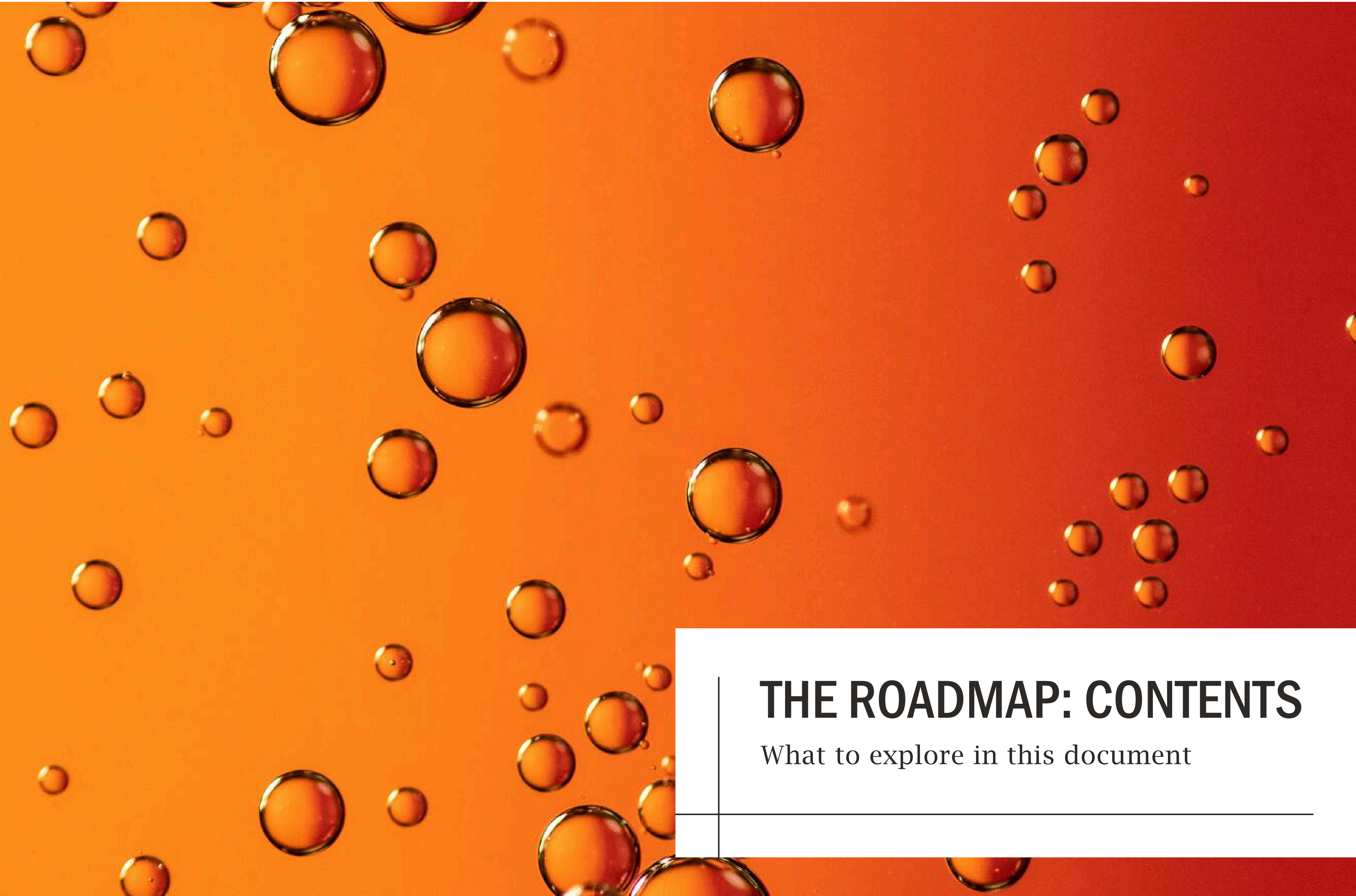
ROADMAP TO HYDROGEN

Understanding the transition to hydrogen fuels



THE ROADMAP: CONTENTS

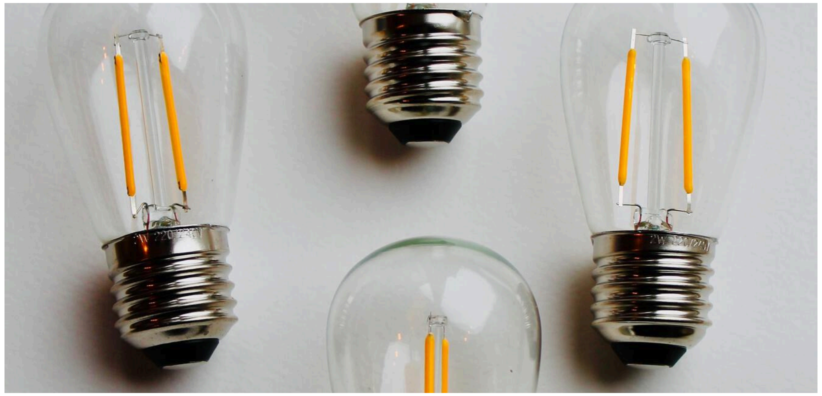
What to explore in this document

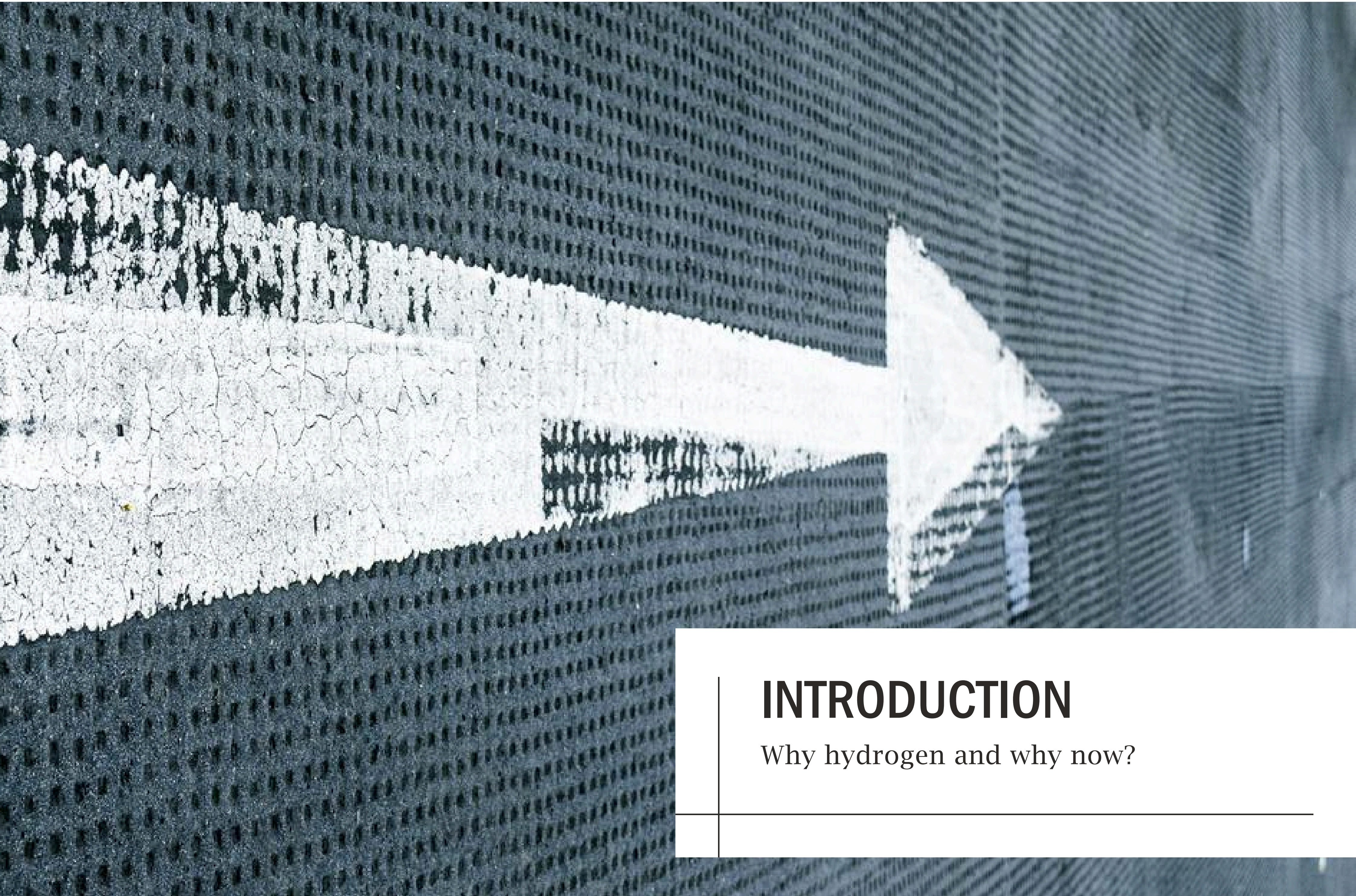
FEATURED CHAPTERS

Welcome to the roadmap to hydrogen handbook.

Through our projects, the Frontier team works with a wide cross-section of the hydrogen community.

This handbook is the first step towards sharing insights and facilitiating conversations around the future of hydrogen.





INTRODUCTION

Why hydrogen and why now?

TO REACH THE GOAL OF NET ZERO, WE NEED TO USE ENERGY MORE EFFICIENTLY, AND PRODUCE IT FROM SUSTAINABLE RESOURCES. PART OF THE ANSWER WILL BE TO DECARBONISE ELECTRICITY