bukhara, famous for its historic sites[273], and in Tashkent misses the nature on sunny days when you can enjoy the ancient signposts of the Silk Road shining in the sun. In fact, the country's solar irradiation levels are comparable in the south to the levels in southern European countries such as Spain and Italy. When Lola travels back to her parents' she crosses thousands of solar PV panels which, like flowers, turn to the sun to catch the sunlight which will later become electricity, and then via electrolysis clean hydrogen to feed the spectacular lights of the cities.

In her research, Lola has discovered that her country looks quite different from the time before she was born. The energy sector is a good example of how Uzbekistan has evolved quickly, achieving economic growth leveraging green technologies and international openness. In 2040 the total power generation installed capacity is 59 GW of which 12 are thermal capacity and the rest is renewables while in 2020 the total installed capacity was only 12 GW in total[274]. Most of the old power generation assets were built during Soviet times and relied on old technologies, all managed by the state-owned energy company Uzbekenergo, which was unbundled in 2019, kicking off a rapid transformation of the country's energy sector.

Lola's contribution to the working group assignment is the chapter dedicated to the power plant where her uncle worked his entire life. It is located on a river, which has a special history in the story of these territories as in the past it was an important passage on the way out of the desert of Turkestan[275]. Her uncle was from the little town of Shirin, a few km south of Tashkent[276]. The Sirdarya power plant is located roughly 1.9 km northeast of the city of Shirin, not far from the border with Tajikistan. Next to it lies the local Turbine Hall museum, which has transformed the 3 GW oil and thermal power plant into a modern exposition space inspired by the similar old London predecessor. In 2020 ACWA Power[277] began the construction of the 1.5 GW Sirdarya combined cycle gas-turbine (CCGT) power plant as part of the Uzbekistan government's plan to improve the efficiency and capacity of its electricity production - while boosting economic growth and reducing the environmental impact. The project was transformational as it added 15 percent of Uzbekistan's power demand and 8 percent of its total installed power capacity. Built originally to run on natural gas, in 2040 the plant reached the target of 50 percent green hydrogen utilisation and is on track to achieve 100 percent green hydrogen for all its operations by 2050, in line with the government's low-carbon strategy. Hydrogen is supplied both via local production and imports along the Sir Darya river.

Sirdarya combined cycle gas turbines. Source

Reflecting on past and future

Lola is on her way home after the celebration. Tonight the streets are full of celebration ornaments but empty of people. Walking slowly to her apartment on time to admire the dawn from her bedroom window, she starts thinking about the country's first hydrogen strategy in 2021[278]. By 2050 all gas power plants are expected to reach the end of their technological lifetime, while some gas-fired power plants will be repurposed for hydrogen. The energy system will operate on solar, wind, nuclear and hydropower, as well as decarbonised liquid and gaseous fuels. Already in the lift to her small student apartment, she remembers the first day at the Research Centre for Hydrogen Energy: The smell of the testing and certification laboratory for renewable and hydrogen which would later become the institute's biggest department.

Uzbekistan photo. Source: unsplash.com

* * *

It looks like the equinox-effect was not only in the first ray of light from the new day gently embracing the institute and its scholars. It's almost like, on that day, the page was turning on the history of energy in Uzbekistan, and a long-running fossil fuel economy was rapidly being substituted with a green new hydrogen technology that would light the future of the country as a regional leader for sustainable energy.

United Arab Emirates, 2040

Author: Robin Mills

His plan: The OHEC meeting on 14 September, 2040

It was a pleasantly warm day in Neom[279], just over 50°C. Ziad Al Shammary was there for action, not vacation, and his pilotless plane was first in the swarm. The followers buzzed near-silently over the hazy coastal plain as they delivered the constellation of ministers and robot assistants[280] to the floating hotel. The fifth annual meeting of OHEC[281] was in session.

Ziad, only just appointed his country's second hydrogen minister, appeared more relaxed than he was, as he hopped out of the fuel cell flyer and greeted his colleagues and rivals. Some seemed a little dismissive of the young man whose ability they had yet to gauge. He exchanged a few words with the unsuspecting representatives of Chile, Iran, Russia, Libya and Namibia. They murmured polite expressions, and he expressed a slightly naïve question or two to disarm them. He who estimates last, estimates best.

They'd given him the third most splendid suite in the hotel, walls in pastel blue and green, real glass windows, not electronic projections, facing all four compass points. Sunsets are redder, more infernally magnificent than when he was growing up. The forest of wind turbines, solar panels and electrolysers to the east was only 15 years old, but already seemed faintly antiquated.

He had visited Neom as a young engineer, when a choice of a career had been a gamble. "*Hydrogen,*" his aunt had advised, and been proved right. In the 2020s, he had been looking for a way out of the disease, drought, depression, depopulation and dissension across southwest Asia. The primordial element had seemed an escape, not a return.

Westwards, the modern blades floating on the Red Sea, each towering twice a Great Pyramid[282], were turning vigorously in the evening breeze, powering cavernous fans sucking a two-century carbon legacy back into the ground.

His robot parked itself unobtrusively in the corner of the room, taking his instruction on coordinating meetings. The Chief Hydrogen Buyers had come personally, the two-hour hyperplane hops still a remarkable concession in a near-virtual world. India, Germany, Korea, America, Bangladesh and other economic heavyweights. But they could sweat a little; he would see them later. Only the uncertain reaction of the Chinese delegate to his little coup worried him slightly.

But first, he had a few details to settle. He concentrated intently for a few moments so his neural circuit would make him appear in Sydney, just as the holographic projection of Savreen Kaur twinkled before him. In the Australian winter, she sat in front of a fireplace warmed by a near invisible blue flame.

"*We will make hydrogen so cheap that only the rich will burn wood,*" she commented drily. Indeed, the fireplace was an affectation. Electric heat pumps instead of crude fuel heat almost every home around the world outside the chilliest northern climes these days in 2040s.

"*If we still allowed burning wood, you know you're one of the few who could afford it,*" he responded. Since their PhD days designing electrolysers in Cambridge together, they had stayed close. Scion of a wealthy Australian mining family, Savreen had hardly needed the qualification, but the knowledge she'd acquired had taken her from rich to true plutocrat. The historically wealthy figures, Rockefeller, Gates, Getty, Musk and the others, were quaint beside the hydrogen trillionairess.

"*So our AI has OKed the legal code,*" he told her. "*Our lawyers will approve the human language précis this evening, not that they'll find anything to object to. Tshwane has cleared the transfer of the platinum assets. Congress is holding up the photoelectrocatalysis IP, but they're shooting themselves in the foot if they deny its use in the US. I don't believe anyone else knows what we're up to, apart from the Russians. I'm just concerned about Mingxia's reaction.*"

She arched her eyebrows. "*That is the one slight worry. It's only them, and your friends over there, that might get in the way. But I will handle Mingxia through the diplomatic channels. In the end, they won't dare risk their supply. Siberia isn't enough to replace the Gulf and Australia together.*"

"*I can handle the people here. They won't like it, of course, but they will go along for a cut of the pie.*" Indeed, a pie worth half a trillion a year, that would triple within a decade. And, more than the simple figures of euros, the electricity that kept nearly every vehicle droning down the world's roads and rails, the basic materials forging the new global economy, it was the control of the climate puzzle.

The next day, he rose before dawn and ran a virtual 5 km along the beach. The nearshore green water over the dead corals gave way to the deeper blue offshore. The immersive reality could render the sounds and smells, the balance, and the rosy *vistas* of sea and mountains almost perfectly, but still not the feel of sand under your feet or dewy morning air in your lungs. Outside, the wake of the Jupiter was washing on the shore, as the world's largest hydrogen carrier ran silently west to Suez and eager customers in southern Europe. Close to the morning Venus, another bright star was probably the international space hotel.

He was first of the ministers to the conference chamber, as his country was first to seize the potential of the first element. The others drifted in, expecting routine. They were served coffee synthesised from hydrogen and captured atmospheric carbon dioxide, a reasonable approximation to the bean version[283].

First came the technical presentations. Strong demand to replace remaining fossil fuels, to make synthetic food, manufacture graphene for hyperjets and orbital vehicles, kept demand booming. Two more countries had reached net-zero this year, gearing up hydrogen purchases to keep their grids running through sweltering, stuffy, still weather. OHEC's low production costs gave them the edge over competitors.

But were they pushing H_2 and C prices too high? There was talk of new hydrogen manufacturing in the Sahara and the Gobi, and on giant floating islands, populist Chinese politicians promising to break OHEC. Maybe they could entice some competitors to join the organisation?

The ministers' finance colleagues in Canberra, St. Petersburg and Isfahan were all itching to raise output, talking of hastening decarbonisation and releasing the brake on the global economy. But the hydrogen arbiters quickly reached agreement for only a moderate boost in the 2040 targets. That seemed to conclude matters. But on the delegates' retinas appeared a new agenda item.

Ziad spoke: "*Before some of us were hydrogen ministers, they were hydrocarbon ministers, and will know their history. Rockefeller controlled the transport of oil, and the club of Vienna controlled its supply. Eighty years on, we cannot repeat those approaches: the sun, wind and waves are everywhere. Last year the price was half what it is today. Next year, it may be half again or twice. This volatility is not good for those who rely on hydrogen for our economies, it is not good for consumers who need predictable affordability, and it is not good for anyone who desires a liveable climate.*

We have a new vision, that will bring order to this chaos. When our system here writes the final communique, it will announce that my government is buying H To Mining and merging it with our hydrogen industry. The combination will control 30 percent of world hydrogen production capacity, a quarter of atmospheric carbon sequestration, 70 percent of the key catalytic metals, and, most of all, all the essential IP on ultra low-cost hydrogen manufacturing and conversion."

He had been waiting to be sure it came as a surprise, and his fellow ministers were silent, hovering between the need to hear more, and their desperation to get out of the shielded room to communicate home for instructions: "*We prefer not to do this unilaterally. For true market stability, we need your cooperation, and you will all have the option to take a stake in the physical assets, the material synthesisers, the renewable energy fluxes, and, for those who want it, the oil and gas reformers and the carbon dioxide reservoirs.*"

Mendeleyeva nodded a quick apology and slipped out, probably to broach a separate deal with Mingxia. That was expected. He watched the others in his peripheral vision, leaning back with half-feigned insouciance. Despite the conversation of yesterday evening, he was not absolutely sure of the Chileans.

Nobody else moved, though, and he sensed some visible relief that they were not being cut out, some jealousy at being demoted to second place behind a young upstart minister. That was the best he could have expected. The struggle of the 2020s, the cloudiness and false starts of the 2030s, had been replaced by hope, then clarity, optimism, perhaps now even a touch of hubris. For now, he had put his region firmly back in the global economy's nucleus.

Picture of Dubai. Source: Rawpixel

Turkey, 2040

Author: Argun Karaçay

Izmir, a place for reflection on the green hydrogen market's evolution

It's a wonderful evening in Izmir, a city with thousands years of history[284] and the nice May weather helping me enjoy my coffee. I am rocking in my chair, remembering how hydrogen debates started in the early 2020s and picturing my own notes at the time.

2021: Prologue

"Turkey is one of the most dynamic regions in the world for renewables. Throughout the last decade, Turkey has tripled its installed renewable capacity to around 45 GW and invested nearly $40 billion in renewable energy projects with different sources such as wind, solar, hydro, geothermal and biogas. The relative development in wind and solar energy is especially impressive as wind and solar installed capacities reached 10 GW and 9 GW, respectively. Building on this background, the energy community started suggesting that, based on its track record, the country had the opportunity to take a

leading position in the renewable energy transition.

In 2020, Turkey's Ministry of Energy and Natural Resources (MENR) published a white paper aimed at starting formal discussions for determining Turkey's hydrogen roadmap. As a result, a fresh question started to emerge in 2021: will Turkey be able to position itself as a pioneering country in green hydrogen?"

2040: Izmir as the multi-use case study for a diverse hydrogen economy

My mind jumps back to today in Izmir and my rocking chair. I'm reflecting on how the hydrogen market has evolved, as Izmir has exemplified.

One of the ancient cities of Turkey in the pearl of the Aegean coast, Izmir (Smyrna was its ancient name) has been a shining star within Turkey which inspired a green transition for cities and achieved a far-reaching status with its vision. The city was the first in Turkey to participate in the European Bank for Reconstruction and Development's sustainable cities programme two decades ago with a vision to be the country's green transition pioneer.

As the city is hosting the vast majority of refineries and steel manufacturers, its position created considerable momentum for the Turkish industry's vision of a green energy transition. Today, the giant refineries located in cities including Petkim, Star and Tupras are running on 100 percent green hydrogen in their processes. The giant steel manufacturers also produce green steel. Of course, this achievement was not made in the blink of an eye. After grey hydrogen, blue hydrogen was used for some years until 100 percent green hydrogen utilisation was achieved through the massive deployment of, in particular, off-grid wind and solar capacity dedicated to green hydrogen production.

Petkim plant. Open source

Izmir residents enjoy green hydrogen-powered ferries when they go to their offices in the morning and get home in the evening. The city is also home to bunkering businesses and green hydrogen exports through its 100 percent renewable powered harbours. Ships in the region use the city to fuel their engines with green hydrogen. Hydrogen bunkering became a big industry that employs thousands of Izmir residents. Of course, hydrogen exports through hydrogen carrier ships are mostly destined to Asia, from where they are then exported to Europe. There they usually go through the Southern Gas Corridor, which in previous decades was used solely to transport gas but now mostly carries biomethane and green hydrogen.

The city's local gas distribution grid was the first grid to supply 20 percent hydrogen-blended gas approximately 15 years ago. Last year it was also the first grid to supply 100 percent green hydrogen for heating purposes.

Izmir. Source: Author

The city's bus fleet is also colourful. Sixty percent of its buses run on green hydrogen, while the remaining 40 percent is composed of 100 percent renewable electricity. Private car ownership has declined sharply to 30 percent within the last decade. Most city residents drive to supermarkets with hourly rented cars, of which most run on hydrogen fuel cells. Of course, if you have a specific tendency towards old electric cars, you may choose them through your app's filter of 'preferred fuel'. Recent surveys of the Turkish Auto Dealers Association showed that almost 35 percent of users over 50 tend to prefer electric cars over fuel cell, especially for better acceleration.

* * *

As I am getting ready to go in town to meet friends, my thoughts move to a broader question: "*Have we become one of the leaders in green energy and green hydrogen development*?" I tend to think so.

Turkey has achieved a landmark of installed capacity development in wind and solar over the last decade. We've reached 110 GW of installed wind capacity and 150 GW of installed solar capacity, a growth of approximately 13-fold within last two decades. The majority of this new capacity comes from off-grid plants that produce green hydrogen.

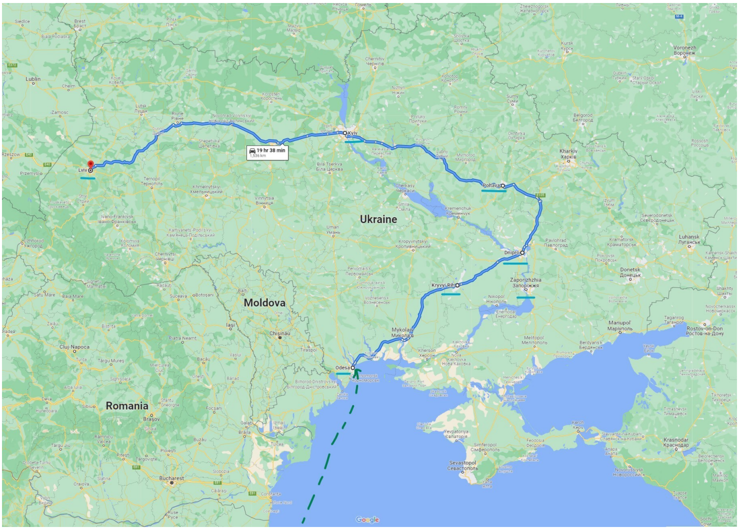
Turkey also enjoys the benefit of having become a net exporter of green hydrogen. The country used to suffer from budget deficits, most of which came from the bills of imported oil and natural gas. TANAP, which was used to transport Caspian gas to Europe, has now turned mostly into a green hydrogen export route to Europe from Turkey. Such a transformation of the country's existing transmission and distribution grids, and the vast ability to construct renewables, opened a window of opportunity for Turkey to become an important player in the global green hydrogen market.

Meanwhile, the beautiful city of İzmir continues to set a strong example for the rest of the country on its way towards a greener future. And I disappear into the night to enjoy it.

Ukraine, 2040

Author: Andrey Bondar

It's one of those rare occasions when Edith - the young virtual-worlds architect working at one of the largest XR immersive experience travel companies - decided to combine her dream vacation of taking a cruise with her research project for a new chapter in the company's virtual worlds – Ukraine. To do so, she decided to board a cruise liner from Thessaloniki that stops in Ukraine's biggest port city, Odessa. She takes a road trip around Ukraine to try and grasp the hyperbolic changes that have taken place in the past decade.



Overview of the trip. Source: Google maps

After passing Bosporus, the elegant cruise ship powered by green ammonia, with special safety precautions due to its toxicity[285], headed north to Ukraine. It passed GWs of gigantic offshore wind farms that are coupled with offshore hydrogen production rigs operated by Ukrainian and European energy companies. The cruise passes a busy sea route where barges with green ammonia and liquefied hydrogen are headed to the Danube[286] for further export of the hydrogen upstream all the way to southern Germany, from where it will be used to power European industry[287].

Edith arrived in Odessa and took an evening walk through the local bars. The next day she rented a self-driving car to go to Kyiv, with stops in Dnipro and Poltava.

On the way to Dnipro, she noticed the endless corn and wheat fields filled with wind turbines. Harvesters work diligently to collect the seasonal crops. The machines use hydrogen as their fuel[288], and green ammonia-based fertilisers for soil productivity.

The fresh flour and sunflower oil are produced at factories where the primary source of energy and heat is generated with a mix of biomethane and green hydrogen. Biomethane plants are not uncommon, and became the supplement energy source for the agricultural sector.

The flour is exported around the world, including France, where it was used to bake fresh croissants for the guests and delegations gathered to commemorate the 2015 Paris Agreement's anniversary.

The car passed Kryviy Rig - an industrial city that transformed from one of the most polluted cities into a city with clean air and opportunities for engineering talent. Here, along with Mariupol and Zaporizhia, top-quality green steel products are manufactured[289]. Hydrogen is used both for the direct reduction of iron from local deposits, and for energy storage[290], allowing for the provision of stable and dispatchable power from the surrounding solar and wind farms for the heavy but clean industry.

A large volume of low-carbon clean hydrogen is also produced with nuclear energy in this region. Local energy companies decided to build small modular reactors to generate emission-free energy that could be used for for hydrogen production for the local market[291]. This nuclear technology, in combination with hydrogen's ability to store energy long-term, helped Ukraine fulfil its promise to phase out coal power by 2035[292].

The steel is shipped to western and northern Europe where new wind turbines are produced. In some cases, those turbines end up back in Ukraine and close the truly '*green loop*' of the energy with steel-producing industries.

Nothing of the described would have been possible without the joint effort undertaken by Ukraine and the European Union. The deeper market integration opened opportunities for initial material funding that kick-started the transition which keeps contributing to the energy sovereignty and self-sustainability of the partners.

From the Dnipro region the road trip continued further north to Poltava, where the conventional gas-producing industry has found the next big opportunity to produce low-carbon and green hydrogen. All the way from Zaporizhia to Poltava, GW-scale H_2 factories produce the gas to be injected into a refurbished gas pipeline with several new H_2 dedicated routes[293]. Most of the hydrogen is then transported to the western border to fulfil Ukraine's ambition of becoming an energy exporter utilising its vast territories with great potential for rewables[294].

Edith stopped in Kyiv to explore the city with all the historical sites and new architecture, to enjoy the fashionable restaurants and the local nightlife. Next stop was Lviv and the Carpathian Mountains.

In Kyiv she took the new, locally assembled hydrogen train[295], and within three hours she was in Lviv, absorbing the unforgettable atmosphere of old streets and the smell of freshly roasted coffee. The city is home to many branches of international energy trading companies. These companies want to be closer to the infrastructure that helps to plan for the winter period – the underground gas storage facilities were previously used for seasonal gas storage and are now used as a storage hub for hydrogen[296] from Ukraine and central Europe.

More than 30 billion cubic metres of hydrogen can be stored in the underground storage sites and freely traded by the companies according to the market demand. Another known location, which she did not visit but had hear about, is the historical salt caverns near the Romanian border. Formerly a source of wealth for the Austro-Hungarian Empire, these salt caverns have been in part revived for the whole new purpose of hydrogen storage, while also being used for recreational services in the top-tier hotel chains nearby.

Thanks to a group of enthusiasts who have embraced blockchain technology for the energy sector, today every kilowatt-hour of energy is being transparently traced from the primary source of energy — renewable — to its gaseous form of hydrogen or other green gas. This way traders know exactly what belongs to them in the underground storage, and are able to trace the origins of the hydrogen.

Furthermore, these certificates and blockchain deliver information on the exact source and emission content of every energy carrier all the way up to the final product, so that we, the consumers, are aware of the emissions footprint of everything we buy. Moreover, it allows the financial institutions to have a clear picture of how to select their portfolios to meet emission targets, enabled by the whole economy having its carbon footprint measured.

Edith took a last look at her watch. It was time to finalise her trip and go back to making the virtual world work again. She made a note to underline the Ukrainian hydrogen economy in her design of that virtual Ukraine in 2040.

Romania, 2040

Author: Lavinia Tanase

The EU prize winner in 2040

"*A dystopia is an imagined community or society that is dehumanising and frightening. A dystopia is an antonym of a utopia, which is a perfect society,*" I read from a poster in the room.

It was an important day in 2040, and I was reflecting on how Romania had almost become a utopia in the global hydrogen economy and energy transition. There were just a few hours left until the winner of the 2040 Race for Decarbonisation was announced, and until we would learn whether Romania had won the race for the fastest decarbonisation among Eastern European states.

"*We' re going to win, we must win,*" I say to myself as I park my fuel cell car and start walking towards the Constanta Casino, an architectural gem on the seashore of the historical port city of Constanta[297]. My smart watch starts beeping, reminding me that there are two hours to go.

Over the past six months, after we submitted our final application to the European Commission, we have worked hard to organise a national event to cover the competition and results. It's a high-stake event aimed at recognising the progress from the past 20 years and inspiring a push for the future. It's designed to bring together all the stakeholders who were deeply involved in the energy transition – from the government, the ministry, the regulator – Autoritatea Nationala de Reglementare in Energie (ANRE) — to the national gas and electricity transmission and distribution system operators, consumer authority, NGOs and associations, prosumers, producers, lenders, and so on. In short, everybody along the energy value chain, financing and acting in public energy policy was welcome. We invited guests from the European institutions including ENTSOG, ENNOH, ACER, the EU-DSO body, the EU Clean Hydrogen Alliance[298], the European Investment Bank.

"Are you nervous?" I ask my colleague, Andreea, as I enter the room. I see she is madly refreshing the competition's webpage, in hopes of an early announcement.

"I'm biting my nails, of course. And you? How can you be so sure we even have a chance at winning?"

While admiring a miniature model of the electrolyser plant built in the nature-rich Dobrogea region[299], close to the Black Sea's mammoth offshore wind park commissioned in 2030, I respond, *"Well, how can they not? The criteria for the competition are very objective, and include a target number of hydrogen valleys, material contribution to the decrease of green hydrogen prices and jobs. Romania ticks all of those criteria. Look at this amazing piece of engineering of almost 4 GW electrolyser capacity built at large, in the Black Sea, somewhere between Constanta and Mangalia. It feeds itself with the wind electricity from the Black Sea wind farm. And also, the prize award team and wider European institutions are aware of our progress, since they have been getting our reports every year. We have received close €20 billion[300] in grants and loans* *to implement all changes to our energy system between 2021 and 2040. We have made sure to use these funds wisely building out the projects from plans to reality, we followed through. I mean, I'm surprised you ask yourself this question – you, as our creative director, helped us put all this in the speech that we have prepared for this presentation."*

"Sure," Andreea replied with an almost trembling voice. *"But we started using natural gas from under the Black Sea in 2026 from which we are still producing blue hydrogen with carbon capture and storage*[301]*. We're not only producing green hydrogen. Do you think this could be a low scoring point for the jury?"*

"Good question," I said. *"But remember that our initial National Hydrogen Strategy in 2023*[302]*, which is the basis for everything that happened afterwards, set some clear objectives for Romania, given its particularities. Specifically, it mentioned that the hydrogen produced locally in the country cannot only come from renewables, but also from gas, since we have several billion cubic metres under the Black Sea. Everything unfolded after Romgaz took over the contract from ExxonMobil back in 2023. I remember as if it was yesterday the moment when the operator, Petrom, along with OMV, declared the start of operations in 2026. That was a big win for us. If you remember, in Romania's National Energy and Climate Plan, approved by the European Commission in July 2021, one of the objectives was for Romania to draft legislation to promote investments in the Black Sea and modify relevant laws. And this happened soon thereafter."*

"You're diverging from the question," she replied. *"We know all this, we inserted it in the application, but..."*

"Andreea, we do not have time to debate substantive things now, let's please go over the main points of the speech again," I interrupted, wanting to make sure we were ready to deliver our

speech impeccably and thank everyone present for having made this energy transition possible.

My smart watch beeped again, reminding me to go over the main points of the speech. We planned to deliver it as a geographical travel through Romania and a time-lapse trip from 2021 until today showcasing the most important developments in hydrogen and for the energy transition.

I started repeating what I would say about Romania's journey to becoming a European hydrogen economy leader, and the birth place to the 1,000th hydrogen valley in the world.

"*They say life is not about having or doing, but about being. In Romania, to the contrary, everything is about tomorrow, what will tomorrow bring and what can we do? Thus having worked hard to achieve a clean energy transition allows us to breathe and let the 'being' manifest itself, without worrying. We have evolved from a country with very high potential to do pretty much anything to an actual decarbonisation hub in Southeast Europe. Please allow me for a time journey from 2021 to today.*

*Back in 2021, we were off to a rough start – we did not have a clear strategy for hydrogen, we were lagging behind a number of other countries globally. We did, however, have a National Energy and Climate Plan (**N**ECP) covering the period up until 2030.*

This NECP[303] *foresaw an important role for hydrogen in the transport, gas, and power sectors, without introducing clear plans and objectives for the future. We were missing a comprehensive framework for the use of hydrogen. In September 2021, the European Commission endorsed Romania's National Recovery Plan (NRRP), which outlined plans for the recovery of the country in areas including health, transportation and energy following the disbursement of almost €29.2 billion in non-refundable funds and loans. Only 41 percent - around €12 billion was targeted at enabling a clean* *energy transition and fostering green investments*[304].

Unlike in the NECP, the NRRP emphasised the role of hydrogen in the energy and transport sectors, with a clear goal to accelerate the decarbonisation of the energy sector by phasing out lignite and coal fired-power plants by 2032 and facilitating the deployment of renewable and alternative energy sources, such as green hydrogen.

What was very helpful to reaching this goal, and at the core of Romania's later success, was one of the clear objectives of the NRRP – the so-called Reform 4: developing a favourable legislative and regulatory framework for future technologies, in particular for hydrogen and storage solutions and removing any administrative obstacles to develop the renewable hydrogen sector, with a focus on transport, as well as on the gas and electricity sectors[305].

The Reform 4 triggered the emergence of the Hydrogen Strategy in 2023. It was such a happy moment to have moved from a puzzle of fragmented initiatives to a unified Hydrogen Strategy. Finally, we were nabbing our opportunity to make informed and comprehensive decisions regarding the future of hydrogen in the country.

Truth be told, we were a tad bit behind the momentum already building since 2019-2020, when other European countries such as France, Germany and Norway had already published their national hydrogen strategies. This delay was caused by the confusion among domestic actors on the role of hydrogen in a decarbonised Romanian economy. Despite being a potent candidate for the energy transition among other energy vectors, hydrogen[306] *alone cannot yield a decarbonised economy: action must be taken at the national policy level.*

So, what happened after the Hydrogen Strategy was put in place in 2023? I will draw your attention to nine key developments and will detail some of them:

1. The legal and political environment became steady and clear, *which made Romanian energy landscape attractive for private clean energy investments and for the exploitation of the natural gas resources in the Black Sea (including required attention to mitigating carbon emissions and methane leakages).*

2. We worked hard to arrange funding*, made project submissions, received grants, and followed through with investments along the whole energy value chain to fulfil the national objectives on energy and climate change.*

In Romanian we have a saying, "God offers you the means but does not put them in your bag." This time around, we did not sit around waiting for our bag to be filled and miracles to happen, we actually made them happen.

From the approximately €12 billion of investments in the energy sector up to 2030, we successfully used all the financial instruments available at the EU level and obtained adequate allocations. We invested massive amounts of Romanian and EU money in building new renewable energy capacity (approximately €1 billion[307]) and thus reinforced Romania's status as the country with one of the most significant renewable energy potentials in the EU. We could host the largest on- and offshore wind farms. In addition, we invested in interconnections with our neighbours, both in gas and electricity, thus the level of electricity interconnectivity increased to 17 percent in 2030 and to 30 percent by 2040.

3. We reinforced and modernised our power and gas infrastructure, including hydrogen storage

On 31 December, 2021 the government issued an Emergency Ordinance indicating that the national gas distribution systems could be extended through investments from the distributors, third parties *and local authorities. This had a major impact on how things later unravelled.*

We have invested in the modernisation of the gas and electricity grids by introducing more digitalisation, as well as additional distribution and storage systems.

Considering that Romania's natural gas transport system was arguably one of the oldest and worst performing in the EU back in 2021, it was a widely known fact that the reliance on the existing gas infrastructure was not sufficient and that large capital-intensive investments needed to be deployed for new dedicated hydrogen infrastructure to emerge. The national gas TSO, Transgaz, considered using the existing methane infrastructure for hydrogen transport and planned to assess the economic and technical feasibility of injecting hydrogen and synthetic methane into the natural gas infrastructure[308]*.*

Storing and managing hydrogen flexibility was a key to resolve, and we did it. The availability of suitable formations to develop storage sites for seasonal hydrogen storage represents an opportunity for Romania and offers it a competitive advantage compared to other EU states. Romania has always enjoyed the perks of having a diverse geographical landscape, and in 2020 DEPOGAZ Ploiesti[309]*, the unbundled subsidiary of ROMGAZ*[310]*, Romania's biggest national natural gas producer, was operating underground natural gas storage facilities which had the potential to be used for hydrogen storage in the medium- or long-term*[311]*. Romania's inheritance of salt caverns over 2,000 years, in particular, offered it the opportunity to create suitable saline storages for hydrogen – similar to the Netherlands and Germany*[312]*. That offered a critical differentiator and flexibility of easily accessible resources to Romania's hydrogen trading within Europe.*

4. We created the 1,000th hydrogen valley in the world

As you may remember, the goal of having 1,000 hydrogen valleys by 2040 worldwide and a couple of hundreds in the EU alone was announced[313] during EU Hydrogen Week 2021.

Romanians materially contributed to achieving this goal: the 1,000th hydrogen valley in the world is Dobrogea[314]! Naturally, such an achievement comes with an increase in the number of jobs and a serious decrease of the production costs of green hydrogen.

We have placed our bets on producing hydrogen in the country and transporting it to the EU via either the emerging European Hydrogen Backbone or ships. As studies found[315], it was in some cases cheaper and more secure to produce hydrogen outside Europe and import it (this depended heavily on transport costs). However, we aimed high and realised we could materially contribute to the production of hydrogen as a country with a significant renewable energy potential in Southeast Europe rather than importing it from outside the EU. We started exporting hydrogen to Austria, Germany and beyond, banking on our geography. In fact, the roll out of domestically produced renewable and low-carbon gases (in this case hydrogen) decreased Europe's dependency on imports of fossil fuels, strengthening the resilience of the entire EU energy system.

We were vibrant as a country and eager to elicit change. Hence, we became involved in a lot of EU Important Projects of Common European Interest[316], which provided EU funding for hydrogen.

The Blue Danube project, for example, was a real success. Around 1.5 GWh, or over 80,000 tonnes of green hydrogen/year, are now produced in Romania at competitive prices and shipped to Austria and Germany using liquid organic hydrogen carrier technology[317]. Conventional inland waterway vessels, which used to load liquid fossil fuels, were well-suited for the main logistic routes on the Danube River and could be re-used, accelerating the energy transition[318]

Blue Danube project overview. Source Verbund

This project turned Dobrogea[319], a region close to the Black Sea and the Danube, into a hydrogen valley. As a result, we created around 80,000 jobs for Romanians between 2023, when the Hydrogen Strategy was adopted, and today. We will not stop here[320]. The real number is actually much higher if we consider the implications of the Romanian hydrogen economy for EU contractors and subcontractors. This is important to mention as it was a criteria for winning the 2040 Decarbonisation Race.

What is more, considering the high amounts of hydrogen that we started producing in Romania, especially from 2030 in Dobrogea, we managed to achieve the goal of creating a liquid and competitive hydrogen market in the EU. Even though the initial goal expressed by European Commission Vice-President Frans Timmermans and Energy Commissioner Kadri Simson to achieve liquidity by 2030 was a bit too ambitious[321], it was achieved in 2035. We are now *in 2040 and we are happy to say that we can trade hydrogen at the TTF-hydrogen, the NBP-hydrogen and the Southeast Europe Hydrogen Trading Hub.*

5. We contributed to reducing the cost of production of green hydrogen

The availability and cost of green hydrogen directly depends on renewable energy sources, their price and availability. Romania's extensive local renewable energy potential, and the EU climate policies that aimed to increase CO_2 costs and eliminate the allocation of free CO_2 allowances, enabled an environment whereby the green hydrogen produced in Romania became more price competitive than grey or blue.

Hence, starting in 2030, hydrogen in Romania goes for less than €2/kg, in line with European Commission President Ursula van Der Leyen's statements[322].

6. We remained colour blind on clean hydrogen but aimed for net-zero overall

Romania's Hydrogen Strategy did not formally move away from blue hydrogen, since it is the country with the biggest natural gas reserves and production in the EU after the Netherlands[323]. But it did focus on green first. Even though it could provide a steady flow of hydrogen for the industry and other demand areas, blue hydrogen at material scale required investments for CCS, whilst offering only 90 percent capture rates[324]; this could have potentially rendered it non-economical in the longer term due to high carbon costs compared to green hydrogen. Nonetheless, blue hydrogen continued being produced in Romania, making use of the sizeable natural gas reserves under the Black Sea from 2026 onwards and enabling the top-up of flexible hydrogen volumes whilst green hydrogen was *being scaled and became gradually competitive*[325].

7. We managed to heat our homes with hydrogen and renewables, while preserving our forests

I remember the day when the news of an EU directive prohibiting the use of wood for home heating from 2023 hit Romania like a comet, as almost half of Romanians used to heat their houses with wood[326]. *It turned out to be fake news, however the NRRP did introduce (i) the extension of the gas network towards the rural areas with no access to any other source of heating and (ii) the plan to use other feedstock for heating and cooling rather than wood*[327].

As a reminder, two decades ago, in Romania's built environment, heating was primarily satisfied through biomass (forest) combustion and district heating, again mostly powered with fossil fuels. Along with wood, natural gas accounted for over 40 percent of our heating. Therefore, hydrogen was a good alternative in some cases to electric heat pumps in housing (for example in older housing stock) and could play a substantial role in decarbonising the heating and cooling sectors[328]. *To introduce hydrogen and renewable gases, the national gas distribution grid had been extended towards the urban and rural areas, with little to no access to energy for heating, in a number of regions, including the Oltenia region*[329]. *Initially, the NRRP provided for the construction of almost 1,900 km of gas distribution by 2026, transporting at least 20 percent green hydrogen produced from the electrolysers' capacities*[330]. *This network was envisaged to transport 100 percent green hydrogen by 2030, which started happening only from 2035*[331].

Next to hydrogen, other energy sources played a large role in saving forests and greening the heating demand. Individual heating systems using solar, wind and geothermal power were installed. Up to 4,200 stationary capacities for high-efficiency combined *power and heat production were switched to green gases, flexible to accommodate abated natural gas as well, replacing all lignite and coal capacities by 2026 and providing green heating.*

8. We enabled a just energy transition in the coal-intensive regions and left no-one behind

In the NECP, the coal-intensive regions were at the core of the decarbonisation and just energy transition plans. Romania faced and had to tackle important challenges during the energy transition, especially with regard to the reconversion of mono-industrial and carbon intensive regions such as Gorj, Valea Jiului or Oltenia. The former was included in the European Platform for Coal Regions in Transition, and, as a consequence, a transition strategy was developed. Furthermore, the Territorial Just Transition Plans that were created for six of Romania's counties - Mures, Hunedoara, Gorj, Ploiesti, Galati, Dolj - provided for measures to reskill and upskill the workers in these regions.

Initially, the closing of coal plants was expected to take place through 2032. But the Hydrogen Strategy issued in 2023 prompted this to happen earlier, in 2026. In order to rapidly replace the closed coal power plants, new jobs in renewable energy, including hydrogen, played a key role in supporting the regional decarbonisation targets.

Romania asked for and received large funds from the EU Modernisation Fund to support this transition in the coal-intensive regions. Even to this day, there is still work to be done in these areas.

9. We focused on public and commercial transport in order to make the hydrogen economy visible to citizens, including through hydrogen buses in Constanta, Cluj, Timisoara and Bucharest[332]

Romania is a vast country covering almost 240,000 km^2. Hence, *the transport sector is important.*

An opportunity for hydrogen deployment was seen and used for heavy duty road transport[333] *and in the rail sector, since the maritime and aviation sectors represented only a relatively minor share of energy demand in Romania's transport sector.*

As for the passenger cars, hydrogen-fuelled cars were also deployed — despite international controversy — since, in Romania people need cars with driving ranges of over 500 km. Currently, according to estimates, the hydrogen refuelling station network in 2040 encompasses around 120 stations, with around 60,000 fuel cell vehicles on the road[334]*. Back in 2021 we had very few highways connecting the country, but now we can drive on the highway from Bucharest to Cluj and Oradea — opening the roads for car and freight transport to the west towards Hungary and further. We can also use the highway connecting Bucharest with Suceava, the north part of the country, and we are finishing a direct link to Serbia (Timisoara) with ample electric and hydrogen refuelling opportunity. I am happy to say that last week I managed to drive my fuel cell powered car from Bucharest all the way to my parents' countryside farm, close to Iasi, in the northeast. There were 3 OMV Petrom refuelling stations on the way , however I did not need them as a full tank's range at a steady speed of 90 km/h is 600 km.*

As for the railway sector, two decades ago, it was still dependent on fossil fuels for 57 percent of its energy use. It has since been electrified and there are now plans for hydrogen fuel cell trains, thanks to availability of competitive green hydrogen. I know I am excited to be travelling in the first hydrogen powered train from 2045.

Steps were made on public transport buses, too. We now have 280 hydrogen buses in the country, spread between Constanta[335]*, Timisoara, Cluj, Iasi and Bucharest*[336]*. Isn't it fun to be able to travel* *around the cities in one of these modern miracles?"*

Dobrogea's secret spice to the success: Seeking synergies and aiming high

I pause the rehearsal of my speech to reflect on our success in turning Dobrogea into a hydrogen hub.

"The hydrogen produced in Dobrogea using renewable energy from the large on- and offshore wind power plants is exported to Austria and Germany with inland vessels via the Danube, but also used to support Romania's industry, such as the steel plant Liberty Galati and the cement factory LaFarge Medgidia.

In Romania, there are significant opportunities for the deployment of hydrogen across sectors, with the largest potential in industry and transport. Certain areas simply could not be decarbonised through electrification. In 2021 the largest demand for hydrogen was in the steel and glass sectors, as well as replacing fossil fuels in the production of high temperature heat. An important principle that aligned us with the EU was the correct application of the principle of additionality in the 2023 Hydrogen Strategy, which stated that only new renewable capacity that would not have otherwise been installed should be used for clean hydrogen production. This protected us from the so-called cannibalisation of renewable energy from electrification.

The Romanian steel sector, although relatively small, was still dependent on a conventional fossil fuel-based steel making process. Up to 2030 and beyond, steel making at the Liberty Galati plant became a bit greener. Now it uses half green, half blue hydrogen for steel production.

As the Energy Policy Group colleagues predicted back in 2021[337]*, I realise that indeed the green hydrogen from Dobrogea is used for* *feeding the municipal district heating systems (Constanța), with big plans to soon feed at large-scale the maritime and aviation transport sectors – ships docking in Ports of Constanța as well as planes taking off from Mihail Kogălniceanu International Airport.*

The Port of Constanța is on the verge of becoming a portal for hydrogen exports. The shipyards in Constanța and Mangalia are contributing to Dobrogea's transformation into a hydrogen hub, while the local authorities and several private companies have already created an extensive knowledge-sharing hub and work sites where ships that run on clean hydrogen can be built and retrofitted. A couple of days ago, the first long-haul transport ship built entirely in the Port of Constanta shipyard was commissioned.

The vision of the Romanian decision makers to transform Dobrogea into a hydrogen hub was achieved thanks to the links between the offshore wind farms in the Black Sea and the hydrogen value chains; and, also, on the basis that Dobrogea, was home for most of the country's onshore wind in 2021, around 3GW. Dobrogea also manifested the highest renewable energy potential, with an estimated total natural capacity of 94 GW[338]*. By 2030 Romania already had 5 GW of electrolysers installed, and materially contributed to achieving the 2030 target of 40 GW electrolysers in the EU*[339]*.*

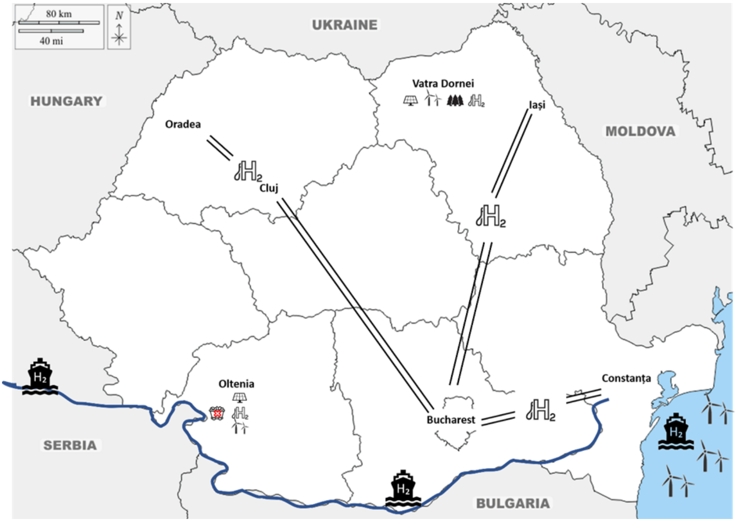
It has taken us almost 20 years to reach the stage where Dobrogea can be called a hydrogen valley. But in the longer term, I do agree that by tapping into Romania's affordable and significant renewable energy potential, Dobrogea can further develop into an even larger-scale, international and export-driven hydrogen valley[340]*, benefiting from the Port of Constanta, from the Danube Channel and from the country's natural resources and well-positioned geographical location."*

I turn right back to the speech to rehearse the final words.