AND USE IT MORE WIDELY. BUT IT IS RECOGNISED THAT NOT ALL ENERGY USES WILL BE TRANSFERABLE TO ELECTRICITY – IN PLACES, IT WILL BE TOO EXPENSIVE, NOT RESILIENT ENOUGH, OR SIMPLY TECHNICALLY INFEASIBLE.
THIS IS WHERE HYDROGEN COMES IN.

HYDROGEN IS A SMART SOLUTION

We use more energy in winter than in summer. And we often use energy at times when solar or wind power is not producing. That means we have to store vast amounts of energy for the times we need it most – and storing (and transporting) electricity is costly and space intensive.

Many industrialised nations lack the space to accommodate all the renewable production facilities they'd need to serve domestic demand. In the future, they will need to import sustainable energy from places where conditions are more favourable: regions that offer a good mix of sunshine and wind speed, like North Africa, Patagonia and the Gulf Region.

Transporting and storing energy as a gas or liquid is much more efficient than transporting electricity – it's cheaper and it uses less space. And hydrogen provides a means of transportation and storage: it can be produced, for example, from natural gas and from green electricity, and it can be transported across the world by pipelines and ships.

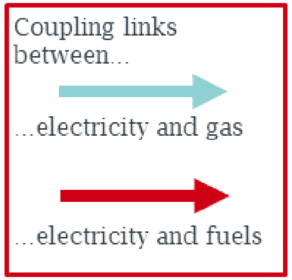
What's more, hydrogen can form the base for other gases, such as synthetic methane and ammonia, and for various liquid fuels that resemble fuels we commonly use today, like petrol, diesel and kerosene.