Final thoughts: Utopia became a reality

"*You see, things have changed and life has taken its course. But we made this transition happen and turned it to our advantage. Did I think back then that all this was a utopia? Yes, I did. I am happy to have been proven wrong.*"

This was the last line I repeated before walking onto the stage. We turned off the lights, turned on the big screen and waited for the results from Brussels to come in, any moment now. The public was nervous, but we were very hopeful to win.



Source: Author's collection

Greece, 2034

Author: Katerina Sardi

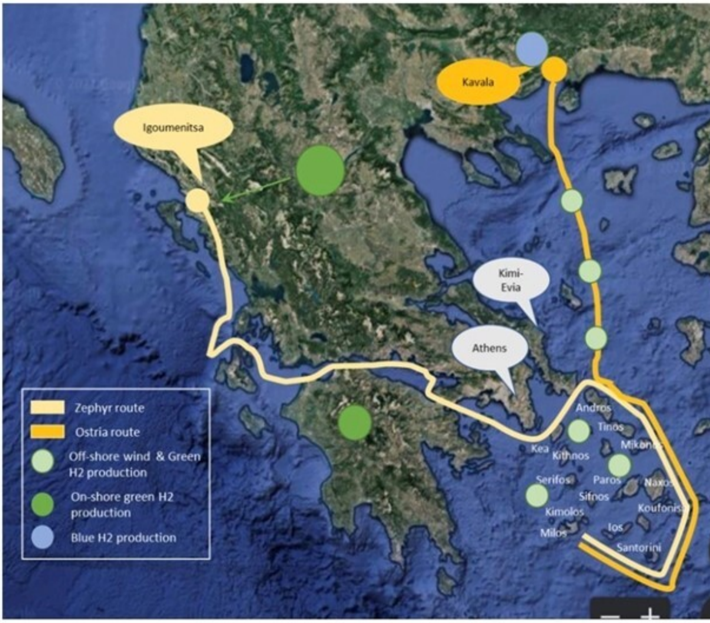
Hydrogen offset credits, Kasa's sailing trip in Greece

It's Tuesday, 15 August, 2034, somewhere in the Aegean Sea. A group of 32 university students are on a sailing cruise. They're from different parts of the South Mediterranean: Greece, Italy, Croatia and the West Balkans. It is the heart of the Greek summer. One of the students is called Kasa.

Kasa's trip was booked seven months ago, through the specialised platform #Collect4Green. This is the sixth year that #Collect4Green offers trips to the South Mediterranean and awards each traveller hydrogen offset credits (HOCs) to be used during the winter months to offset CO_2 emissions produced by household activities burning conventional natural gas, such as heating and cooking.

Views from Greece. Source: Shutterstock, [Taiga]

HOCs were introduced at the European level as part of the 2030+ revision of the European Emissions Trading System (ETS), which extended the sectors covered by the system to households. HOCs are generated through carbon-free leisure activities such as island hopping in Greece. One HOC equals 1 kWh of carbon-free energy demand. The #Collect4Green app tracks the user's HOCs generated throughout any linked trip. The trip was promising to be a great adventure, visiting islands that were connected to mainland Greece's electricity network, so that demand was met by power produced on the mainland and through local wind and solar PV. Small electrolysers installed locally produce hydrogen as a fuel for ships and local heavy vehicle transport.



Trip overview. Source: Google Earth

The students, including Kasa, were now lying at the stern of two 50-foot Catamarans moored offshore, near the small island of Kimolos[341] at the heart of the Cyclades island complex. Kasa was enjoying a watermelon cooled in one of the vessel's fridges, operating with electricity produced through a combination of PV power and fuel cells. Kasa loved technical details, and was mentally going through the boat's fuelling and propulsion features. Each vessel comprises a mainsail of 120 m^2, a smaller auxiliary sail of 80 m^2, three 250 W solar panels, a 148 kW fuel cell operating on hydrogen and a lithium-ion battery as propulsion back-up. The on-board tank holds 600 litres of liquid hydrogen stored at a temperature just below -252,87°C[342]. The tank capacity is enough for the boat to travel at its full speed of 35 km/h for 12 hours[343]. Thanks to advances in technology, in part pushed by developments in aviation and developing space travel[344], the cost of cryogenic components for H_2 containment and transport has substantially decreased post 2030 so that even comparatively lower budget cruise boats like this one were now equipped with liquid H_2 tanks. Both boats also have a 400-litre tank that can hold hydrogen in gaseous form, at a pressure of around 350 bars. This is enough for an additional two-hour cruise in the absence of wind.

From former mining towns and ports to hydrogen hubs, sailing with Zephyr and Ostria. The hydrogen catamarans, co-powered by green and blue hydrogen

Kasa was reflecting on the trip on two Catamarans so far, and the energy wonders that made it possible. It was amazing to be sailing between Greek islands, with the occasional use of fuel, and to be offsetting emissions through HOCs.

The first Catamaran - Zephyr, named after Zephyrus, the Greek god or personification of the west wind - commenced its journey from the port town of Igoumenitsa[345] in northwest Greece eight days ago. It carried students from the West Balkan region and Italy who travelled from their home towns with the relatively new hydrogen train speeding around the Adriatic Sea. Igoumenitsa is now a major hydrogen hub. The town receives green hydrogen in liquid form carried by trucks from the White Dragon[346] hydrogen centre in Western Macedonia, near the former mining town of Ptolemaida[347]. This is the area that hosted most of Greece's lignite plants until about a decade ago, and for more than 50 years had been a lignite mining community. Now it is home to a 5 GW electrolyser connected at the electricity transmission system, and receiving certified green electricity from around the country to feed the electrolyser for making green hydrogen from local water resources[348]. The produced green hydrogen is transported to various clients via dedicated transmission pipelines, operating as part of the European Hydrogen Backbone, transporting hydrogen to western Greece for consumption at the distribution level, including fuelling sailing boats like Zephyr.

Naturally, Zephyr started the trip with a full tank of hydrogen. She travelled south in the Ionian Sea between Italy and Greece, sailed through the gulfs of Patras and Korinthos, and through the Korinthos Canal before entering the Aegean Sea. The weather was good that wind and solar energy were adequate to power the trip. Any excess power was stored in the lithium-ion battery and subsequently used for charging devices onboard such as laptops and phones. Household activities and appliances such as hot water, cooking, and refrigeration were powered through the PVs and hydrogen fuel cell. Hydrogen propulsion was required only for a few hours, and this was rather fortunate as hydrogen refuelling stations around western Greece are still scarce.

The second Catamaran, Ostria, commenced its trip at the Gulf of Kavala, in the north east Aegean Sea. Ostria is named after a southerly wind in the Mediterranean Sea. Like the Zephyr, Ostria uses hydrogen for propulsion when wind is not available and to power appliances as a supplement to electricity produced from the PVs. Hydrogen for Ostria was supplied from one of the nearby blue hydrogen plants with improved capturing technology[349]. CO_2 produced as a by-product of blue hydrogen is stored at the dedicated underground CO_2 storage facility (UCO_2S) in the depleted oil fields of the Prinos complex, near the Kavala Gulf. The area has developed significantly over the past decade, hosting not only the hydrogen production and liquefaction facility, but also green ammonia production used as a fuel for large-scale ships. Vessels carrying liquid CO_2 from industrial facilities around Greece to be stored in the UCO_2S are often seen in the Kavala Gulf.

Ostria travelled south before meeting Zephyr on the southern side of Evia island. Refuelling was necessary, but this was no problem for Ostria. The island of Evia is hosting large-scale wind energy production for over 20 years. Comparatively small-scale electrolysers with a capacity around 1,000 kW can be found in several locations across the island. They produce hydrogen from green electricity that would otherwise be curtailed, as the electricity grid in the area cannot accommodate large amounts of wind power at all times. There is no dedicated hydrogen network on the island yet, so that hydrogen is typically used as a fuel for inland and seaborne transport. Cruisers typically stop at the port Kimi for refuelling with compressed hydrogen. Other refuelling options exist along the vessel's southern route, thanks to a number of floating wind farms equipped with small-scale electrolysers.

Today, the two ships met on the narrow pathway between Evia and the island of Andros, in the north part of the Cyclades, where the island-hopping adventure, including the earning of HOCs, would continue.

* * *

Kasa turned the attention to the watermelon and her fellow green travellers. The sun was shining over the endless waters, and she felt the wind and water drops on her skin. What a wonder that water-contained hydrogen molecules that now helped to power the world including its leisure and tourism.

Italy, 2040

Author: Carlo Degli Esposti

My decarbonisation motorbike ride

This year I have crowned the dream of a lifetime: crossing Italy on my hybrid-fuelled tourer motorbike. I had been longing for it; a chance to discover all those hidden corners of my country. Now that I am reaching the end of my career, the bike allows me to visit those points where Italy has been able to decarbonise its energy generation and consumption.

The engine mounted on my motorbike tells a lot about how things have evolved in this country over the last 20 years, and what I've seen in person. There were, indeed, great expectations about hydrogen and the role it would play in the last two decades. Unfortunately, these have been only partially met, particularly after the Covid-19 pandemic in the 2020s. I was curious to discover in person what could be observed on decarbonisation while riding across the country.

From the Alpines to the coast, good neighbours and the importance of water

My trip began in the western Alps, close to the large industrial cities of Turin, Milan, and Genoa — their main access to the sea. In this region, the power interconnection capacity with France has been expanded via High Voltage Direct Current cables installed in road and railways tunnels.

I am meanwhile making a small mental side note about the choices in energy policy that our neighbours have been pushing in recent years. Considering our never-ending dependence on energy imports, it's still an important factor in understanding how the Italian energy landscape has evolved.

"France has indeed taken the wise decision not to abandon nuclear power generation, but to reinforce it. At that time, this decision went clearly against the EU energy taxonomy presented by the European Commission in 2022[350] *and caused political debates between the conservatives and the green parties in Brussels and in every member state. I remembered that the last, unexpected extended brownout that affected large parts of Europe, after a prolonged 'Dunkelflaute' in January 2032, forced politicians to call for any available low-carbon resources back in service, nukes in particular. This was done to avoid the severe consequences that the series of power outages would have had on the society and on the relationships between member states."*

My mind wanders back to the Italian energy landscape of 2040.

Thanks to these power interconnections and the availability of a significant increase of stable energy supply from the French border, Turin and Milan have been going through a series of wise local changes to support a significant decarbonisation of the heating and transport sectors, thanks to the increased production and use of green hydrogen.

The increased interconnection with France has also allowed for the installation of large seawater desalination plants on the Tyrrhenian coast around Genoa. One of these plants is located in the decommissioned refinery area of Busalla, to satisfy the enormous increase in demand of demineralised water for green hydrogen production. This same plant supplies water to residential and agricultural users, not only in Turin and Milan, but all across the north western Po Valley as well. This is where I have decided to go today. Leaving Turin, crossing the sweet landscape of the Langhe, the region of the great red wines of Piedmont, and the narrow valleys of the Ligurian Apennines, finally ending on the coast near Savona.

The construction of these impressive desalination plants has become a serious need over the last 15 years, during which extreme weather conditions have become more frequently in northern Italy, with long droughts alternating with catastrophic heavy rains and floods. Over this period, despite the evidence, the regional water administrations have proved once again incapable of correcting its plans, going on disregarding the severe needs of water management works to comply with the measures indicated in the Water Framework Directive and the River Basin Management Plans. The economic losses, including that of lack of water resources, have been beyond imagination.

Savona. Source: Kayak

On to Milan and the story of mobility

I left the coast and the beauty of Genoa behind and crossed the mountains to Milan. In the Italian economic capital, mobility and heating have been significantly transformed by the use of hydrogen.

My mind takes a minor detour. *"The use of electric batteries and vehicles for mobility has been slow due to the need to implement charging points at scale. It was impossible to expand the distribution network to assure a sufficient number of charging pods in the historical city centre. This was as much a problem for Milan as for any other Italian urban area, whatever its size.*

Increasing social awareness about the sustainability problems posed by the extraction of minerals for batteries in poor countries like Bolivia and Democratic Republic of Congo was expected to deter people from buying electric cars. But the problem proved to be small.

Instead the recharging networks developed much slower than the strong demand, causing huge queues to form in front of charging stations, made worse by the fact that charging time was longer than expected and battery efficiency much lower than foreseen. The reality of the charging process slowly disincentives the choice of battery cars for private mobility — in favour of hydrogen vehicles.

In Milan, as in all other Italian cities, distribution operators initially tried to deploy a massive 350 kW of fast frequency charging stations[351]*. These fast chargers were so stressful on the overall power distribution network that they required reinforcement to supply an adequate number of charging stations at peak time. The conversion of existing tank stations into multi-hub fuel suppliers proved to be much easier: installing dedicated electrolysers producing hydrogen on spots, and leveraging the existing gas network to supply hydrogen from the city outskirts, was showing to be economic and doable."*

The landscape in Milan, and more generally in the entire Po Valley, has changed tremendously.

Solar countryside, slow growth, imports

I left Milan and took the long drive towards the seaside on a route out off the mainstream travelling path, moving along the highway. I crossed Crema, Cremona, Mantua, Ostiglia and finally Ferrara, from which I reached Ravenna and its byzantine beauties.

The countryside had changed from a blend of rural landscape and mid-size industry to large fields of solar panels at 4 metres above the soil, visible everywhere. Thanks to the strong push from the national and local governments for a strong deployment of agrivoltaic plants[352], the use of land has evolved from pure agricultural production to a mix of agriculture with energy.

That said, we could have had more solar.

It was estimated that Italy would need to install 75 GW of new solar generation capacity, corresponding to a surface 600-750 km^2 of land surface, to cover the demand from green hydrogen by 2030 with domestic energy. That's slightly less than the 1 percent of the unused soil.

Unfortunately, these plans proved to be too ambitious. The growth rate would have implied doubling the speed of new renewable capacity installation compared to the period from 2010 until 2020. This, combined with the scarcity of rare minerals[353] in the following years, has created a structural shortage of raw materials supply for PV and inverter[354] manufacturers, forcing the growth rate of renewable generation penetration, and of green hydrogen use, to slow significantly.

This shortage of local clean hydrogen supply has been partially mitigated by the conversion of a large part of the natural gas transport system into the main vehicle to convey a part of the residual demand in hydrogen from North Africa. I will be seeing the result of this major gas system turnaround once I get to the south, especially in Sicily.

Clean air in the Po Valley

While driving, one upside of decarbonisation became evident. The strong decarbonisation of heating, transport and industrial production has cleaned the Po Valley's air. Until 2030, the air quality was one of the worst in Europe, costing several hundreds of premature deaths per year. One of the very few positive steps undertaken by the regional governments of the north was to tackle this issue with draconian measures to promote the use of hydrogen for heating from 2026 during certain weather conditions saturated hospitals in for entire weeks in a row. It fully comparable to those Great Smog days in London in 1952. A quick uptake of hydrogen rescued the air quality.

The initial estimates foresaw the need for a tremendous growth in the use of hydrogen instead of heavy combustion oil and methane between 2030 and 2050 - from 2 percent to 20 percent of the final primary energy consumption. The last estimates seem to confirm that the target of 20 percent clean hydrogen use in the final primary energy consumption will be reached in 2044, thanks to the promotion of energy efficiency measures for buildings and increased hydrogen imports from North Africa.

Refining sites transformed

The long trip across the Po Valley brought me to the sites of Italy's former main refineries, which were closed one by one all along the period between 2025 and 2040. Cremona, Mantua, Ferrara and Ravenna were largely dismantled or re-converted into green hydrogen production sites, with high concentrations of electrolysers and fuel cells from the last generation (with nominal the power of some a few hundred MWs). The significant amount of heat co-produced by the conversion process in electrolysers allowed for the extension of centralised decarbonised heating and cooling networks covering large districts around these former refining sites.

Adriatic offshore wind to gas hubs

My trip continued along the Adriatic coast, towards Pescara. The landscape has changed significantly. Despite all the talk until the end of the 2020s, the Adriatic Sea turned out to be an unexpectedly profitable location for the installation of new offshore wind farms, in particular leveraging the presence of dismissed gas extraction platforms along the Italian coast.

These former gas sites have been reconverted in power-to-hydrogen hubs, connected by an efficient HVDC network which, besides granting a high load factor to hydrogen production, has helped to improve the overall security of supply for the Italian power system. Twenty years ago, in 2020, there was no expectation that offshore wind energy, particularly floating, would have contributed so much to the decarbonisation of the Italian energy system. New types of wind turbines, based on the cyclonic conveying of air into the turbine[355], allowed the use of much lighter and irregular winds for the production of electricity in an area characterised by wind gusts, but no regular inflows.

HVDC network. Source: Author

After enjoying the views of Pescara, it was time to ride towards Rome. I planned to visit a couple of friends there who had recently been elected as members of the Parliament. I considered not going. I was aware they may not appreciate my concerns about the completion of the last, crucial steps in the decarbonisation of the Italian industry. Pleading for the reintroduction of nuclear energy in the Italian mix[356], relying on melted salt reactors that have been largely deployed in other parts of the world over the last 20 years, and became the most secure technology to provide large amounts of reliable electricity. This was certainly a debatable expectation.

Southwards, the Mediterranean hydrogen hub: Through Apulia and Basilicata

There was one last step in my trip: the long descent towards Sicily to visit what many stakeholders in the Italian and hydrogen energy markets over the last 10 years considered to be the Mediterranean's hydrogen hub.

Before getting there, I had two stops: Apulia and Taranto, and Basilicata. These regions host the highest concentration of renewables in Italy and the largest potential for oil extraction, respectively. To my great surprise, the largest Italian steel production factory, based in Taranto, has fulfilled its plans, through the long and uncertain path, to cover its entire needs of green hydrogen (approximately 300 kt/year) to decarbonise its production (6 Mt/year of steel)[357]. The supply is provided by a large import terminal that allows ships carrying green hydrogen produced in UAE to extract the hydrogen content from the liquid organic hydrogen carriers (LOHC) used for shipping the green hydrogen. This approach, combined with the local solar-supported supply of hydrogen, allowed the relaunch of the green steel production in what once was one of the most polluted industrial sites in Europe.

But what about Basilicata? Once I left Taranto and paused in the beauty of Matera, I arrived in the Agri Valley, known for decades as an unexploited 'Italian Texas'. The valley has finally installed sufficient low-carbon assets to increase its oil production, and to bring it close to its estimated potential of 150,000 barrels per day, after a long and harsh fight with local communities and environmentalists. Oil is refined locally in a new, dedicated cracking plant, combined with one of the most efficient carbon capture installations, and is used mostly for plastics (hence being allowed as use case), with carbon being used for other purposes on site such as the production of e-fuels.

I reached Sicily after the bike run across Calabria and the crossing of the Strait of Messina.

Traditionally, energy in Sicily has come from North Africa. Now, the gas and oil pipelines from Algeria and Libya are accompanied by a strong electricity interconnection with 10 GW of traditional and floating offshore wind installed in the sea between Sicily, Tunisia and Malta, interconnected by another meshed HVDC marine network that will soon stretch up to Greece, Sardinia and the Balearic islands. The deployment of these HVDC networks allowed for the installation of another farm of water desalination plants on the southern Sicilian coast. This additional water production allowed for the installation of further hydrogen generation capacity by large-scale electrolysers close to the former refinery locations in the region (Milazzo, Priolo and Gela), but above all it averted further desertification of the interior part of the island. Despite all improvements, the local water pipeline system, affected by losses for more than 50 percent of its capacity in 2015, is still undergoing a profound reinforcement process. The quality and efficiency in water supply have promisingly improving.

The parallel reinforcement of the pipeline and electrical interconnections to the mainland and Sardinia are still far from complete, but it is increasingly supporting the re-routing of the excess volumes of hydrogen imported from North Africa (via the gas interconnector to Tunisia, and the one, launched in 2035, from Libya), or produced locally, towards the north of Italy and the rest of Europe, facilitating the access to clean hydrogen for European landlocked countries.

Famous final words

Crossing the Italian peninsula waas a real adventure, and I am happy to have taken my hybrid (e-fuel and electric) motorbike and not my hydrogen fuelled car. Finding hydrogen fuelling stations outside the main highways and the main connection roads is still not that easy, but the construction of an HVDC power network dedicated to the supply of multi-fuel (hydrogen and syngas), and charging stations is underway. It is a promising step towards fully decarbonising Italy's transportation.

At the end of the motorbike journey across Italy, I feel comfortable in saying that Italy is on the right path to become a true example of how the transition towards hydrogen, as one of the vectors of energy transition, can be successfully achieved.

It is even more impressive to think of how this all happened. It happened despite the never-resolved issue of complex administrative and permitting burdens. There is a chronic unpreparedness of administrators at all levels, hierarchically and geographically, to tackle energy related issues. The population also remains fundamentally idle in the face of dramatic climate change impacts in the Mediterranean basin, where prolonged droughts have become endemic.

Pushing decarbonisation to its extreme will require Italy to walk a few extra and (costly) miles. The decarbonisation of the last grey power generation capacity will be a real challenge. But I have just received a call from Rome: "*Why did you not stop over? We wanted to talk to you about those melted salt reactors you talked to us about to the point of boring... The minister wants to see you, she wants to take action!*"

Germany, 2040

Author: Konstantin Lenz

The snowy solar and heating

It is a very cold morning, after dropping below -10°C overnight. But it's beautiful out there. The sun is shining from its deep January angle. In my little garden, the snow from recent days is still white and untouched. Magically, small ice crystals dot the window. The prints of my footsteps in the snow lead to the firewood pile at the back of the garden. Modern heating systems can be so developed, clean and advantageous, but they will never be able to replace the cosiness of a fireplace. Out on the street, however, the bright white snow has turned into a mixture of brown and grey mud. On city streets, some things never change.

I look over to the old oven in the living room, with the ashes from yesterday evening. OK, I admit to myself, the need to clean it every time I light it is a clear disadvantage. My annual delivery of stacked cubic metres of wood, which has to be carried from the street into the garden, is always a welcome extra workout session. Moreover, a fireplace with a glass of red wine is unbeatable. But having it as the only heat source could be challenging, so we can be happy to live in the 21st rather than

19th century.

I look at the output of my rooftop solar installation: 0.0. Obviously, given that it's covered in snow. I could climb up on the roof to clean it — similar to the efforts needed in the fireplace, but without the cosiness and the red wine.

We live in a modern world, but still not in a perfect world.

Illustration of the snowy roof with solar PVs. Source: Shutterstock

Building the solar installation on the roof was a challenge. It is a flat roof covered with black tar paper. When I renovated the tar paper in 2020, bringing up also an insulation on it, the roofer said it hadn't been replaced in 90 years and suggested to putting a fourth layer on the roof. Disposal of tar paper is horribly expensive, so people leave it where it is, as I did. But as a result, the roofer recommended not using solar cells with a steel framework. A few years later, some fantastic rollout layers of solar cells became available[358]. You roll it out on the roof, fix it on the tar paper, cable through the chimney to the house's electricity headquarters in the basement, and that's it. OK, the snow is still an issue – modern but not perfect. And there's no bonus of red wine when consuming solar energy.

I go down to the basement, passing by the heating cube with its blue light which has to work hard at these low outdoor temperatures. This is the hottest device on the market, containing more computing power than Apollo 11 (although it doesn't fly me to the moon). It's a hybrid heating system combining a heat pump with a gas burning facility, able to take natural gas or hydrogen or a mixture of both. It optimises the use of electricity or gas depending on the actual market prices, and the heating is integrated in a balancing energy pool. The display in the living room shows the outdoor and indoor temperatures, the actual condition and running mode of the heating system, as well as current prices of natural gas, hydrogen and electricity. It also shows the current mixture of natural gas and hydrogen in the gas grid. The gas grid operators run the blending of hydrogen in the gas grid in a flexible way, optimising the price, carbon footprint and security of supply. And of course, all this information is available on my smartphone.

Deeper dive on heating: From Bauhaus to hydrogen

My house is over 110 years old, built around 1929 by a Bauhaus architect. It is part of a larger ensemble of row houses in south west Berlin. The whole area is under monument conservation rules, so you are not allowed to change much.

A simple heat pump was not sufficient for such a house since due to the monument conservation it is not possible to isolate the façade. At these low outdoor temperatures, the radiators need 60 to 70°C of inlet temperatures, but a heating pump is only able to deliver 50°C. So efficiency declines at these low temperatures[359].

Using hydrogen to heat private houses was not seen as an option in the beginning of the hydrogen economy, which was called the c*hampagne* of the energy transition[360]. But reality turned out differently. Not only do we now produce green hydrogen from the electrolysis of water through renewable energy, but turquoise hydrogen has also taken an important role in the energy mix. Turquoise hydrogen is made out of natural gas using methane pyrolysis[361], producing hydrogen and solid carbon. The large amounts of solid carbon were a challenge at first, as the market for it was relatively limited in the 2020s[362].

However, once large amounts of free material was available, the chemical industry got creative and helped create new materials such new plastics and inputs for graphene batteries[363][364]. This helped graphene batteries breakthrough. They're made from a single layer of solid carbon and generally[365] have no better energy density than other battery technologies that have popped up in the last 20 years. But their price is very competitive, since they don't need expensive raw materials. So a huge number of stationary graphene batteries, small and large size, were built using, for example, former coal mines or coal plant locations, storing electricity in times of surplus and transferring it in times with a lower offering.

No speed limits on Vulcan: Driving towards the future

I leave the house feeling the hit of cold air mixed with sunshine. The cars on the street are partially covered with ice and snow. On the cars connected to charging stations, the snow has melted away on the windows, thanks to automatic heating systems that take electricity from the grid in order to preheat them. Scratching wind shields is a relic of the past, only needed with old-timer cars. Usually people just don't run them in this cold weather. And I was considering whether to take my old-timer for a ride, or my electric car.

"How to continue operating old-timers was and is still a big issue. Also I have one with six cylinders and 300 horsepower, nearly 40 years old now. Of course, it is in the garage and is used only if the weather is nice. But the sound of a real car is still an unbeatable joy," I think to myself.

"Have you ever considered why all the small kids love old steam locomotives, even if modern trains are much faster and convenient? I think it is due to their imperfection. Old trains are noisy, smell and need love, and sometimes they are sick. They often have names and grow personality along with age. Somehow it is the same with old cars, they have a personality and people give them names. Mine all did. They were part of the family and it was sad when they had to leave. Electric cars don't get names any more, if they are broken, you give them away for circular re-processing. It is comparable with electric golf carts, have you ever seen a golf cart with a name? No, they only have numbers.

Producing synthetic, environmentally friendly circular fuels for old-timers was a challenge, some auto companies started these projects in the early 2020s[366]*. For example, Porsche worked in the 2020s to make e-petrol synthesised from e-methanol using* *green hydrogen and carbon-capture*[367]*. It succeeded in producing e-gasoline and e-diesel using Fischer-Tropsch*[368] *synthesis with carbon made out of biowaste or direct air capture, but the main challenge for was to gain trust from the owners to use these fuels. The carmakers were forced to give wide guarantees to the owners for any kind of engine damage that might be caused by these synthetic fuels. Meanwhile, gas stations changed their business to provide high-voltage chargers that can provide nearly 1,000 km of range within 10 minutes. They still have one or two fuel dispensers, mostly used for old-timers offering e-fuels sorts like Super Fossi and Super Syn, as well as Diesel Fossi and Diesel Syn. Super and Diesel Fossi are highly taxed, and often not available any more, but there is still a market for it — although neighbours don't look kindly on its use. E-fuels are not highly taxed but are relatively expensive. All incentives are geared towards encouraging citizens to drive mostly electric."*

My mind drifts back to the sunny, snowy present. My old-timer will remain in the garage today, and I take a seat in my preheated electric Porsche Vulcan. Susi, the on-board computer, welcomes me. It already knows where I want to go, and the autonomous driving starts immediately. The streets have not changed much in the last 20 years — cars are standing on the sides, many of them connected to charging stations you find every 10 metres along the street. The breakthrough of autonomous driving had an unexpected side effect - most people don't use public transportation any more for short and medium trips. Trains and buses are used only by people who can't afford to own a car or make use of car-sharing. If the car leaves you at your destination, it automatically searches for a parking place, tells you how far it is, and you call it to come when you need it again. Or you call a shared car through your smartphone. This is what many people do, especially in city centres. In cities and on country roads you still have to be on the steering wheel controlling the computer driving. However on Germany's a*utobahnen* (highways) you are allowed to sit back, take a nap, read, play a game, or whatever else you like. And yes, there is still no speed limit in Germany.

For long-range travel, aeroplanes are still the top choice. Their fuel is now largely based on clean hydrogen or its derivatives[369] .

I don't need a plane today. I'm going to the house-warming celebration and launch of the new hydrogen production plant on the outskirts of Berlin, which I worked on. It consists of several newest-generation electrolysers, with an efficiency of more than 80 percent, large-scale graphene batteries to store the electricity, and a connection to the district heating grid, where the waste heat is fed in and a private direct pipeline connected to a small refinery provides clean hydrogen to produce synthetic fuels. The plant is connected to the high-pressure hydrogen pipeline grid, where hydrogen is transported to huge salt cavern storage facilities along the shores of North and Baltic seas, to be further traded and used across the European Hydrogen Backbone. The produced oxygen is used for different purposes. The water input for electrolysis is supplied from cleaned industrial wastewater.

Driving to the new plant, one sees how cities have changed since the 2020s. The remaining buildings look more or less unchanged, yet every spare space is covered with PV installations, especially on the roofs, resulting in large amounts of renewable power produced during the summer, with excess renewable energy stored for the winter as hydrogen. Building the caverns in salt domes was a large investment and increased the salt level of the Baltic Sea significantly, which had fallen in the decades before. Yet, it did make Europe nearly independent from global imports of hydrogen. For the extreme cold peaks in our abated power generation, and to produce turquoise hydrogen, we still receive limited volumes of natural gas from pipelines and via global traded gas markets on LNG ships. Those gas volumes are taxed for carbon.

The hydrogen plant is surrounded by solar panels, and today most of them are covered with snow. Still not everything is perfect in terms of humans' ability to harness unlimited solar power – snow breaks that dream in this case.

My mind drifts away again to future. *"The first commercial nuclear fusion power plants are under construction, having progressed since the 2020s*[370] *and are now way above time schedule and budget. Some things never change. Policymakers are already discussing flat rates for electricity as result of this progress. But this will probably need another 10 to 20 years. Within one person's lifespan, we started with a world fuelled by oil, putting the first man on the moon*[371]*. We ended with a nearly fossil fuel-free economy in most of industrial countries, with unlimited energy from fusion in visible commercialisation range, and with the first human steps on Mars."*

II

Part Two

Part II. The journey on the map

In this second part, we will visit 10 countries (see green dots in the map below):

Illustration of countries visited along the book. Source: Google and editors

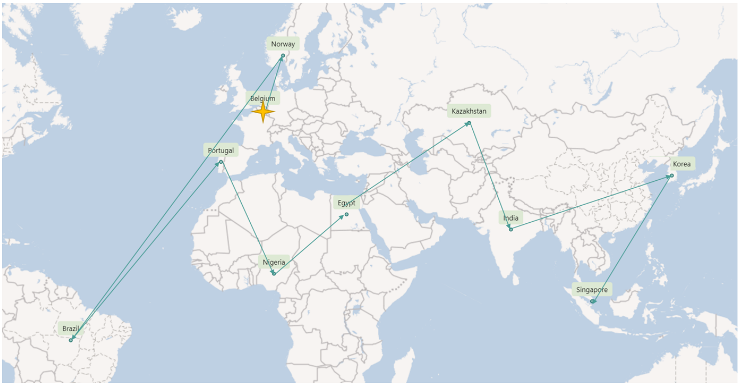
Starting in Belgium and finishing in Singapore, we visit countries following a specific and deliberated order that allows the reader (i.e., the traveler) to take a round-the-world tour as she or he would do in real life, without interruptions.

After Belgium, we visit Norway and move to Brazil. From

Brazil, we come back to Portugal and continue with Nigeria and Egypt.

We continue to Kazakhstan, then India, Korea, and we finish in Singapore.

See the complete journey below:



Map illustrating the whole journey. Source: Google and editors

Note: The maps included herein are without prejudice to the status of or sovereignty over any territory, to the delineation of international frontiers and boundaries and to the name of any territory, city or area. Locations are indicative.

Belgium, 2026

Authors: Jens Mosselmans and Daniel Cortez Cazas

Brussels, September 2026, a hybrid workspace on the outskirts of the city centre, a green setting

As a Belgian lawyer, Norma had always been fascinated by the potential of hydrogen as a clean and sustainable energy source. She had dedicated years of her career to advocating for clean hydrogen adoption in Belgium, and her efforts had finally paid off when the federal government - following the announcement by Flemish Region - announced the country's hydrogen strategy in 2021. Belgium was set to become a hydrogen hub in Europe.

One sunny morning in 2026, Norma was sitting in her workspace, going through the latest news about Belgium's progress in becoming a hydrogen leader. She came across a linked article dating back to 2023 at the bottom of a recent news story, which brought back memories of the early days of her hydrogen advocacy.

The article highlighted Belgium's pioneering efforts in enacting the first hydrogen law worldwide that regulated the transport of hydrogen through pipelines. It was a significant step towards establishing a hydrogen market and infrastructure in the country, and Norma vividly remembered the challenges she had faced in the aftermath of this legislation.

Back to the past (2024)

Norma had been tirelessly working with policymakers, industry experts, and environmental organisations to work on projects the benefits of hydrogen and its potential in reducing greenhouse gas emissions. She had faced resistance from some quarters who were sceptical about hydrogen's viability as an energy source and its potential for mass adoption.

In replacing fossil fuels, offshore wind energy can also play an important role as an energy source for green molecules – wind farm in Ostend. Source: Unsplash

But Norma was determined to use her expertise in energy law to help draft a comprehensive hydrogen law that would regulate the transport of hydrogen through pipelines and establishing the regulatory framework for the future hydrogen market organisation. She had argued that Belgium's strategic location at the heart of Europe, with its extensive pipeline network, made it ideal for transporting hydrogen from production sites to consumption centres across the continent.

After months of hard work, Norma's efforts had finally paid off when the hydrogen law was passed by the Belgian parliament in the course of 2023. It was a major milestone in Belgium's journey towards becoming a hydrogen hub, which began with the gradual development of Belgium's hydrogen infrastructure, starting with the industrial clusters and scaling up to a full-fledged hydrogen backbone as the demand for hydrogen molecules would increase.

Back to the present (2026)

As Norma reminisced about those early days, she could not help but feel a sense of pride and satisfaction. The newspaper article from 2023 was a reminder of the progress Belgium had already made.

Still, not everything had gone smoothly. Several legislative shots were taken without awaiting the final adoption of the European regulatory framework. After all, Belgium already had an extensive hydrogen transportation network of 600 kilometres of pipelines, which was the second largest in the world at the time after the USA. Nevertheless, this network had been built by a private company to supply its industrial customers in Belgium, France and the Netherlands. Much battle of legal procedures and lobbying preceded in order to strike a fair balance between the designation of an unbundled single Hydrogen Network Operator (HNO) and the rights of the private operators of the hydrogen transportation network.

Construction and repurpose of natural gas pipelines. Source: iStock

In the meantime, Norma is actively involved in advising clients on the legal aspects of hydrogen production, distribution, and utilisation. She had helped companies navigate the complex regulatory landscape and had worked with policymakers to ensure that the federal and regional hydrogen strategies and frameworks could be reconciled and aligned.

She was currently representing a company that was repurposing decommissioned natural gas pipelines to transport hydrogen from production sites in the coastal and harbour regions to industrial clusters in the heart of Europe. The project was a significant undertaking, involving extensive regulatory approvals, environmental assessments, and stakeholder consultations. But Norma was confident that it would pave the way for a market and economy in hydrogen molecules (and H_2-derivates) in Belgium and beyond.

As Norma pondered over the progress made, she could not help but feel optimistic about the future. She believed that hydrogen would play a crucial role in decarbonising Belgium's energy system and reducing its greenhouse gas emissions.

Norma's phone rang, interrupting her thoughts. It was her colleague, Emma, calling with exciting news. "Norma, you won't believe it!" she exclaimed. "The hydrogen pipeline network project has been approved, and construction is set to begin next year!"

Norma could not contain her excitement. The project had been a labor of love, and seeing it come to fruition was a dream come true. She thanked Emma for the update and hung up, feeling a surge of pride and satisfaction.

Fast forward to 2035

Belgium had indeed become a leading hydrogen hub in Europe, with a well-established hydrogen ecosystem that encompassed all stages in the value chain.

The hydrogen pipeline network had been successfully completed, connecting hydrogen production sites along the coast to industrial clusters in the heart of Europe. It had become a critical infrastructure for transporting hydrogen efficiently and reliably, enabling its use in various sectors, including industry, electricity production and transportation.

Belgian ports offer development opportunities for large-scale hydrogen projects. Source: Unsplash

Several large-scale hydrogen production projects had also been implemented, utilising both blue and green hydrogen technologies harmoniously. Blue hydrogen, produced from natural gas with carbon capture and storage (CCS), had been deployed alongside green hydrogen, produced through electrolysis powered by renewable energy sources. This combination had helped Belgium achieve a balanced and sustainable hydrogen supply chain, meeting its climate goals while ensuring energy security.

Norma had also worked on innovative projects that utilised hydrogen for energy storage and grid balancing. Large-scale hydrogen storage facilities had been built, allowing excess renewable energy to be converted into hydrogen and stored for later use. This had helped address the intermittency challenge of renewable energy sources, making the energy system more resilient and sustainable.

Moreover, hydrogen molecules had become a key ingredient in Belgium's industrial processes. Industries such as steel, chemicals, and refining had successfully integrated hydrogen into their operations, reducing their carbon footprint and enhancing their competitiveness in the global market. Hydrogen had also enabled the production of green chemicals and fertilisers, contributing to a circular and sustainable economy.

As Norma looked back on the progress made, she felt a sense of pride in being part of Belgium's hydrogen journey. She had witnessed the country's transformation into a hydrogen hub, with a thriving hydrogen industry, a robust infrastructure, and a sustainable energy system.

But Norma was not one to rest on her laurels. She knew that there were still challenges ahead, such as the need for continued investment in research and development, the development of international hydrogen trade agreements, and addressing social and environmental impacts. However, she was confident that Belgium was well-equipped to tackle these challenges and continue its path towards a greener, more sustainable future.

Norway, 2035

Author: Catherine Banet

West coast, mid-Norway, 7 March, 2035, 7 am – a hydrogen plant

Warming her hands around a cup of coffee, Ingrid, supervisor of the hydrogen production and processing plant for transport and consumption, looks at the sunrise over the inner fjord from the upper roof of the building, on her way to the plant's control room.

She enjoys this moment, reflecting on what has been achieved since the project's inauguration, and the tasks still ahead for her team. Working in a building that won an award for best industrial architecture adds an extra motivation in this early morning. Optimising the location of the plant inside the fjord and minimising its visual and environmental impacts were part of the winning criteria. It was an important permitting requirement too.

Picture: Norwegian fjord (c) Catherine Banet

Renewable or low carbon hydrogen? Both, please

Ingrid is taking over as the night shift is leaving. Hydrogen is flowing in and out of the compressor plant at full speed for transport into the undersea pure hydrogen pipeline system.

Ammonia from the low-carbon hydrogen produced from natural gas with carbon capture and storage (CCS) is shipped by boat to the international markets, while renewable hydrogen produced by electrolysis of water from offshore wind parks is transported through the dedicated pipeline to a receiving terminal in Germany.

Separating routes for low-carbon hydrogen and renewable hydrogen were put in place progressively once the Norwegian offshore wind production delivered sufficient electricity to be used for hydrogen production. Ingrid thought of some of the history on this.

At the start of the project, an assessment was done on the extent to which the natural gas resources on the Norwegian continental shelf were sufficient to carry on the project. The question of the use and taxation of offshore wind production for hydrogen to Europe was heavily debated in the Norwegian parliament. Similarly, politicians, industries and unions spent long hours arguing around the need to keep the future surplus of energy production for domestic use, and how to account for national needs and cooperation with European partners. The grounds of this collaboration, the European Economic Agreement, has shown its resilience, with a few adaptations adopted over the years.

In the end, the government coalition parties agreed that developing in parallel hydrogen production from natural gas with CCS, and hydrogen production from water via electrolysis using renewable energy, would be fundamental to striking a good balance of revenues for Norway while ensuring good resources management. This approach mirrored the conclusions of early work by the International Renewable Energy Agency on global hydrogen transport, based on the transport of ammonia by boats and of hydrogen by pipelines[372]. In the pipelines going to Europe, there is therefore renewable hydrogen, commonly called green hydrogen. This hydrogen will be instrumental for European countries for fulfilling EU target requirements for renewable hydrogen.

Another source of pride for the coalition parties was that the pipeline was assembled using local contractors who won the contract. Ingrid's mind circled further.

Hydrogen hubs concept for Norway

What one cannot imagine from the shore is that a hydrogen storage site is laying on the seabed of the fjord. Hydrogen is used by the local industrial park gathering companies within steel production and fertiliser sectors, among many others. In addition, hydrogen is delivered to the domestic consumption market as fuel for coastal ferries and heavy road transport, and as security against intermittent power supply to fish farms. This inner-fjord, and the valley around it, embodies the hydrogen hub vision carried out by a cluster of local and national actors 15 years ago.

Ingrid joined the company when it was negotiating the project's inclusion on the EU's list of Projects of Common Interest. Putting together the financing for all projects was challenging, and some smaller projects in the hydrogen hub did not materialise. For example, plans for a hydrogen neighbourhood, where homes produced and consumed hydrogen (e.g. from waste) and fuelled hydrogen cars, did not materialise. But the technology and knowledge developed was used in other projects around Oslo, within a more densely populated area.