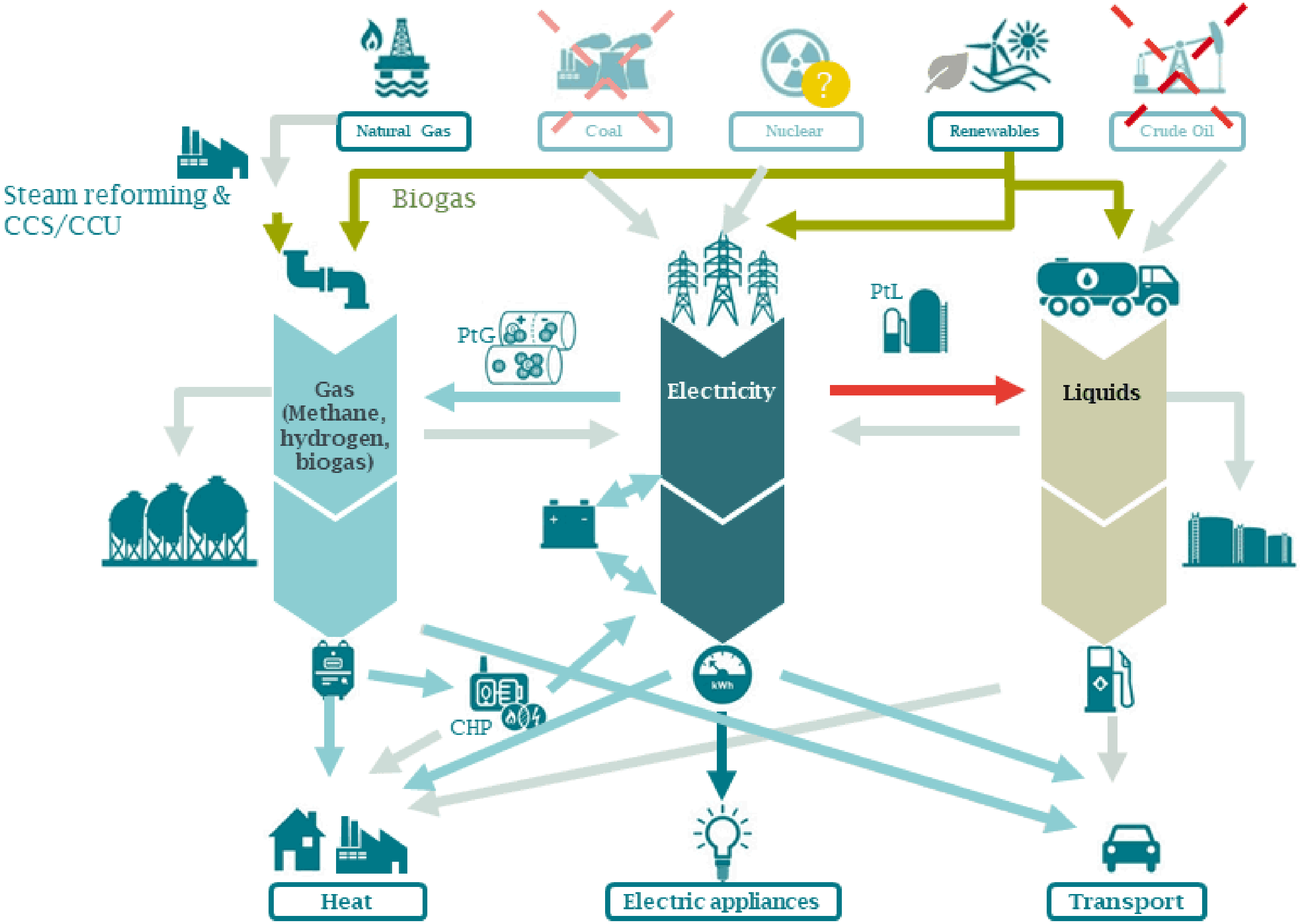
UNDERSTANDING THE ECONOMICS OF HYDROGEN

The transition to hydrogen is therefore fundamental in meeting global energy targets. That's why we've put together this Hydrogen Handbook.

As countries across the globe seek to develop supplies of, and demand for, low-carbon hydrogen, understanding the key drivers and mechanisms will be essential. The seven sections of this handbook cover the most important aspects of the transition to hydrogen: from the business case, to government support mechanisms, to the global market.

PLEASE SEE DIAGRAM ON NEXT PAGE


Coupling links between...
...electricity and gas
...electricity and fuels


Natural Gas
Coal
Nuclear
Renewables
Crude Oil
Steam reforming & CCS/CCU
Biogas
PtG
PtL
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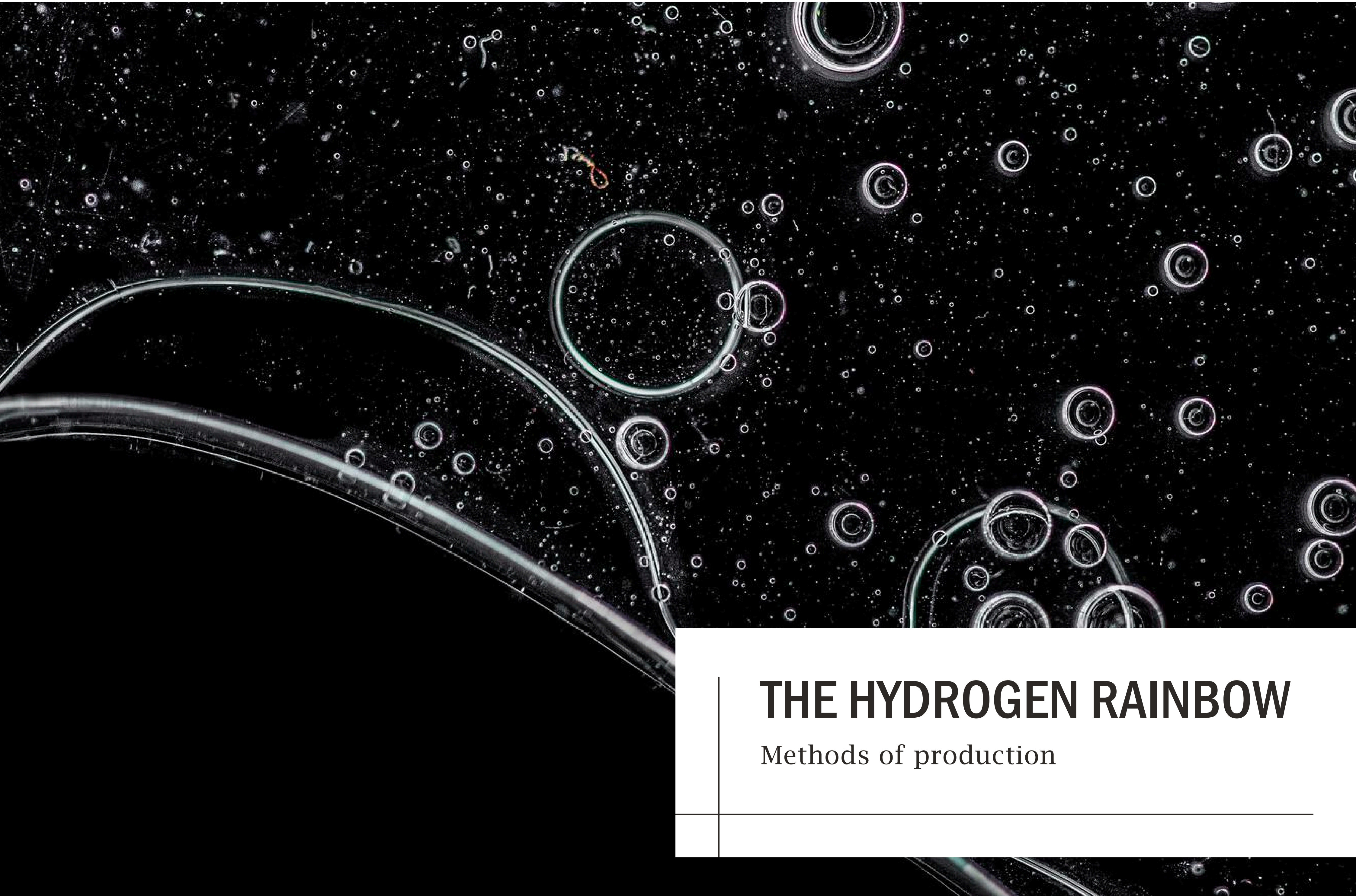
Electricity
Liquids
CHP
kWh
Heat
Electric appliances
Transport