The infrastructure was developed through financial mechanisms including investments in equity from a French and Danish joint venture to accelerate the electrolyser capacity across the Nordics[373].

Permitting for the pipeline was challenging, but there was a momentum created by the signature of a political memorandum of understanding[374] and industrial partnerships. The EU Energy Purchase Platform AggregateEU[375] continues to be instrumental for Ingrid's company in signing hydrogen sales agreements with European buyers. The pipeline is part of the Nordic hydrogen backbone developed in collaboration with Nordic countries and partners from EU countries.

Ingrid's mind raced to enjoy the moment again. The winter is ending and the snow is slowly melting, feeding the waterfalls. It's a reassuring moment after many years of financial and geopolitical uncertainty following the disruption of energy markets as a result of the war in Ukraine, the repeated threats from Russia, and the chaotic acceleration of the energy transition in Europe. It is now the second year of hydrogen delivery, and the focus for European customers will be on filling hydrogen storage sites for the next winter.

Molecule Jazz Festival - community engagement

Ingrid's phone rings in her pocket. It is her German colleague, Karl, calling from Essen. He is on his way to a weekend at the annual Molecule Jazz Festival, organised in the neighbouring city. Their respective companies are founding members of the festival, and have invested in several local cultural and social projects in favour of local communities. They are even sponsoring the H_2High triathlon, the second biggest run after Norseman.

Celebrating European value chains

During the jazz festival, they serve locally brewed cider from the apple fields around the fjord. Being from the rural countryside of southern Germany, Karl already looks forward to raising his glass of Norwegian cider, for a "skål" to what they both call the "solidarity molecules", both in the glass and in the pipeline. He likes to compare the cider press process with an electrolyser producing hydrogen from renewable energy sources, just as fruits. The juice – or gas – can be stored, fed into the grid and used in diverse processes. In a further hydrogen analogy, apple cider uses certification schemes to ensure trust. You can run state-owned facilities or local cooperatives alike to hydrogen. The most important common denominators remain for both - sustainability and reliability.

Final thoughts on solidarity molecules

When holding his traditional opening speech at the festival, Karl often turns to his French friend, Mathieu, who runs a car show for hydrogen vehicles during the festival event. Karl bought his hydrogen car manufactured by Mathieu's company. It is now boarding time for Karl, who embarks with his car on the hydrogen-powered ferry to southern Norway from the German coast.

Picture: Pixabay, Norwegian map & zero emission cars, Catherine Banet

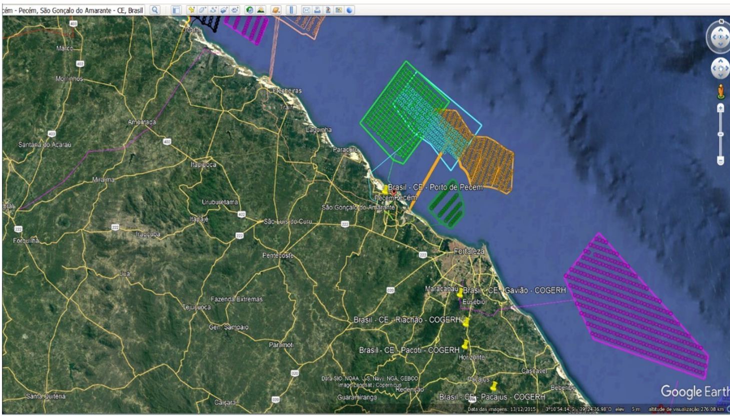
Ingrid wishes him a safe and green journey – thinking how wonderfully the European value chains of "solidarity molecules" are now working in practice.

Brazil, 2035

Author: Luiz Piauhylino Filho

Green H2 – Brazil, 11 February, 2035

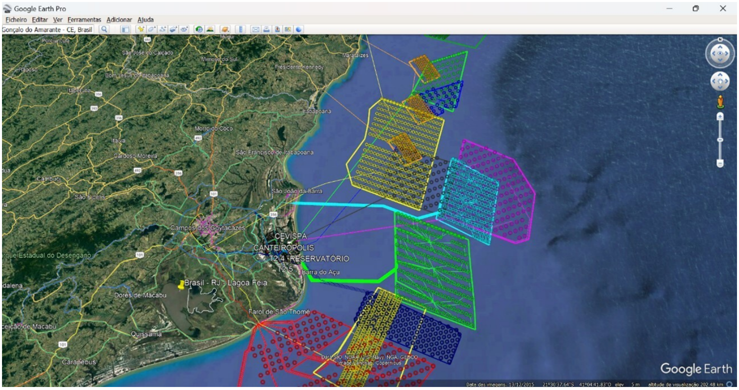
11 February, 2035, flying from Portugal to Rio de Janeiro, Brazil to visit our green hydrogen projects in the world's champion of renewable energy, with over 92 percent of renewables in its energy production matrix[376]. My plane is still 55 km from the coast of the state of Ceará[377], and I can already see offshore wind and solar parks and their huge green hydrogen platforms, where they are producing, compressing or liquefying and exporting green hydrogen to Europe. By 2050, Europe will need to install more than 3,350 GW of new renewable generation. I can't count them all, but I know there were more than 15 GW of offshore wind parks installed in operation in that region. Environmental licences for more 100 GW[378] are still pending.



Source: Author's research permits offshore wind.

In another half hour, I will start to see the state of Ceará and Pecém port[379], where many pipelines are coming from the sea to supply green hydrogen to industries at the port such as green steel, green ammonia, green methanol and sustainable aviation fuel (SAF) producers.

In three hours I will land in Rio de Janeiro. But in about 50 minutes, from the right side of the plane, I will be able to see the second biggest port of Brazil in operation, Açu Superport[380], also surrounded by offshore wind and solar parks, onshore wind farms and onshore floating solar farms. A huge green hydrogen project for green steel manufacturing has been built there, with 2 GW from onshore floating PV and 1 GW from onshore wind farms to produce 100,000 tonnes of green hydrogen per year to our offtaker.



Source: Author's research permits renewable energy.

Touring from Rio to Açu Superport in Hydrogen spirits

I arrive in Rio de Janeiro after 10 hours of flying. I decide to stay a couple of night to meet old friends. On 14 February,2035, I rent a Toyota Mirai, fuelled with green hydrogen, to drive four hours back to Açu Superport and see our projects in operation. On the way, I see many fuel stations selling green hydrogen produced locally from the ethanol reforming system also installed in gas stations. Brazil has more 40,000 gas stations that have been selling ethanol for more than 40 years.

Source: Unplash

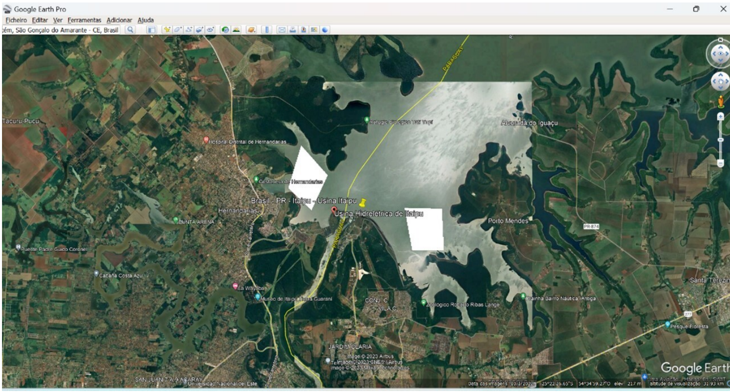
Just 20 km from Açu superport, I reach the location where our projects are producing green and renewable energy to power our 2.5 GW of electrolysers inside Açu Superport, close the green steel plant. The energy production at the site is amazing, 2 GW of floating solar in a lake located less than 20 km from the port, surrounded by 1 GW of shore wind farms, all connected through direct transmission lines. Our green hydrogen is receiving more than 90 percent of off-grid energy to ensure a very competitive levelised cost of energy.

Source: Authors photo collection.

After spending a few hours supervising the energy production site, I drive more 40 minutes to Açu Superport, and check the 2.5 GW of electrolysers plant, where I stay for a few days.

Flying out to Foz do Iguaçu

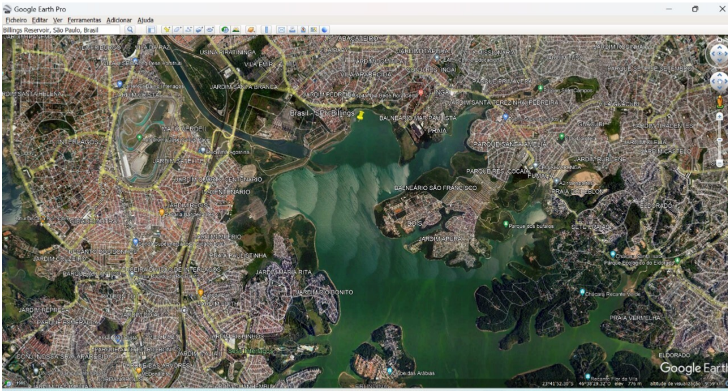
After few days in the region, I catch the green hydrogen based SAF fuelled plane from the airport of the city of Campos[381] to fly to Foz do Iguaçu[382]. Here I will visit our second green hydrogen project, the biggest "Green hydrogen"/"Green Ammonia"/"Urea" project in Brazil. This project involves 2 GW of floating solar at Itaipu reservoir[383], and 1 GW hydro energy from Itaipu to produce fertilizer for the agriculture of states of Paraná, Mato Grosso, Mato Grosso do Sul, and Goiás.



Source: Authors planning overview of Itaipu.

Sao Paulo - making use of its water for industry and transport

Now São Paulo is waiting for us. Before landing at Congonhas Airport, I fly by the Billings Reservoir, with 10,700 hectares of water surface, only 23 km from São Paulo's city centre. This project involves 1 GW of floating PV, plus renewable energy from the grid. It powers 800 MW of electrolysers and produces 40,000 tonnes of green hydrogen to fuel buses for the metropolitan area of São Paulo, and chemical and fertiliser industries located in Cubatão, close to Santos Port.



Source: Billings reservoir near Sao Paulo, author.

Final reflections on Brazil hydrogen future

During this week spent travelling and visiting all those projects in Brazil with a levelised cost of hydrogen below €2 per kg, we can see how the country has developed in the past 12 years to become one of the biggest producers of green hydrogen for itself and for the world, making economies cleaner, more sustainable and cheaper. In Brazil, we burn less gasoline and gas oil, we import less fertiliser, we produce domestically and in a sustainably. We are producing electrolysers for our projects domestically, eliminating the need for imports. We also produce SAF for domestic aviation in several states. The Brazilian oil company Petrobras is converting its oil platforms into green hydrogen platforms to produce green hydrogen. Twelve years ago, Petrobras was the biggest gray hydrogen producer and consumer in Brazil. Brazil has around 250 GW of installed capacity from all energy sources, however, if the country decides to support the European market with only 10 percent of the green hydrogen and its derivatives demands, we need to install more 300 GW of new solar and wind parks within 28 years.

Finally, it is time to go back home to Portugal to check with my daughter how our green hydrogen project at Sines Port is going, and eat a delicious cod fish with Portuguese red wine from the Alentejo region, capped off with a Pastel de Nata for desert.

Portugal, 2030

Author: Maria Eduarda Piauhylino

The thriving Portuguese green hydrogen market

This is a story of what the Portuguese hydrogen market will look like in 2030, with an overview of the impact on the local economy and hydrogen-related stakeholders.

Lisbon, 30 May 2030.

It's almost summer time, and here I am leaving Lisbon to enjoy a few days at the beach. I've just crossed the bridge over the Tagus river and the first toll, leaving behind the city traffic. I am headed for the A2 south to the Algarve, so I can enjoy the first warm summery days.

It feels amazing to be finally driving my fuel cell car down south for the first time. Life has changed so much in the past eight years, and I'm so happy to see how far we've came. We are now living in an era of green solutions and reducing carbon emissions to the minimums. We can finally retire old electric cars, which have been accumulating in a piles of used metals, for which I hope someone can soon find a solution [384].

Source: Creative Commons license, web image of route A2 South

Along the A2 South towards the Algarve, I will pass through the Setubal and Alentejo region. At exit nine, after about 45 minutes of driving, I quickly decide to make a quick pit stop around Sines to fill up my car with locally produced green hydrogen and look around.

From the exit I reach IP8 and make my way through Alcácer do Sal, where I start seeing large-scale solar plants and wind farms on the horizon. Sometimes I even lose site of the end of these massive solar plants. As I drive, I contemplate the beautiful and typical Alentejo landscape and reflect on how the Portuguese government has done an excellent job in preserving the environment and promoting a renewable energy market at the same time, proving that a world where we live in harmony with the environment is possible.

Source: Creative Commons license, web image of Alentejo solar plants.

Today, this region around Sines is considered the largest renewable and green hydrogen hub in Portugal and one of the largest in Europe, producing and exporting green hydrogen and its by-products to European countries including Germany and the Netherlands. It's impressive how the Portuguese national hydrogen strategy[385] (EN-H2) has helped to transform Sines and the surrounding cities in the past few years. It amuses me how the little villages that had nothing but small farmers, fishermen and elderly people is now a vibrant and pulsing town, full of buildings, shopping centres, schools and universities and, most importantly, an internationally recognised hub for green solutions. The hydrogen projects have brought to this region a young and specialised workforce. It's made Sines and its surrounding area one of the wealthiest regions in Portugal, bringing up not only the Portuguese workforce but people from all over the world who want to move to the region for excellent work opportunities and quality of life. It's amazing to drive around town and see how many school, universities and institutions are testing new solutions and preparing the next generations to take over the Portuguese renewable and green hydrogen market in a couple of years.

While I drive around town I see the first gas station that sells green hydrogen. The price says €2.35 per kg. My curiosity strikes and I decide to explore a bit more before my stop. This gas station is near the Sines Industrial Zone (ZILS) and I just need to have a closer look at what's happening there.

ZILS is packed with all types of green hydrogen related projects, from small and mid size projects for mobility and blending, to large-scale production of green hydrogen, to large-scale production of its by-products such as green methane, green ammonia, sustainable aviation fuels, and green steel. It's fantastic to see how Portugal became a heavy industry country and now gives a huge contribution to the decarbonisation of the local and European economy. Very soon the green hydrogen produced here will be transported through a dedicated pipeline connection southern Europe to the north, starting in Portugal and passing though Spain, France and Germany (the European H2 pipeline[386]). This pipeline is now under construction and is planned for completion in two more years.

Source: Creative Commons license, web image of Portuguese company PRF – Hydrogen Fueling station

Continuing the drive, on my left side I start to see the hydrogen mobility centre. I can also see the factory where the electrolysers are installed and the green hydrogen is being produced and stored on site. Public buses and municipality vehicles are waiting to be fill up.

Farther ahead, I start recognising several medium- and large-scale green hydrogen producers on both sides of the road. It's impressive to see how this market was capable of sustaining different types of players, from start-ups to large conglomerates. Theses factories are already feeding the green hydrogen into the new dedicated pipeline ring that passes by the factories and connects the producers to the main consumers. Eventually, it will connect to the European Green H2 pipeline too. Some of the smaller and mid-size projects are already feeding a domestic pipeline where the green hydrogen is being blended to natural gas at a rate of 15-20 percent and consumed locally in the Seixal and Setubal region[387].

I will never get used to the feeling of arriving in the ZILS, where once unused land is now a thriving the green hydrogen economy. Nearing the port area, I can see from far away the huge project that transforms the local hydrogen into products such as green methane and green ammonia[388]. These two factories have easy access to the harbour and railway, where they can easily transport and export their final products. I've heard that in a couple of months the first vessel of compressed green hydrogen will make its first test trip, carrying Portuguese green hydrogen to Germany. Everyone is excited to see how this will go.

Source: Creative Commons license, web image of Ammonia project in Sines.

Conclusion

I start making my way back towards the city centre and decide to visit an area where major international electrolyser producers have their own installations and are now assembling different types and sizes of electrolysers. These companies are all doing very well and Portugal became an interesting place to produce and export the electrolysers, due to government incentives and geographic location.

Continuing on my way, I find some other fuelling stations where the prices range from €2.35 to €2.50 per kg of hydrogen. I choose a fuelling station with a restaurant nearby, where I fuel up the tanks, have lunch and contemplate everything I have seen, before heading south to enjoy the beautiful and sunny days.

Nigeria, 2045

Author: Ben Egbe

A honeymoon bus trip - on the road to see the new hydrogen economy

Mr. Icha's son had just bade goodbye to the last guest at his traditional Nigerian marriage ceremony. As he walked back into the compound, he noticed the lonely figure of his father holding a small glass cup containing "kai kai", a local gin[389]. He began to think about how best to reward his father for all the support. He and his new wife decided to invite him to join them on their honeymoon. Their plan was to visit the renovated Yankari games reserve in the Northern part of Nigeria[390]. Amid the still-to-be-heard music gyrations, the sounds of the ukulele, drums fading in the background, he approached his father and made his invitation. Even though it was not in his immediate plans, to Mr. Icha the thought of a cross country trip that will traverse the length of Nigeria was more appealing than staying alone in the village.

Source: Common Licence; Flickr – the best of an African drum. Just like an energy hub, the African drum pulls together dancers, singers, by-standers, on-lookers and elders into a web of joyous dancing gyrations.

While his son wanted to fly to the reserve, Mr. Icha preferred go by road to view the effects of the hydrogen economy on Nigeria's landscape. His son protested, but he was adamant and his son grudgingly accepted. Still, his son kept wondering why in 2045 anyone would prefer to sit on a bus for 14 hours when you could fly and arrive in an hour. He was also concerned about the accidents and kidnappings that had become incessant over 20 years ago. Mr. Icha, who had retired from the Energy Transition Department in the Vice President's office after 40 years, was excited to have the opportunity to ride one of the luxurious hydrogen-fuelled buses now prevalent for long distance travels in Nigeria and West Africa. To allay his fears, Mr. Icha showed his son data that suggested that as the economy had improved and security forces paid more, the kidnappings and insecurity had declined drastically.

Mr. Icha decided to show his enthusiasm for road travel by telling his son about how he had worked on developing policies for two key sustainability projects for his department that set the pace for the adoption of the hydrogen economy in Nigeria[391]. He retired in 2035, before the projects could be funded and executed. He mentioned that the projects had largely been delayed due to funding. Investors were looking to see how the early adopters - Namibia[392], Morocco[393], Angola[394] and South Africa[395] - would fare. He read in the papers that the projects have now been funded by the Africa Green Fund (a fund set up by the UNFCCC to address loss and damage after the 2023 COP28 climate conference [396]). He remembered the lush design, the sleek equipment, the massive electrolyser piles and the solar farm adjacent to the industrial building housing the electrolysers. He chuckled when he remembered his good friend, a lead engineer who travelled to Ireland and Germany to learn and transfer the hydrogen technology to Nigeria. The friend would not return to Nigeria after the training. Well, thank God the others did return, he muttered under his breath.

Riding through the fossil fuel Past

They boarded the hydrogen-fuelled bus in Warri township[397], a town in the south of the country once renowned for its contributions to the fossil fuel economy. That industry contributed to 6.33 percent of Nigeria's GDP and about 90 percent of its export as far back as 2022. After a quiet period following the dwindling fossil fuel business and the gradual mix of its energy portfolio with renewables, especially solar, Warri is now steadily repositioning itself as a fledgling hub for global ICT manpower and energy infrastructure repurposing. When asked by his son's wife, Mr. Icha explained that Warri's revenue had been steadily declining since the international oil companies had left. The indigenous companies that took over have struggled due to largely inadequate financing, a hostile operations environment and host community demands.

Source: Common Licence. The Northern Times. Photo by Matti Blume – the bus Mr. Icha may have used for the road trip.

The primary economic mainstay for Warri was the gas pipelines being repurposed to transport hydrogen, and as required, ammonia, to the chemical complex about 200 km away in Eleme, he added. The complex in Eleme produces the fertiliser required by most farmers in the country and exports to neighbouring countries.

After travelling over 200 km from Warri, he was quick to point at the Eleme complex when the bus passed it[398]. He noted that a structure that was not in the original plan seemed to have been included. He called his former apprentice, now a manager, Mrs. Shata, who confirmed that the Eleme complex had been extended to include a methanol production unit, and a power generation section that runs on ammonia[399] and powers the entire hub. It uses ammonia for this generation and supplies its excess electricity to the national grid.

About three hours after passing Eleme, just when it seemed the journey was becoming boring, Mr. Icha suddenly sat up, noticing the large stretch of forest covering several km. This was the forest project his last company engaged in, to offset the carbon released into the atmosphere from its projects, including one called Wazobia[400]. Wazobia was first planned to produce grey hydrogen, using methane but without carbon capture and storage capability. This was largely because of the abundance of methane in the country, and the nascent state of the solar PV sector. The carbon price in 2045 at about $510 per tonne of Co2 perhaps justifies the effort, Mr. Icha thought. But he had scarcely cleared his thought, when his son's wife asked what the difference was between grey and green hydrogen. He explained that grey was not fully clean, as you still had to use methane for the hydrogen production and released some carbon into the atmosphere, whereas with green, water was the only residue. His department invested in the tree planting project they had just passed in order to to offset the carbon emissions. That fossil past was now increasingly disappearing.