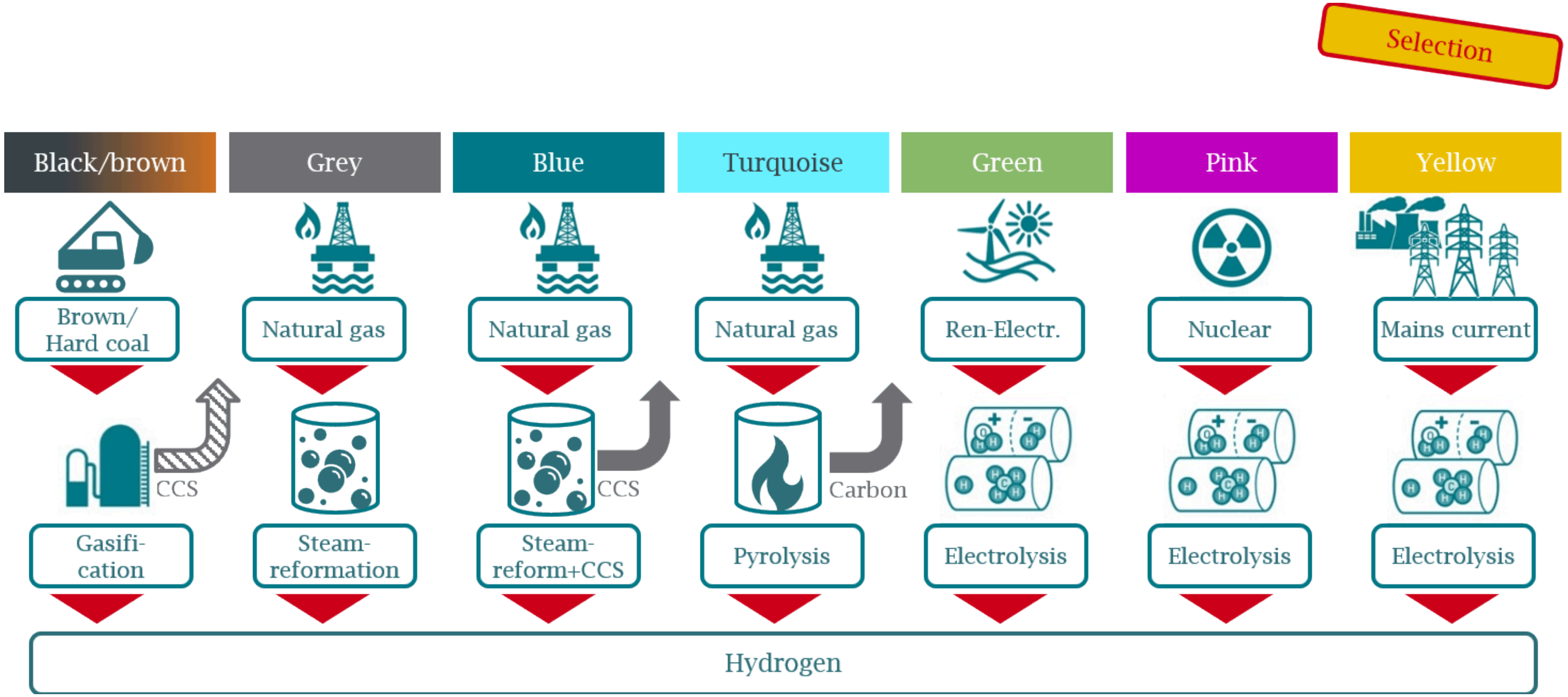


THE HYDROGEN RAINBOW

Methods of production

LET'S START AT THE BEGINNING: HOW EXACTLY IS HYDROGEN PRODUCED?

There are several competing methods, which have given rise to a colourful naming convention – with each 'type' of hydrogen given a different colour code according to the inputs and technology used to make it.
Hydrogen produced with renewable electricity by electrolysis, for example, is commonly called 'green'. And hydrogen produced via steam reformation using fossil fuels, like natural gas, is labelled 'grey'.