Wazobia: The hydrogen hub by the banks of the river Niger, and its slow progress

Finally, the bus reached the Wazobia Hydrogen Hub, and suddenly Mr. Icha could not wait to disembark and take in its full image. When he did, all he could utter was “wow!”. Even though it had taken a decade to complete, its completions was a dream come true, he told the first person that cared to listen - his son’s wife.

The Wazobia Hydrogen Hub is the country’s pilot green hydrogen project. Its initial phase comprises a minor electrolyser facility, hydrogen storage and compression facility, shipping and dock area, multi-purpose refuelling station that doubles as information and maintenance section, and a large[401] solar farm with capacity to produce about 0.2 GW at peak, coupled with electrolysis. The solar farm not only gets the electrolysis going, but sells its excess power generation to the national grid. It is located by the banks of the river Niger, en route to Bauchi, where the Yankari games reserve lies. Most of the hydrogen buses must stop to refuel and run checks at the hubs station when on long distance trips. The hub is the product of a public-private partnership involving foreign governments, agencies, local players and the Nigerian government leading the policy coordination that was critical in making it happen[402].

Even though the complex’s first phase was not fully finalised, several components were in use - the refuelling stations, the solar farm that produces the power required for the electrolysis process and the dredging of the river to allow for the easy access of the ships expected to transport hydrogen to Europe in compressed or liquid form. A key aspect of the project still outstanding was the high-pressure storage cylinders[403]. This suffered significant delays as the project engineers were not certain which vendor technology would be more practical in the face of continuous offers of newer technologies and resulting cost competition. The mandate for the project was to be able to compete with other global hydrogen producers, since they all share a common market inter alia in Europe, hence addressing best economic means of storage would be key[404].

Even now green competition continued, leading to all boats rising with the tide of the energy transition, Mr. Icha thought with a smile.

As he took in the sight, he recalled several policy errors he felt had delayed the adoption and implementation of renewable energy and hydrogen as one of the solutions in the toolbox of energy carriers and as storage. How he wished those policy makers had been on top of their game and that implementation had not been an issue.

"I could have been driving a hydrogen car by now," he told his son. "Well, perhaps by 2050!" his son responded. "You know EVs have the moment, father."

Source: Common Licence; USAID/Power Africa (sustainablegoals.org.uk) – what a solar farm may take in terms of landscape.

As the bus prepared to leave the hub, Mr. Icha noticed a long queue of well-maintained trucks streaming into the valley and could not hide his curiosity as he asked the hydrogen refuelling station manager about them. These were hydrogen-powered trucks recently introduced by a technology-based start-up that focuses on long distance logistics and associated efficiencies. As the journey continued, he started looking out for more hydrogen trucks, trying to determine the ratio of diesel to hydrogen trucks. When he arrived at the game resort, he told his son that he pegged the ratio at about three to seven, compared to zero to 10 in 2023. Diesel trucks did still prevail, slightly, in 2045[405].

Conclusions – reflections on the hydrogen future at the Yankari games reserve

Once arrived, they realised that the game reserve was now largely powered by solar panels and batteries, enhanced with a fuel cell power generation whenever the grid went off. That was symbolic. On their last visit in 2023, the reserve had had its own diesel generator for backup.

By the end of the day, his son and daughter-in-law had come to appreciate how much the Wazobia hub meant to Mr. Icha, and the extent to which the country's energy mix had changed over 20 years to become cleaner and more sustainable.

The pace with which hydrogen will be adopted in Nigeria will largely be a function of policy, the outcome of first-mover pilot projects in Africa, and the resistance of fossil fuels dependencies.

And just as Mr. Icha was going to bid goodnight to the honeymooners; the food truck that supplied cold food to the game reserve drove in for a delivery, and guess what? It was a hydrogen truck[406].

Egypt, 2045

Author: Amira Korayem

It was 2045, and Nawal woke up to the melodious sound of birds chirping outside her window. It had been two decades since she had moved to Al-Fayoum, seeking solace from the bustling city of Cairo. And even after all these years, she still cherished waking up early to the symphony of nature. As she sipped her morning coffee on the balcony, she perused the newspaper, until she was captivated by one particular headline.

A new chapter in Egypt's technical education: Empowering the future workforce.

Nawal read with excitement about the inauguration of a local technical school opening to students that day. Over the past couple of years, Egypt had witnessed the rise of technical schools, producing skilled mechanical and electrical technicians predominantly working in hydrogen production plants and transport networks. With the hydrogen economy flourishing in the region since 2025 and the country's population steadily increasing, these technical schools had become increasingly popular.

Recognising the value and importance of a skilled workforce to its future, Egypt had taken proactive measures to introduce and support alternative paths of education. As a result, Egypt was now the North African hub for technical education, with an impressive 70 percent of the skilled workforce graduating from such institutions.

Eager to witness the impact of technical education first-hand, Nawal and her daughter hopped on their bikes and rode to the school. As they pedalled along, regional trains powered by hydrogen whizzed by. These trains never ceased to amaze Nawal - they were a symbol of how much had changed in the past two decades. Egypt's trains were now fuelled by either renewable power or hydrogen, as local hydrogen production had become a significant part of the country's energy landscape. Many trains still traversed Al-Fayoum, carrying cargo destined for Europe and affirming Egypt's position as a crucial logistics hub.

After dropping her daughter off at the school, Nawal set off on her favourite route to a nearby café. It was a long ride from their home on the outskirts of the city, but the fresh air and picturesque surroundings made it worthwhile. Cycling along the dedicated bike paths that cut through the lush agricultural fields of Al-Fayoum, Nawal marvelled at the country's commitment to preserving existing farmlands. Since the initiatives that started in 2019, Egypt had invested in a range of projects aimed at safeguarding agricultural areas, coupled with ambitious desert greening efforts along the northern and eastern coastlines. Additionally, focused efforts were made to rehabilitate lands suffering from soil degradation between 2011 and 2014. The satellite imagery of Egypt proudly displayed the progress made in these endeavours, showcasing vibrant green areas flourishing along the banks of the Nile.

Settling into her favourite corner of the café, Nawal opened up the newspaper, catching up on the news before commencing work. As a research energy engineer at Fertiglobe, one of the leading hydrogen-producing companies in the region, she was deeply invested in Egypt's journey towards sustainable energy. Today she started with an article titled "The Impact of the Hydrogen Economy on Egypt" - written by none other than her husband, Yousef, a prominent journalist.

Yousef, not one to shy away from expressing his opinions, had raised concerns about Egypt's hydrogen production and its significant environmental ramifications. The establishment of large industrial cities like Suez and Port-Said, driven by hydrogen plants, had forced many locals to seek refuge elsewhere, yearning for quieter and healthier living environments.

With a mix of curiosity and trepidation, Nawal opened her laptop, shifting her attention to her own research and analysis.

"Nawal,"Yousef interjected. "Would you like another cup of tea?"

Grateful for his offer, she smiled and nodded, and he disappeared back into the café. Nawal closed her laptop again, reclined in her chair and marvelled at the splendid, timeless view before her. How many people had basked in this view over the past thousands of years?

Returning with a steaming cup of tea and a hint of freshly cut mint leaves, Yousef joined Nawal at the table. Both looking out at the view, Nawal posed an unexpected question. "If our ancestors were here to witness us and our country today, what do you think they would feel? Would they be proud?"

He sat silently for a moment, putting his arm around her as he thought it over. "They would be proud. Proud of our resilience, our ability to overcome countless obstacles, and the progress we have achieved. Our ancestors, the Pharaohs of old, were ambitious visionaries, unafraid to push the boundaries of what was possible. And so are we. We have persevered, standing tall today, our spirits as indomitable as the pyramids themselves."

A gentle chuckle escaped Nawal's lips. "You do have a way with words, Yousef."

Grinning, he replied, "These words have echoed in our hearts for years, and one day, they will manifest into reality."

Intrigued by her husband's perspective, Nawal pressed further, her gaze fixated on the waning light. "But do you think our parents could have made different decisions, leading our country towards a more independent path separate from Europe?"

Yousef exhaled deeply. "That's a complex question that deserves more than a day's contemplation. Our history, the intricate web of geopolitics, and the myriad variables at play—we must carefully unravel this tapestry to truly comprehend the possibilities."

Sharing a knowing smile, they acknowledged that the pursuit of answers to such profound questions would be an ongoing journey. They sat in blissful silence, their hearts ablaze with hope, determination, and an unwavering belief in the boundless potential of their beloved Egypt.

Kazakhstan, 2049

Author: Dr. Venera N. Anderson

Hydrogen Silk Roads and Hubs

"For centuries, fame and fortune were to be found in the west – in the New World of the Americas. Today, it is the east which calls out to those in search of riches and adventure. Sweeping right across Central Asia and deep into China and India, a region that once took centre stage is again rising to dominate global politics, commerce, and culture" (Frankopan, 2015).

Hydrogen Silk Roads - prologue

The young camel looks awestruck. The proud animal resembles a majestic monument not bothered by the winds sweeping through the rolling steppes. Only eyes are moving, mesmerised by the far-away trains flying like enormous metal brown arrows in the grass. These cargo trains are carrying "green gold"[407] – clean hydrogen - to Europe, the continent on a mission to liberate itself from fossil fuel dependence.

It is September 1, 2049. I am travelling through Kazakhstan, with stops at the hydrogen hubs near the Caspian Sea and onwards to Astana, where I will present my analysis of the country's contribution to building a global hydrogen economy.

Intermezzo on Kazakhstan

Kazakhstan is the world's largest landlocked country. It is bordered by Russia to the north, Kyrgyzstan and Uzbekistan to the south, Turkmenistan and the Caspian Sea to the west, and China to the east. The country has a population of 18.7 million, a land area of 2,717 300 square kilometres, and a coastline of 1,894 kilometres on the Caspian Sea[408].

Kazakhstan in Asia. Open source

Flashback to childhood & Hydrogen silk roads

It's the day before my business meetings begin, and I'm patiently waiting for my camel to rejoin the group on the overnight trek near the Caspian Sea. It's a thrill to relive my early childhood days when I rode camels with my parents in southwestern Kazakhstan. In school I was captivated by geography and history and always wanted to visit the sites of ancient civilizations. I wanted to explore the legendary Great Silk Road, envisioning my ancestors travelling and conquering Eurasia. Peter Frankopan describes the such road as *"a network that fans out in every direction, routes along which pilgrims and warriors, nomads and merchants have travelled, goods and produce have been bought and sold, and ideas exchanged, adapted and refined. They have carried not only prosperity, but also death and violence, disease and disaster. In the late 19th Century, this sprawling web of connections was given a name by an eminent German geologist, Ferdinand von Richthofen (uncle of the First World War flying ace the 'Red Baron') that has stuck ever since: "Seidenstraßen" – the Silk Roads*[409]*."*

On the territory of modern-day Kazakhstan, the Great Silk Road started at the borders of China. The primary route ran through Semirechye, in south Kazakhstan, the cities of Sairam, Yassy, Otrar, Taraz, Central Asia, Persia, the Caucasus, and continued on to Europe. The first president of Kazakhstan, Nazarbaev, proclaimed that "the unique geographical location of Kazakhstan – at the very centre of the Eurasian continent – has contributed to the emergence of transit corridors between different countries and civilizations since ancient times.[410]"

In the 21st Century, given its geographic location and sheer longitude, the country has played a pre-eminent role in forming the so-called New Silk Road. For example, in September 2019, President Tokaev noted that five railway lines and six international auto routes enabled the delivery of goods from China to Europe and back, through Kazakhstan, in 15 days. Shipments by sea took two to three times longer. He proclaimed that the national programme of infrastructure development, Nurly Zhol, coupled with China's One Belt, One Road initiative, would revive the former greatness of the Great Silk Road[411]. The One Belt, One Road initiative was launched during Chinese President Xi Jinping's visit to Astana in September 2013, spotlighting Kazakhstan's key role in China's Central Asian strategy to develop overland trade routes with the European Union[412].

Furthermore, geopolitical events of the 2020s highlighted the importance of multiple transit routes through Eurasia as crucial components of energy security and economic growth for the nations connected by the New Silk Road. For instance, the Trans-Caspian International Transport Route, also known as Middle Corridor or the Iron Silk Road, became especially important for Kazakhstan. It provided various links from Xian, in China, to Istanbul, in Turkey - through Kazakhstan by rail; by sea from Baku, in Azerbaijan, across the Caspian Sea; and by rail through Georgia[413].

Private investors, such as Wagenborg Deniz LLP, contributed to the Middle Corridor's viability by offering an alternative to the existing cargo route through Russia - using barges to transport cargo trains across the Caspian and Black Seas.

Thus, by with its partners connected by the New Silk Road, Kazakhstan had solidified its position as a premier trade and logistics hub in Eurasia.

Decades ago, my parents and I stopped on camel trips to observe passing trains. Back then, the cargo trains were full of "black gold" (fossil fuels) from Kazakhstan's abundant stock of natural resources.

Now, in 2049, the New Silk Road had also become the Hydrogen Silk Road, connecting Kazakhstan's hydrogen developers with European and Asian hydrogen importers.

Hydrogen hubs concept coming to Kazakhstan

The following day, I woke up to a glorious sunrise, eager to start my visits to hydrogen hubs in the Mangystau Region. I drafted the beginning of my presentation before the rest of the camel trekking group woke up:

"Kazakhstan has historically been known as Central Asia's largest energy producer and fossil fuels exporter. In 2020, oil and gas industries and related sectors represented 17 percent of the GDP, with oil providing most of the country's export earnings and serving as the key source of government revenue. Coal accounted for nearly half of the country's energy supply, more than 70 percent of its electricity generation, and over 20 percent of its final consumption[414].

Then, a few decades ago, Kazakhstan set out ambitious clean energy transition plans. In 2012, the government launched the 'Kazakhstan 2050' national strategy, which called for the country to generate up to half of its energy consumption from 'alternative and renewable' sources. In 2016, Kazakhstan ratified the Paris Agreement. In December 2020, President Tokaev announced the country's commitment to achieving carbon neutrality by 2060. And in September 2021, the Kazakhstani government presented a draft 'Net-Zero Carbon Emissions by 2060' strategy[415].

In the same decade, Kazakhstan realised the importance of hydrogen energy in meeting its national decarbonisation goals. For example, President Tokaev tasked the government with prioritising hydrogen and creating the Hydrogen Energy Competence Center *at KazMunayGas National Company*[416]*. In June 2022, a Green Hydrogen Alliance was created, with the participation of companies from Kazakhstan, Germany, Italy, and Spain*[417]*. By 2049, hydrogen served as a bridge to Kazakhstan's decarbonisation strategy, focused on expanding renewable energy sources. This clean energy solution has started to decarbonise different high-emitting sectors, such as energy, transport, and industry. It is also playing a vital role in balancing intermittent electricity generation from renewables, grid stability, and electricity demand*[418]*".*

I snap back from thinking about my presentation. The main focus of my trip is on green hydrogen hubs, although Kazakhstan has explored the possibility of producing blue hydrogen from gas and coal[419]. I am especially interested in learning about the transformation of southwestern Kazakhstan, previously known as an oil and gas hub, into a coastal green hydrogen hub[420].

Thirty years ago, my visit to the Norddeutsches Reallabor project - a consortium of over 50 northern German partners from business, science, and government that attempt "holistic system integration" through sector coupling with green hydrogen - served as one of the main inspirations for my research concept, which could be selectively applied in the US coastal regions[421]. I am eager to explore whether a Kazakhstani coastal green hydrogen hub, like the ones in Europe and the USA, has served as a solution for building a hydrogen economy, especially in its early stages. I complete my discovery by exploring two amazing projects.

Amazing future of hydrogen – what do big and bigger projects mean for Kazakhstan?

My visits to Hyrasia One[422] and Fortescue Future Industries' (FFI's)[423] projects exceed my expectations, so I add the following notes to my presentation:

"Kazakhstan has always had substantial renewable energy potential[424], much of which was developed over the past 30 years. In 2021, the technically feasible wind potential was estimated at 920 billion kWh/year. Nearly half of Kazakhstan has wind speeds of 4-5 metres/second at the height of 30 metres. The most significant wind potential lies in Western Kazakhstan, the Atyrau and Mangystau regions near the Caspian Sea, and the northern and southern parts of the country. In 2021, the potential for solar energy development was at 2.5 billion kWh/year. The country usually has an average of 2,200-3,000 hours of sun out of 8760 hours per year[425].

The picture below shows the rich solar and wind potential of Kazakhstan.

Hyrasia – Mangystau region

Hyrasia One, a subsidiary of Swedish-German company SVEVIND Group, developed one of the world's largest green hydrogen production facilities in the Mangystau region of southwestern Kazakhstan. The energy from the wind and sun is transported to a facility close to the coastal city of Kuryk to produce green hydrogen via water electrolysis. The project uses a desalination plant with 255,000 cubic metres per day, a photovoltaic and wind facility with a combined capacity of 40 gigawatts, installed in the vast steppes of the Mangystau[426] region. The annual output of 120 terawatt-hours is used to supply an industrial park of electrolysers on the *coast of the Caspian Sea, with an overall capacity of 20 GW. Since the 2030s, Hyrasia One has produced up to 2 million tonnes of green hydrogen or 11 million tonnes of green ammonia annually. This is equivalent to one-fifth of European green hydrogen imports planned for 2030. The project implementation created 3,500 jobs during construction and nearly 1,800 new permanent jobs during the phased commissioning of the facilities*[427].

Fortescue's green hydrogen projects in the Atyrau and Mangystau regions

I am fascinated by the magnitude of Fortescue Future Industries' green hydrogen production and renewable energy projects. In 2022, the Kazakhstani government and FFI signed a framework agreement on the sidelines of the UN's COP27 climate summit to explore projects in various regions of Kazakhstan, including Mangistau and Atyrau[428]*. All of these projects, primarily Hyrasia One, use transportation options for global and domestic customers via 1) hydrogen pipelines or blending with LNG, 2) ship (ammonia and, possibly, hydrogen), and 3) rail or road (ammonia)*[429].

More importantly, these coastal green hydrogen hubs also transport green hydrogen to their European and Asian customers through railroads and barges via Caspian and Black Seas. These monumental projects use titanium-based hydrogen alloys[430] *created with readily available metals in Kazakhstan. The country has vast reserves of chrome, manganese, iron, and titanium ores, which are used to develop hydrogen storage at affordable prices, versus those produced with rare earth metals*[431]*. By 2049, the proliferation of Kazakhstani's green hydrogen hubs enabled the transformation of the New Silk Road into the Hydrogen Silk Road, linking Kazakhstan's green hydrogen developers with the hydrogen markets in Europe* *and Asia."*

Final thoughts

I am pleased with my visit to the Kazakhstani Caspian Sea coast. Sitting aboard a hydrogen-fuelled plane – yes, Airbus delivered on its 2035 promise - on the way to Astana, I am writing my last presentation notes. I am full of memories, feelings, and new perspectives on the development of the hydrogen economy in Eurasia. It's a journey with landscapes and views that most people can only see in the movies. I also wonder if my camel misses me since I already miss tracing the Hydrogen Silk Road with him.

Astana, Kazakhstan. Open Source.

"*With almost 30 years in the rear-view mirror, I can confidently proclaim that Kazakhstan and its global partners unlocked the country's hydrogen potential and connected it to the global hydrogen economy. However, the country's transformation from a major fossil fuels exporter to a Eurasian green hydrogen leader continues. Kazakhstan still faces limitations, such as relatively scarce water resources and the need to continue transforming its energy regulation system and tariff-setting system to improve energy efficiency, upgrade its technological base and phase out coal*[432]. *Kazakhstan needs to focus on building its local hydrogen economy by using revenues and knowledge transfer from global hydrogen export*[433]. *In doing so, Kazakhstan will decarbonise its emissions sectors and achieve its carbon neutrality goals. I am excited since, during my journey through the Hydrogen Silk Road and hubs, I witnessed how hydrogen is already transforming Kazakhstan beyond one's imagination.*"

I am done with my presentation as I arrive at the Nur Alem Museum of Future Energy in Astana[434]. I smile as I see familiar faces from the global hydrogen network involved in Kazakhstan's decarbonisation. After viewing eight floors dedicated to various clean energy technologies, we are invited to the opening of a new addition to the museum, "Hydrogen in Kazakhstan." Everyone is ready to hear about Kazakhstani progress towards carbon neutrality. The president of Kazakhstan looks at the sea of people in front of him and opens the forum with a quote by Alan Kay[435]:

"*Dear guests, supporters of Kazakhstani decarbonisation. The best way to predict the future is to invent it. Thank you all for inventing our future with us….*"

Where did I hear this quote before as well?

India, 2040

Author: anonymous, with help of open AI. The article has benefited from peer review by India energy experts.

New Delhi, 2040

Source: image generated with help of AI.

It was the year 2040, and India was leading the way in the hydrogen revolution on the back of its transition away from fossil fuels. It had been close to two decades[436] since the government first announced its ambitious plan to transition the country to a hydrogen-based economy[437], and the progress made since then was nothing short of remarkable.

Siddharth woke up to the sound of his phone buzzing with notifications from his colleagues at India Hydrogen Corporation, one of the largest hydrogen producers in the country. The company was at the forefront of the hydrogen economy, and Siddharth had been there since its inception. He quickly scanned through the messages, noting updates on the latest hydrogen-powered buses being rolled out in Mumbai and the progress made on the new hydrogen fuel cell manufacturing plant being built in Pune.

Siddharth finished his morning coffee and headed out to the office on his hydrogen-powered motorbike. Making his way through the busy streets of New Delhi, he couldn't help but notice the number of hydrogen refuelling stations that had sprung up across the city. The government had invested heavily in building the necessary infrastructure to support the hydrogen economy, and it was paying off. Fossil fuel refilling had been converted to hydrogen and electric charging stations, and mobile hydrogen dispensers delivered fuel to those who did not have time to drive to fixed stations.

At the office, Siddarth was greeted by his team, who were working on India Hydrogen Corporation's a joint venture with a Korean company to develop a new type of hydrogen fuel cell that could be used in both cars and trucks. This was expected to revolutionise India's transport sector[438], which was one of the largest contributors to the country's greenhouse gas emissions.

Later in the day, Siddharth attended a meeting with the Ministry of New and Renewable Energy, where they discussed the latest developments in the hydrogen industry. The government was committed to making India a global leader in the hydrogen economy, with a target of producing 10 million tonnes of hydrogen annually by 2040, en route to a net zero-emissions economy by 2070[439]. Energy independence was expected by 2047[440]. The use of carbon capture for coal plants, re-use of that carbon in concrete and synthetic fuels together with hydrogen, and recycling of that carbon through direct air capture technology, were finally being implemented. The latter had become cost-competitive, after a subsidies race in the 2020s between Europe, the US and other high-income countries helped to lower the costs of critical decarbonisation technologies.

Siddharth couldn't help but feel proud of the progress the country had made in such a short amount of time. Over two decades since 2021[441], India had gone from being heavily reliant on fossil fuels to becoming a world leader in the hydrogen economy. The transition had not been without its challenges, but the benefits were clear to see. The air quality in the cities had improved drastically[442], and the country was well on its way to meeting its emissions reduction targets. There were reports in newspapers of a significant decline in airborne respiratory diseases - as the energy transition helped the country overcome the alarming Air Quality Indices seen in the 2020s.

As Siddharth returned home at the end of the day, he reflected on how much had changed since the early days of the hydrogen revolution. The country had invested heavily in research and development, and the universities were producing and attracting some of the world's top scientists and engineers[443]. Technical schools, from which mechanical and electrical technicians that were mostly working in hydrogen production plants and transport networks, had become increasingly popular across the country. The solar, wind and nuclear energy targets India had set since the 2020s, under commitments to the Paris Agreement, had enabled it to produce domestic hydrogen and steadily provided white and blue collar jobs for all those university and technical schools graduates[444].

Siddharth stopped at a hydrogen refuelling station to top up his motorbike before getting home. He noticed a group of students from a nearby technical school who were on a field trip to learn more about the hydrogen economy. The students seemed excited and full of enthusiasm for the future, talking about recent visits to a number of green steel, green refining, and green fertiliser production centres.

Siddharth overheard one of the students describing what she saw at a green steel plant they visited:

"The sight of hot metal gushing out of the towering furnaces, accompanied by the deafening noise and sparks flying everywhere, was really amazing! What was even more impressive was the green technology being implemented, including stacks of solar powered electricity feeding containerised electrolysers. These machines silently split water into hydrogen and oxygen, with the hydrogen replacing coke needed for steel production in the new furnaces that operate at much lower temperatures, emitting only water instead of CO_2. It was amazing to witness how this revolutionary approach to steel making reduces carbon emissions and enables India to export net zero-emissions steel around the world without any carbon tax. Gone are the days when global steel industry accounted for 7-9 percent of annual carbon emissions. This is so exciting - Indian steel competing on par with European steel makers[445]", she concluded.

Siddharth couldn't help but feel optimistic about what the future held for India.

He arrived home and settled in for the evening with a cup of tea, scrolling through his news feed. He came across an article about how the hydrogen economy was driving economic growth and creating jobs in India. He felt proud of the part he had played in the country's journey towards a more sustainable future.

As he sat back, looking out at the sunset, he thought about how his ancestors would view the country now. He knew they would be proud of the progress made, but he also knew there was still so much work to be done. But with the government's commitment to the hydrogen economy as alternative to coal power baseload - the road to net zero emissions was becoming more clear in his mind.

Mumbai, 2040

Source: image generated with help of AI.

As the sun slowly disappeared beyond the horizon, Niti couldn't help but feel a sense of hope for India's hydrogen future. She worked as a technical consultant for a wide range of emerging green hydrogen manufacturing firms in India, which provided world-leading electrolysis, transportation and storage, shipping, fuel cells, engines, turbines and desalination solutions. The work put Niti at the heart of the Indian green hydrogen ecosystem.

It had taken a concerted effort from the government and private sector to make India a leader in the production and use of hydrogen in manufacturing.

Niti thought about the countless initiatives launched over the years to promote the use of hydrogen in India. There were hydrogen-powered buses and trucks on the roads everywhere, including Mumbai, hydrogen fuelling stations dotted throughout the country, and hydrogen-powered trains transporting goods and people across the vast expanse of India. Local Mumbai green refining firms[446] were providing most of that clean hydrogen fuel.

She thought about the technical schools that had popped up all over the country, churning out skilled technicians who were building up clean energy production, desalination plants for seawater to create additional clean water resources, hydrogen production plants on- and offshore[447], and transport networks. She remembered the satellite pictures of India showing large areas of greenery and thriving agriculture. These were made with massive investments in desert greening projects, and they were powered by hydrogen made from industrial wastewater[448] in combination with desalination seawater hydrogen projects. There was a mandatory[449] oversizing of offshore green hydrogen production. Together, all of this enabled India to provide for 10 percent of global agriculture supplies.

Sipping her tea, Niti felt a sense of pride in the progress that India had made. But she knew there was still a long way to go. There were challenges to overcome and environmental concerns to address. She thought about her family outside the city, who were also benefiting from the rise of the hydrogen economy. Yes, she thought, hydrogen is not just an urban myth but a reality - it helps the whole country, including its agricultural hubs.

Niti was confident that with determination and hard work, India could continue on its path towards a brighter, cleaner future. As she gazed out at the setting sun, she felt a sense of optimism for what lay ahead.

Bengaluru (former Bangalore), 2040

Source: image generated with help of AI.

It was the year 2040, and Suresh woke up to the sound of the chirping birds outside his window. As he got out of bed and stretched, he marvelled at the breathtaking view of the Bengaluru skyline from his penthouse apartment. Bengaluru had come a long way since the days when it was known as the "Garden City". It was now the Digital Head City of India, a hub for technological innovation, and a leader in the digital revolution.

As he sipped his coffee, Suresh reflected on his role as the CEO of HydrogenIQ, a hydrogen trade firm that was transforming the energy landscape. His company had developed an AI-powered platform that analysed market data to help companies make strategic decisions regarding the hydrogen trade. With the global demand for clean energy on the rise, hydrogen had become a crucial element in the global energy mix, and Suresh's company was playing a critical role in shaping the industry's future.

Suresh took a moment to appreciate the hard work and dedication that had gone into making HydrogenIQ a success. He knew that his team's tireless efforts had helped propel Bengaluru to the forefront of the global hydrogen trade scene. He couldn't help but feel a sense of pride and satisfaction knowing that his work had helped shape the city's future as a leader in the clean energy space.

As he prepared for another busy day, Suresh knew that there were still challenges to overcome. With new technologies emerging every day, he and his team would have to stay ahead of the curve to continue their success in the fast-growing hydrogen trade industry. But he was ready for whatever the future held, and he was excited to see what new innovations and opportunities lay ahead for HydrogenIQ and the Digital Head City of India.

He wondered whether to take metro to work - formerly named Namma Metro, now Namma Hydrogen. Or he could take a hydrogen-fuelled bus. Hydrogen had improved the public transport sector, helping to both reduce air pollution and alleviate Bengalurur's nightmare traffic congestion. He to take the bus. As he saw the bus pulling in, a sign on the wall next to bus stop caught his attention: "2047, the year of full energy independence, is just seven years away".

Domestically generated green hydrogen surely helped this, he thought with a smile.

Korea, 2050

Author: Kwang Tae Lee

I wake up at 6 am on April 6, 2050, in my apartment in Seoul, South Korea. First thought: I need to go to work today, even though yesterday was a special national holiday celebrating South Korea's achievement of its carbon neutrality target. The national goal was set in 2020, amid an intensifying climate crisis[450]. It was a long, tough journey for South Korea, whose economy was weakened by a shrinking population. The goal could not have been reached without the country's dramatic but positive rally for hydrogen.

I'm tired after spending three days on a business trip visiting hydrogen facilities, which are representative of South Korea's hydrogen economy.

On the first day, I flew to the Jeju province. It's an island covering around 1,800 square kilometres, some 80 km off the southernmost part of the Korean peninsula. Blessed with the magnificent Halla mountain and beaches, Jeju Island is one of the country's most visited tourist destinations. It also enjoys exceptional conditions for domestic wind and solar power. In fact, unlike the mainland, Jeju used to suffer from an overproduction of renewable energy – until the province decided in 2022 to use its excessive renewable energy to produce green hydrogen, starting with the construction of 12.5 MW facilities. The plan to transform Jeju into a hydrogen production centre greatly helped South Korea to increase its supply of green hydrogen[451].

The Jeju Island (Source: Public Domain)

On the second day of my business trip, I headed to Uljin and Pohang in the east. With 10 nuclear power plants in operation, Uljin County, in the North Gyeongsang Province (or Gyeonsangbuk-do) is home to the National Nuclear Hydrogen Industrial Complex. This was built with advanced electrolysis facilities that started producing over 200,000 tonnes of hydrogen a year in 2030[452]. Located 130 km to the south of Uljin, the city of Pohang is home to the world-leading steel producer POSCO's steel mills. The world's sixth-largest steel maker successfully transitioned to green steel production by implementing hydrogen reduction technology called HyREX. This led to a drop in South Korea's total carbon emissions, as the country's steel industry had accounted for almost 16 percent of the total[453].

Uljin's National Nuclear Hydrogen Industrial Complex Plan (Source: North Gyeongsang Province)

On the last day of my trip, I visited two hydrogen facilities in the western part of South Korea, the National Hydrogen High Tech Industrial Complex in Wanju County, North Jeolla Province, and the city of Pyeongtaek in Gyeonggi Province. Wanju County, which had been well known for having the largest hydrogen fuelling station in the country since 2020, was chosen for the location of the National Hydrogen High Tech Industrial

Complex in March 2023. The facilities in Wanju County entered operation in 2027, inviting more than 72 corporations and research institutions.

Pyeongtaek, which aimed to create a hydrogen-based city life, sought to build various kinds of hydrogen facilities. One of the city's earliest projects was the relatively low-cost $17 million plan to optimise and realise a hybrid CO_2 capture and liquefaction process for the production of blue hydrogen. Launched in June 2022, the project was awarded to a consortium of 11 companies and research institutions, including Hyundai Engineering and Construction[454].

What a trip covering long distances - I clearly deserved a hug to myself for this. It simultaneously exhausted and energised me.

Source: Author's contribution

I pull myself up, quickly shower and have breakfast and a cup of coffee. I water the plants and feed my pet goldfish. Being pure but alkaline, the water produced by hydrogen fuel cells can be used in showers and even for raising fish in fish tanks.

It's all circular: the fish provide organic materials to the water, and the fish tank water can be used to water plants. Then, once processed and filtered, hydrogen-generated water can also be used for cooking and drinking[455].

Hydrogen fuel cells built in city homes and buildings also make it convenient to produce heat and water. Advanced fuel cells, such as High-Temperature PEMFC, developed by Korean companies, have contributed to the broader use of hydrogen[456].

* * *

Carrying a cup of coffee and a book, I hurry to the parking lot and get into my NEXO 2050. The hydrogen car produced by Hyundai Motors has been loved by people around the world since it launched in 2013. The company has sought to become a leader in the production of hydrogen fuel cell vehicles. NEXO, the SUV model, registered 11,000 sales in 2022 - just over half of the global market share. Many other automakers have since launched hydrogen vehicles. But it was the NEXO that inspired South Korea to begin building a hydrogen economy[457].

The low-fuel lamp turns on just as I leave the car park, so I stop at one of the numerous hydrogen fuel stations near my home. The use and storage of liquid hydrogen are now safe, thanks to technologies such as zero boil-off[458]. This allowed for hydrogen stations to be built in the middle of the city on relatively small areas of land.

Once fuelled up, I look out of the window as the car drives itself, watching posters commemorating the carbon-free holiday fly by.

The South Korean government presented its Hydrogen Economy Roadmap in January 2019, a year before setting the goal for carbon neutrality by 2020. The roadmap set out a national vision to become "the world-leading country in the hydrogen economy[459]".

The National Assembly then supported the roadmap by passing The Act for Nurturing Hydrogen Economy and Safety Management in February 2020, to be implemented a year later. This set a legal foundation for administrative measures that enabled the government's drive for a hydrogen economy, including the establishment of the Hydrogen Economy Commission, presided over by the prime minister and comprising ministers from related ministries and other civilian experts, and the enforcement of safety regulations for hydrogen products and facilities[460].

The Ministry of Trade, Industry, and Energy then announced the National Plan for the Fulfilment of the Hydrogen Economy in November 2021. This provided a detailed strategy for achieving the ultimate goal for South Korea to take a leading role in building a global hydrogen economy[461].

Then came the New Energy Policy Outline in July 2022, which reconfirmed the 2019 Hydrogen Economy Roadmap and the 2021 Plan for the Fulfilment of the Hydrogen Economy. The South Korean government's policies offered a clear direction that the private sector could follow with confidence.

Cherry Blossom in Seoul, South Korea (Source: the Author)

On the one-hour drive to work, I think about how thankful I am for the precious opportunity to see flowers bloom on time. Climate change killed many species, including flowers and trees, on the Korean peninsula. Global warming disrupted the blooming of buds, posing a great threat to the environment. Yet, as the power of hydrogen helped to stabilise the climate, Mother Nature brought back flowers, including cherry blossoms, to the lives of South Koreans.

Singapore, 2035

Author: Felipe San Gil

15 January, 2035 – flashback about hydrogen

It was a late afternoon on 15 January, 2035, I had a flashback. Twelve years ago, I was headed on a holiday to Bali, and imagining how hydrogen would change daily life in Singapore in 2035. No wonder, because the global energy trading community in Singapore, where I was an active advisor, had been buzzing with hydrogen concepts since the release of the National Singapore Hydrogen Strategy[462].

It turns out I was quite close to some of my predictions.

Mass transport, chicken rice and hydrogen

On 15 January, 2022, as I waited to board my flight to Bali, I grabbed a quick meal at Changi Airport. I ordered one of my favourites, chicken rice, and started thinking about how Singapore would look in 2035 with the adoption of hydrogen in our daily life.

One impact that came to mind was the use of hydrogen fuel cell electric vehicles (FCEVs) for mass transit and goods transportation, where frequent recharging is inconvenient. These vehicles would replace traditional gasoline/diesel-powered vehicles. As a result most, if not all, vehicles on Singapore's roads geared towards mass transit would be FCEVs. That means the taxi that would take me to the airport would be an FCEV. These vehicles emit only water as a by-product, leading to cleaner air and a healthier environment.

To support the growing number of FCEVs, there would be an increase in the number of hydrogen fuelling stations around the country. These stations are necessary to provide fuel for FCEVs used for mass transit of people, goods and could be located in strategic areas around the country. We would see an increase in the number of petrol stations converted into Hydrogen fuelling stations. In fact, policy announcements in 2022 did offer some hints on this[463].

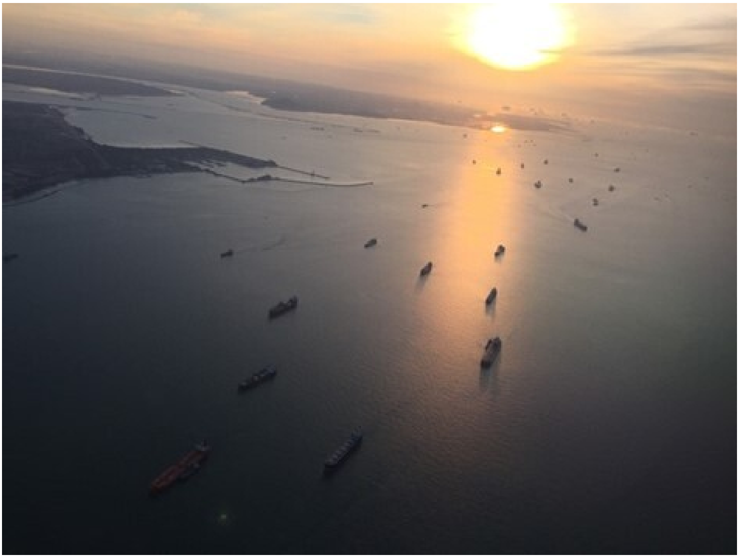
I then realised that the chicken rice I was eating would in the future be cooked using hydrogen. Hydrogen would be used instead of natural gas as a fuel source in Singapore traditional and famous hawker centres.

A hawker centre in Singapore, back in the day. Source: Creative Commons licence

In the future, hawkers around the country would use a hydrogen gas burner. They can provide high heat output, making them well-suited for high-demand cooking applications like these. We would see Singapore's famous chicken rice and other delicious dishes being cooked using hydrogen.

Bird's eye view on Asian energy hub role of Singapore, Jurong Island

As I boarded my flight I realised that the seat next to me was an empty window seat. Lucky me. The view was majestic, as depicted in the the photograph below, with global maritime life streaming to and from Singapore.



Source: Felipe San Gil, in-flight view of the Singapore maritime ecosystem

As I looked from the air, I contemplated how hydrogen would change the landscape of the city as it would turn Singapore into one of Asia's leading hydrogen trading hubs for buying and selling hydrogen as a commodity. Jurong Island would be at centre of this.

Singapore Jurong Island view from Google Earth, back in the day. Source: Erik Rakhou.

The conversion of Jurong Island refineries into a hydrogen import, storage and export terminal could be an illustrative example, grounded in 2022 announcements of policy and projects.

The government's hydrogen strategy spoke of up to 50 percent of power being generated from hydrogen by 2050, and there was a huge dirty fossils bunkering fuels market to be replaced by, for example, ammonia and methanol as hydrogen derivatives[464]. As demand therefore grows, it would become necessary to import hydrogen, or its derivatives, in order to meet the country's needs[465]. A hydrogen import, storage and export terminal would be key infrastructure for importing and distributing hydrogen to users in the country, such as hydrogen-powered electricity generators and regional Asian markets, as well as providing bunkering to international maritime users.

A hydrogen import, storage and export terminal would strengthen Singapore's position as a global hydrogen trading hub, coupled with availability of a highly skilled global workforce and energy trading ecosystem. This would facilitate the trade of hydrogen between producers and consumers in the region by providing a central location for the buying and selling of hydrogen, helping to increase the availability and affordability of hydrogen in the region.

Conclusions – oil tankers exchanged for hydrogen & hydrogen derivatives carriers

All of the above developments, which would become central to the reinvention of Jurong Island, would lead to a change in the landscape of vessels moored in Singapore. As Singapore becomes a hydrogen trading hub, the shape of the hydrogen vessel would dominate the landscape, and crude carriers would be traded as museum pieces instead of global commodities.

Coming back to 2035, I thought about whether I might still enjoy that old fashioned paper version of the Touching Hydrogen book I had packed me for the flight, given that virtual reality and AI occasionally required disconnecting from the digital to rest my mind.

Closing Chapter: Reflecting on the Journey ‘around the world’

Final remarks by co-editors: Erik Rakhou and Rosa Puentes

During the 1970s, David Attenborough, UK climate icon, filmed in 63 locations across 33 countries, with “Life on Earth”contributing to most of his travels. With “Touching Hydrogen Future” our crew of 38 authors, travelled in Jules Verne spirit to 37 countries within 2 years through imagination and writing. Both experiences are, and have been transformative - one showing at the time why Earth is worth living on, other one - 50 years later, showing a path through hydrogen to help continue living on Earth by 2030s to 2050s. This hydrogen future travel rests on shoulders of great authors team, each of whom has become in our eyes an honorary ambassador of their chapter country. The organising, poetically inspired, passionate power behind this is my co-editor Rosa - able to gracefully steer through all bumps we ran into to arrive to now fresh 2nd edition after over 8000 readers picked up the book in over 125 countries.

So what is next for Touching Hydrogen Future - team, it is in many ways watching future being delivered. One hydrogen business developer got my heart when after reading a chapter on India, he wrote - “this helps to see why I love my work and what to work towards”.

With this, I am keen to pass, for further afterword to Rosa.

Erik Rakhou

* * *

As we bring this project to a close, a wave of mixed emotions washes over me. On one hand, there is a sense of relief and accomplishment in completing a journey that began one and a half years ago. On the other, there is a bittersweet nostalgia for the time that has passed and the experiences that we can never recreate. Working alongside a multitude of knowledgeable individuals has been nothing short of extraordinary, as we immersed ourselves in their expertise, dedication, and unwavering passion. Together, we embarked on a transformative journey, striving to make knowledge accessible to all, and I am filled with confidence that we have succeeded in our mission.

In the realm of extraordinary individuals I had the privilege of collaborating with, one person stands out as the driving force behind the success of this book—Erik Rakhou. His unyielding belief in the power of knowledge and collaboration has served as the bedrock of our efforts. Without his visionary mindset, unwavering commitment, and tireless push, this book would remain a mere aspiration. Erik, we owe you our deepest gratitude for your unwavering support and the immense impact you have had on this project.