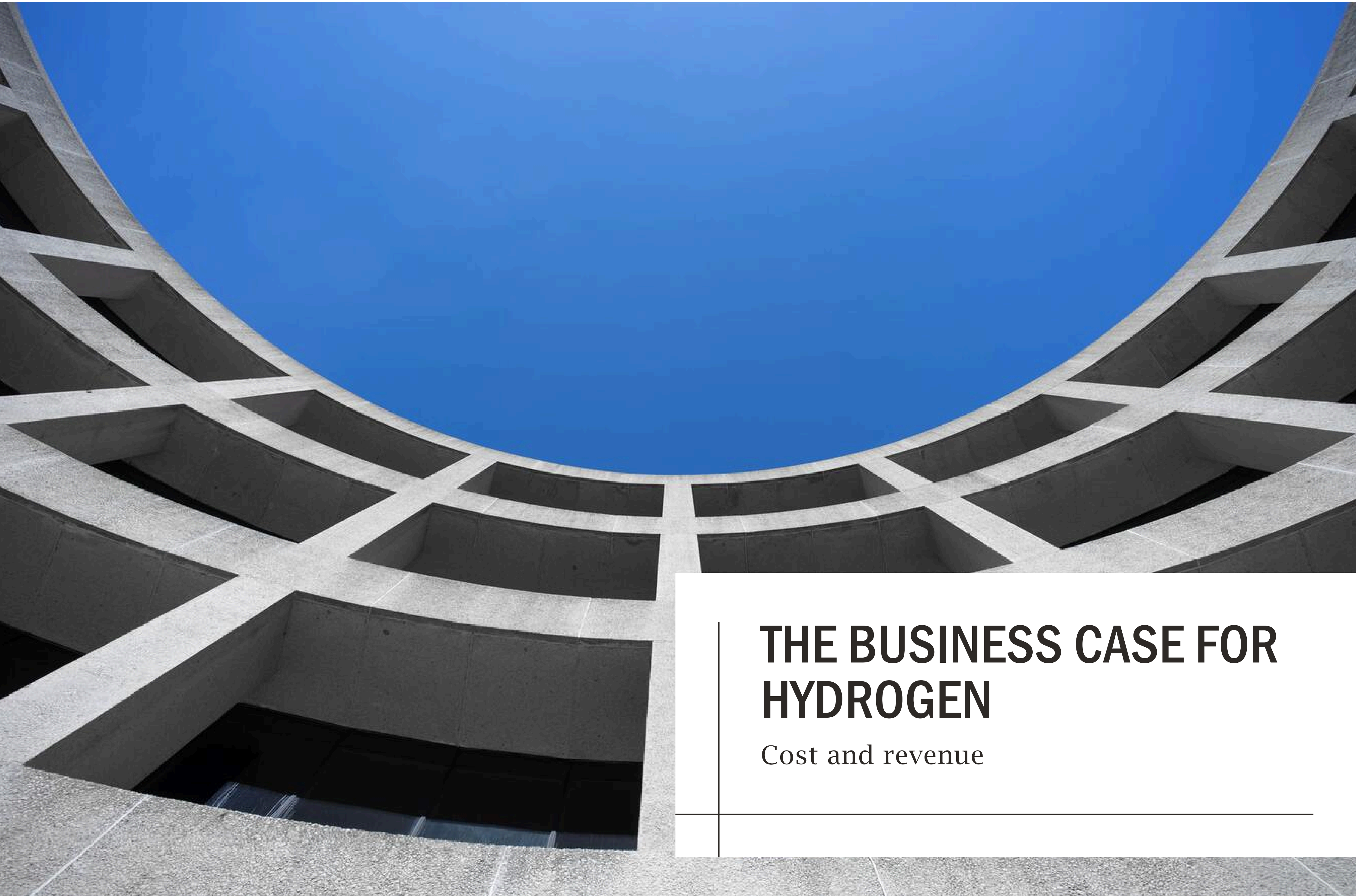
While all of these methods produce hydrogen, there are several differences between them. Costs vary substantially, and different countries have different starting points for each – and differing levels of political acceptance too.

WHAT ARE THE IMPLICATIONS FOR FUTURE HYDROGEN STRATEGIES?

The existence of these different 'colours' means there are a few key questions to ask from the beginning:

- When might each method be technologically and commercially ready?
- Should certain methods be excluded from consideration, based on their carbon footprint or safety concerns (e.g. hydrogen from nuclear electricity)?
- How are the different technologies perceived in different countries – for example with regard to national endowments of input sources, like natural gas?
- Should there be a level playing field – a 'market for all colours' – or should governments intervene to support specific technologies, like green hydrogen, on ecological grounds?

Answering these questions will be a vital first step in mapping out hydrogen strategies for the future.



THE BUSINESS CASE FOR HYDROGEN

Cost and revenue

TO MAKE INFORMED DECISIONS ABOUT THE FUTURE OF PRODUCTION AND CONSUMPTION, INVESTORS AND POLICYMAKERS MUST FIRST UNDERSTAND THE BUSINESS CASE FOR HYDROGEN.

In any business case, there are two main areas to consider: costs and revenue.

COSTS

The costs of producing hydrogen are driven by a variety of factors, which can be broadly grouped into technology, location, scaling and regulation.

- **Technology**: Some production technologies are well established. For these, future costs are more certain. Other technologies are less mature, increasing the level of uncertainty.
- **Location**: The costs of inputs like electricity, transport and capital are all dependent on where production takes place. The cost of a carbon source, if conversion to other synthetic fuels is going to take place, also depends on location.
- **Scaling**: Overall plant design and integration will impact the business case – to what extent are economies of scale possible?
- **Regulation**: Local regulatory frameworks (e.g. taxes and network charges) influence both production costs and users' willingness to pay.

REVENUE

The minimum revenues hydrogen products can immediately obtain on the market are determined by the prices of other 'grey' fuels – plus the costs for CO2 emission certificates, where applicable.