Throughout this transformative journey, my thirst for knowledge has been quenched, and I have been profoundly inspired. The energy professionals I had the honour of collaborating with have exemplified what it truly means to be part of change. Their relentless dedication to finding solutions to the most pressing challenges of our world has inspired me to challenge my own assumptions and broaden my perspectives. Moreover, amidst the whirlwind of work, I am overjoyed to have forged deep friendships with some of these exceptional individuals. It is a testament to the power of shared passions and collaborative efforts. Without this book, our paths may have never crossed, and for that, I am forever grateful.

On a broader canvas, a common thread runs through the chapters of this book, weaving together a call to action—a realization that our work is far from finished. To build a sustainable future, we must ensure that the energy sector becomes a bastion of inclusivity and diversity, drawing upon the vast reservoirs of talent, perspectives, and technologies available to us. It is our collective responsibility to actively seek out and embrace the participation of individuals from different age groups, diverse backgrounds, and ideas that transcend borders. Let us inspire and ignite their passion, encouraging them to join and collaborate hand in hand.

This book stands as a testament to the immense potential we possess to shape the world. It is my hope that its pages will serve as a source of inspiration for the next generation. Within the stories and experiences shared in these chapters lie the seeds of possibility, the impact they can make, and the countless opportunities that await them. It is through their fresh perspectives, innovative ideas, and unyielding determination that we will continue to propel the energy sector forward, leaving an indelible mark on the trajectory of our planet.

As I conclude this chapter, a profound sense of hope and excitement fills my being for the boundless possibilities that lie ahead. The progress we have made thus far, driven by the unwavering dedication and expertise of those within the energy sector, is nothing short of remarkable. Yet, we must remain resolute in our commitment to nurture and empower the next generation of energy leaders, for it is they who will carry the torch and push us into a brighter future.

To the young minds and aspiring professionals who now hold this book in their hands, I ask you to embrace your passion with unwavering conviction and seize every opportunity that comes your way. Be fearless in pursuing your dreams, and always remember that your voice, your ideas, and your contributions are invaluable in shaping a sustainable and prosperous future.

But, in the middle of our ambitious goals and the weight of our responsibilities, let us not forget the importance of personal fulfillment and enjoyment in what we do. As we dedicate our lives to what motivates and inspires us, let us also find moments for self-reflection, revitalisation and the pursuit of our own happiness. It is in these moments that we gather strength, renew our energy, and continue to move forward with enthusiasm. At the end of the day, those are the moments that will matter the most.

Dear reader, I extend my gratitude to you for joining us on this extraordinary journey. Together, let us continue to inspire, uplift, and create a world filled with hope and possibility. With passion as our guide and collaboration as our compass, we have the power to shape a brighter future for generations to come. Let our collective efforts be a beacon of light, illuminating the path toward a sustainable and inclusive world.

Thank you for being part of this remarkable adventure.

Rosa Puentes

Quotes from the authors

"The best way to predict the future is to invent it. This book does just that."

Petar Sofev

"By 2030, Namibia is to become the 'Energy Port of Africa.' Prior to becoming a hydrogen superpower, Namibia contributed a significant amount to the worlds' diamond market. The vast capacity for solar and wind means Namibia can produce some of the world's cheapest Green Hydrogen. Namibia's economic landscape is changing significantly and one to watch out for!"

Oghosa Erhahon

"The read provides a view of what different futures could be. Hydrogen is the main character but also allows other "characters" (nuclear, intermittent RE, batteries, etc. and realistically some remaining fossil fuels) to also have roles in future. Stealing some lines from the also Vernes inspired 2017 movie, Mysterious Island: "Most of us considered Verne's work as nothing more than science fiction, but Vernes, he knew"

Gerhard Human

"In the past 20 years, the energy landscape has evolved at a fast pace and it's not showing any signs of slowing down. With all the emerging countries and technology, the existing energy infrastruc-

ture must adapt to answer new more global problems. Chile's unique geographic combination holds so much potential that is now being realized. Their goal of energy independence is going to bring around huge shifts in their infrastructure."

Eric Ehrhardt

"This adventure partially reflects what is expected for the Colombian hydrogen economy and how significant progress must occur to produce, use and export hydrogen in a cost-competitive way while keeping the 2050 carbon neutrality target within reach. Colombia's abundance of natural resources, coupled with strategic investment for economic development, give the country the opportunity to become a regional leader in the hydrogen field. A challenging, yet exciting ambition to pursue."

Miguel Ballesteros

"2040, Romania – a Southeast European energy and decarbonization hub. We host a hydrogen valley, we produce and export green H2 to the EU, we bank on our talents and geography and we win. We win at life: we can stand tall and proud for having made such unbelievable progress in energy and we breathe, we worry less… hydrogen helped us get here!"

Lavinia Tanase

"In this partly fantastic (maybe a bit utopic) travel across the 8 times zone of wide Russia we discover how the hydrogen power has utterly changed what we once knew as a country mostly relying on natural resources. Now it's one of the top world suppliers for technological expertise with a vast variety of scientific and educational centres. Let's visit its prominent hydrogen hubs and see how they have developed despite all the climate, economical and other obstacles.

May the Hydrogen Force be with you!"

Irina Gaida

"Liverpool, beer and hydrogen are at the centre of the story, as usual, as Tom journeys to Liverpool for a game on the hottest ever April day. Retirement beckons as politics and realism clash in this short nostalgic tale which ends with the reader dying to follow future Tom's exploits travelling Europe with zero carbon emissions to his name"

Tom Baldwin

"Inspiring, funny and sometimes sceptical about the future. This book combines the excitement and "rosy style" that comes when looking into the future with optimism and passion, the fear of failing to achieve the climate objectives and the mixed feelings of how best to ensure a just energy transition. It will make you laugh, reflect, learn.. And eventually, you will either love or hate hydrogen!"

Rosa Puentes

"The book allows us to understand the gravity and complexity of the task in hand, with each country bringing its own opportunities, constraints, and positionality. Although the transition will be far from simple, requiring unprecedented efforts from governments, industry, and citizens, the tour shows the reader the truly exciting opportunities hydrogen offers for all nations. It is not just a fuel replacement, it is a paradigm shift in the way we look at energy systems, with co-benefits across a number of Sustainable Development Goals."

Andris Piebalgs

"Almost 150 years after Jules Verne first envisaged a world powered

by hydrogen, we can map out the changes it will enable within our lifetimes. Through the eyes of today's energy leaders, we paint a picture of a transformed world powered by hydrogen alongside other energy transition vectors, and invite you to join us in building it."

Erik Rakhou

"Ziad Al Shammary has a plan. The 2040 climate as he arrives at the Red Sea resort is heating up, green technologies – a few familiar, a few surprising – have become mainstream. But one thing that hasn't changed is the desire of people and nations for political power, wealth and security. Just like oil, hydrogen is no exception to those machinations – in its own way."

Robin Mills

"The future is uncertain, only the presence is real. Out of it arise unlimited possibilities. This book shows different visions of a hydrogen future. One day we will sit together and see how close we were..."

Konstantin Lenz

"In this book, you could imagine what a transition to net-zero emissions based on hydrogen would entail. It means changes in jobs, demand, cost, life style and capital spending and how we could protect our planet if we work into achieve our vision during the present decade. We invite you to join us to build this future!"

Rocío Salas

"Humans always have flaws. One of the most urgent things to do is just to correct mistakes," said Jeong Yak-yong, the Korean polymath in the late 18th century. Faced with the global climate crisis, what we must do now is just to stand up and go fix the problem.

In our attempts to correct the mistakes, we have a very effective tool, hydrogen. This book will allow all the readers to visualize the way we will be able to achieve our goal of net zero emission by taking advantage of hydrogen, the good old elemental friend of humankind."

Kwang Tae Lee

"By 2049, Kazakhstan will have unlocked its hydrogen potential, connecting it to the global hydrogen economy. However, the country's transformation from a major fossil fuels exporter to a Eurasian green hydrogen leader is yet to continue. As a captain atop a "desert ship," you will enjoy being a part of a future camel caravan experience through the Hydrogen Silk Roads and hubs, witnessing how hydrogen transforms Kazakhstan beyond one's imagination."

Dr. Venera N. Anderson

"This book addresses – amongst others – the bold question 'How will the future of hydrogen unfold in Belgium by 2035?'. The fictional article will make you reflect on Belgium's energy future. The authors also used the current state of affairs as a basis for this forecast, based on personal experiences. An optimistic but futuristic picture is painted of Belgium as a leading hub welcoming blue and green hydrogen, for all applications, including power generation and storage, building on its current position along the North sea coast."

Daniel Cortez Cazas and Jens Mosselmans

Notes

FOREWORD

1 IRENA (2022) Geopolitics of the Energy Transformation: The Hydrogen Factor. This is a conservative mid-range estimate – as IEA netzero analysis shows in “Announced Pledges Case” scenario a lower, and in “Net-Zero Emissions” scenario a materially larger hydrogen role in global energy use; IEA (October 2021) Netzero by 2050.

THE BEGINNING

2 See https://en.wikipedia.org/wiki/The_Mysterious_Island

THE NETHERLANDS, 2029

3 For those willing to take a listening detour on hydrogen 101, here are 2 podcasts of Switched On and Everything about hydrogen

4 See for what black-outs mean for example this article by BBC: What would happen in an apocalyptic blackout? - BBC Future

5 Invented name.

6 NortH2 | Kickstarting the green hydrogen economy

7 The qualification how sustainable hydrogen is in terms of climate impact and carbon footprint, further details e.g. in this hydrogen Council report - hydrogen-Council_Policy-Toolbox.pdf (hydrogencouncil.com)

8 It was connected to now world famous Dutch backbone including a developed network of salt cavern storages – see hydrogen backbone › Gasunie This operated in balance with powergrid, as was professed by study HyWay27

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248 https://www.iea.org/policies/13515-green-innovation-fund-meti-funds-hydrogen-supply-chain

249 METI uses the 3E + S framework to guide its development of the power system in Japan. This framework is intended to ensure that a balance between **s**afety, **e**nergy security, **e**conomic efficiency and **e**nvironment is maintained when changes are made to the power system.

CHINA, 2030

250 Compound Annual Growth Rate (CAGR)

RUSSIA, 2040

251 See Nikolay Przhevalsky | Russian explorer | Britannica

252 https://1prime.ru/energy/20211130/835370528.html

253 Kaliningrad's part of "*Western hydrogen cluster*" of Russian nuclear conglomerate Rosatom, which also included EV batteries manufacturing and recycling plant. Originally built as an export-oriented facility, this plant later was extended to supply the needs on Russian north-west industries and transport (https://tass.ru/ekonomika/12681009).

254 See Nevsky Prospect - Wikipedia

255 See *https://teknoblog.ru/2021/08/03/112946*

256 See Murmansk - Wikipedia

257 See https://www.kommersant.ru/doc/4654965

258 See Yamal Peninsula - Wikipedia

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260 See Norilsk - Wikipedia

261 See https://www.ng.ru/science/2003-12-24/12_future.html

262 See PGM-Based Fuel Cells: Applications for Industry – New Age Metals Inc.

263 See Penzhin Tidal Power Plant Project - Wikipedia

264 See Bering Strait - Wikipedia

265 See Sakhalin - Wikipedia

266 See https://oilcapital.ru/article/general/09-09-2021/vodorod-na-sahaline-laboratornaya-rabota-ili-imidzhevyy-proekt

267 See https://sakhalinecopolis.ru/

UZBEKISTAN, 2040

268 See Tashkent - Wikipedia

269 https://kun.uz/en/news/2021/04/09/uzbekistan-to-develop-hydrogen-energy

270 Source Worldometer

271 https://commons.wikimedia.org/wiki/File:Boukhara_4654a.jpg

272 https://en.wikipedia.org/wiki/Equinox

273 See Bukhara - Wikipedia

274 See minenergy.uz

275 See eg The Syr Darya River - the Queen of Central Asia (people-travels.com)

276 See Shirin, Uzbekistan - Wikipedia

277 See further broader plans, and source here: Saudi Arabia's ACWA Power, Uzbekistan Ministry Of Energy & Air Products Sign Deal On hydrogen - FuelCellsWorks

278 See Presidential Decree formalises Uzbekistan hydrogen energy strategy (powerengineeringint.com)

UNITED ARAB EMIRATES, 2040

279 See NEOM: Made to Change

280 See context for rapidly developing robotics - 27+ Robotics Industry Statistics To Show You How Big It Is In 2022 (techjury.net)

281 This organisation, with a name left for reader to guess, is at present a fiction for avoidance of doubt, yet a plausible fiction – see Opec member urges oil producers to focus more on renewable energy | Fossil fuels | The Guardian

282 See Pyramids of Giza | History, Location, Age, Interior, & Facts | Britannica

283 See Finland serves coffee in machine powered by the air we breathe at Expo 2020 Dubai (thenationalnews.com)

TURKEY, 2040

284 See İzmir - Wikipedia

UKRAINE, 2040

285 See for ammonia promise for shipping, for example: https://spectrum.ieee.org/why-the-shipping-industry-is-betting-big-on-ammonia

286 See VERBUND hydrogen project Green hydrogen Blue Danube

287 See High-level delegation visit to Ukraine

288 See for example: Why are some betting on hydrogen power for ag? | AGDAILY

289 Example of use of hydrogen in steel industry - hydrogen in steel production: what is happening in Europe – part two - Bellona.org

290 See for example, hydrogen Energy Storage - Energy Storage Association

291 See NuScale SMR under consideration for Ukraine : New Nuclear - World Nuclear News (world-nuclear-news.org)

292 See EHB_one-pager_210624.indd (gasforclimate2050.eu)

293 See The promise of Ukraine's unprecedented coal phase-out (energymonitor.ai)

294 See e.g. Renewable energy – UkraineInvest

295 See e.g. Future of mobility: what is known about hydrogen trains in Germany | RailTech.com

296 See Underground hydrogen storage - Wikipedia

ROMANIA, 2040

297 https://en.wikipedia.org/wiki/Constan percentC8 percent9Ba

298 See European Clean hydrogen Alliance (europa.eu)

299 See DOBROGEA Region, Romania - Travel and Tourism Information (romaniatourism.com)

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301 See https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/06/Blue-hydrogen-as-an-enabler-of-green-hydrogen-the-case-of-Germany-NG-159.pdf

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303 Romania NECP

304 Commission endorses Romania's plan (europa.eu)

305 NEW CID ANNEX ROMANIA RRF 13 09 2021 (gov.ro), Reform 4, Page 158.

306 See e.g., IRENA. Hydrogen: A renewable energy perspective (irena.org)

307 Romania's NRRP, as approved by the EC, provided that the country will receive 29.2 bln EUR for all sectors. 41 percent of this amount to be targeting a clean energy transition, while only approximately 1 bln EUR will be dedicated for clean energy production component. H ttps://balkangreenenergynews.com/romania-allocates-eur-3-9-billion-from-eu-recovery-funds-to-zero-carbon-railway/

308 Authors remark - In Romania, about half of the distribution network was made up of polyethylene, this distribution part could be relatively

competitively converted to hydrogen (as e.g. UK research experience showed - Conversion of the UK gas system to transport hydrogen - ScienceDirect).

309 https://www.depogazploiesti.ro/en/about-us/profile

310 https://www.romgaz.ro/explorare

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312 See (PDF) hydrogen underground storage in Romania, the potential, actors and relevant circumstances (researchgate.net)

313 https://www.fch.europa.eu/event/european-hydrogen-week-2021

314 See e.g. H2Valleys | Mission Innovation hydrogen Valley Platform

315 https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_11_H2_Insights/2021-11-18_Slides_Agora_12_insights_on_hydrogen.pdf

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319 Dobrogea, polul de energie regenerabilă al țării. Cum poate câștiga pariul pe hidrogen verde | Digi24

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321 As mentioned by Kadri Simson, Commissioner for Energy DG Ener on 15 December 2021 https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_21_6910

322 https://www.euractiv.com/section/energy/news/lets-reach-for-the-stars-eu-aims-for-green-hydrogen-below-e2-kg-by-2030/

323 https://www.romania-insider.com/ro-second-biggest-gas-producer-eu-aug-2020

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325 https://www.euractiv.com/section/energy/news/romania-will-start-extracting-gas-from-black-sea-in-2026-minister-says/

326 Component 6 Energy, Section F.3, Reform 6 'Increase in competitiveness and decarbonisation of the heating-cooling sector' https://mfe.gov.ro/wp-content/uploads/2021/09/e6f28710212d5a2d963ba440ce587a99.pdf

327 https://romania.europalibera.org/a/lemne-de-foc-interzise-ue/31614058.html

328 EURACTIV: Heating homes with hydrogen fails on economic and climate merit: report; FCH report: "Opportunities for hydrogen energy technologies considering the national energy & climate plans"

329 Component 6, Reform 6, Investment 2 – page 189 NRRP

330 Author's note on context. In 2020, in Romania, only one out of 3 homes had access to the gas distribution network: out of 320 cities, only 246 have access to the national gas distribution network, whereas out of almost 2600 communes, only 675 enjoyed access to this infrastructure.

331 Component 6, Investment 2 of NRRP https://mfe.gov.ro/wp-content/uploads/2021/09/e6f28710212d5a2d963ba440ce587a99.pdf

332 Dobrogea, polul de energie regenerabilă al țării. Cum poate câștiga pariul pe hidrogen verde | Digi24

333 In 2021, Romania´s road transport sector was strongly dependent on fossil fuels and hydrogen seemed one of the solutions that could be deployed to decarbonise energy use in this sector, especially in heavy-duty road transport, which represented approximately 34 percent of the energy use in road transport.

334 The initial NRRP estimations were 30-80 stations for 19 000 - 41 000 fuel cell vehicles on the road, by 2030.

335 https://www.g4media.ro/autobuz-cu-hidrogen-in-teste-la-constanta.html

336 Opportunities for hydrogen energy technologies considering the National and Energy Climate Plans – Romania, Fuel Cells and hydrogen Joint Undertaking, Jul 2020.

337 https://www.enpg.ro/2630-2/

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340 As p*er the EPG study* Clean hydrogen in Romania Elements of a Strategy, Dec 2021

GREECE, 2034

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345 See Igoumenitsa - Wikipedia

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352 Agrivoltaic Systems, A Promising Experience.

353 Rare-earth elements

354 What is an inverter?

355 Cyclonic-flow wind turbine with statoric and rotoric elements

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359 For example of discussions on heat pumps see Heat Pumps: Myths and Facts

- Stiftung Klima (stiftung-klima.de); German 2030 power use forecast up due to heat pumps, e-cars and hydrogen | Clean Energy Wire

360 Some early experiments were and are being conducted in UK, Netherlands and Germany for example. See here: BDR Thermea joins pioneering test of hydrogen energy in Germany (bdrthermeagroup.com)

361 See work done inter alia by BASF - New technologies (basf.com)

362 See Global Carbon Black Market Size Will Grow to USD 22.5 (globenewswire.com)

363 See Fraunhofer flagship research on Graphene and its applications - New study predicts increased market penetration for graphene-based applications by 2025 - Fraunhofer ISI

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365 See broader research on graphene batteries - German Energy Solutions - New generation of supercapacitors to challenge lithium storage (german-energy-solutions.de)

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368 *Fischer-Tropsch process*

369 For detailed discussion on hydrogen in aviation, predicted to reach 40 mt/year by 2050, check: "Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050"

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NORWAY, 2035

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388 Investment of one billion euros will produce green hydrogen and ammonia in Portugal - https://www.portugal.gov.pt/pt/gc23/comunicacao/noticia?i=investimento-de-mil-milhoes-de-euros-vai-produzir-hidrogenio-e-amonia-verdes-em-portugal

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402 As evidenced by current workshops (2022-2023) - policy mix, coordination and implementation will always be key in delivering the Net Zero ambition

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404 As IEA (2023) states: "Hydrogen demand is expected to be less seasonal than that of gas, but pronounced fluctuations in variable renewable energy generation will require measures to create a more stable hydrogen supply for downstream uses, with flexible hydrogen storage being an important option. This will not only allow supply to match demand but will minimise the oversizing of trade infrastructure and technologies for the production of hydrogen-derived fuels, allowing them to operate at higher full load hours throughout the year to keep costs down". "Regions and countries should therefore (...) hydrogen storage needs when devising resource development strategies and plans". Pages 308, 324 – at Energy Technology Perspectives 2023 (windows.net)

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KAZAKHSTAN, 2049

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SINGAPORE, 2035

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463 See Singapore Energy Lecture by Deputy Prime Minister and Minister for Finance Lawrence Wong at the Singapore International Energy Week 2022 (ema.gov.sg)

464 The Port of Singapore is currently the world's busiest container transhipment port, with ship arrival tonnage exceeding 2.8 billion gross tonnage in 2021. Singapore is also the world's largest bunkering hub, supplying close to 50 million tonnes of marine bunker fuel to vessels that plied international shipping routes in 2021. Source info: Singapore national hydrogen strategy.

465 The optimum choice for global hydrogen trade transportation is evolving – global experts follow multiple carriers, eg Ammonia, Methanol, LOHC, liquid Hydrogen, compressed/piped hydrogen as examples. See eg box 2.1 of IRENA global trade report - Global hydrogen trade to meet the 1.5°C climate goal: Trade outlook for 2050 and way forward (irena.org)