Higher revenues are possible if there is a willingness to pay for the green value of hydrogen. This might result from:

- **Voluntary measures** – firms or industry sectors that want to reduce their CO2 emissions for branding reasons.
- **Regulatory requirements** – quotas for hydrogen products, or a tax or CO2 price on more polluting forms of energy production.

In addition, revenue can be made from co-products, like oxygen and heat, or ancillary services, like provision of flexibility in the power market.

Regulatory frameworks also play a part in determining revenues. For example, synthetic methanol can be used in road transport, shipping or as industrial feedstock. As the regulatory framework for the usage of synthetic methanol differs between these sectors, revenue levels for the different applications would also vary.

EXPLORE OUR WORK IN THIS AREA:

Business models for low carbon hydrogen production

The future of mobility

Analysing CO2 lifecycle assessments in the mobility sector from cradle to grave

Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector

The role of hydrogen in heating buildings

49% renewables in buildings by 2030 – How to get there?

Hydrogen options for Northern Ireland

GOVERNMENT SUPPORT

Enabling an early low carbon hydrogen market

LOW-CARBON HYDROGEN IS MORE EXPENSIVE THAN THE HIGH-CARBON FUELS IT IS INTENDED TO REPLACE. TO ENABLE A MARKET, GOVERNMENT SUPPORT WILL BE REQUIRED.

Let's take a look at the key factors in designing that support, focusing on low-carbon hydrogen as a substitute for natural gas in industry.

WHAT ARE THE MARKET FAILURES TO ADDRESS?

- **Cost differential**: At the moment, carbon emission savings aren't fully rewarded by an effective carbon price. This means low-carbon hydrogen can't compete on cost with high-carbon alternatives. Other low-carbon technologies, like renewable electricity and biomethane, have faced similar cost challenges.
- **Limited substitutability and the chicken and egg problem**: Even if hydrogen did cost the same as methane on a per-unit basis, there are additional barriers to uptake: hydrogen is not, in most cases, a direct substitute for fossil fuels. Many end users would face costs and risks if they switched to it – such as those associated with the installation of new kit. This makes hydrogen different to other low-carbon innovations (e.g. renewable electricity), because there's a risk that an investor will build a low-carbon hydrogen plant only to find there's no customer base, because of a delay or failure in policy. Or that an industrial customer will install new kit to enable hydrogen consumption in their plant, only to find no reliable source of low-carbon hydrogen is available, because policy has not been able to enable investment in production. Because of these risks and barriers, any market participant making an investment in one part of the value chain is exposed to policy risk. These risks are very difficult for investors to manage.
- **Technological immaturity**: Important parts of the hydrogen supply chain are technologically immature. This includes carbon capture and storage (CCS) for blue hydrogen production, and electrolysis for green hydrogen. As a result, there are 'first-of-a-kind' (FOAK) risks associated with hydrogen projects. This also means that costs can be expected to fall over time from their current levels.

- **Infrastructure coordination**: The hydrogen value chain includes numerous components: the producer, the transport and storage operator, and the CO2 transport and storage operator in some cases. This adds complexity to the market because most of these elements are not yet well established, and support mechanisms will need to interact appropriately across them all.

In the longer term, if low-carbon hydrogen is to be rolled out for wider use, such as home heating, behavioural barriers may also become important. Most people tend to stick with what they know, rather than switch to new and less well known products. Information campaigns may be needed, just as they were when the use of natural gas was first introduced some 50 years ago.

WHAT ARE THE SUPPORT OPTIONS?

In the long term, an effective economy-wide carbon price should internalise the impact of carbon emissions, which would incentivise efficient decarbonisation and support competition between different low-carbon technology options.

But how should we get the initial investments off the ground?

In our work for governments and investors, we have considered four main categories of intervention to enable the early hydrogen market. These are shown in the table, together with the situations where they may be expected to work well.

TARGET	SUPPORT MECHANISM	EXAMPLE	WHEN WOULD IT WORK WELL?
Carbon price	Tax or emissions trading scheme	A carbon price can allow the low-carbon option to compete with the incumbent fossil fuel-based option.	Carbon pricing will work well where there is an established and liquid CO2 market and a stable policy framework surrounding it. This means it is likely to be an option for the longer term.
		An ongoing subsidy to top up market revenue and to allow the producer to sell the low-carbon hydrogen at a price that can	Producer subsidies can help manage demand risk and policy risk for investors and they may be particularly helpful in the

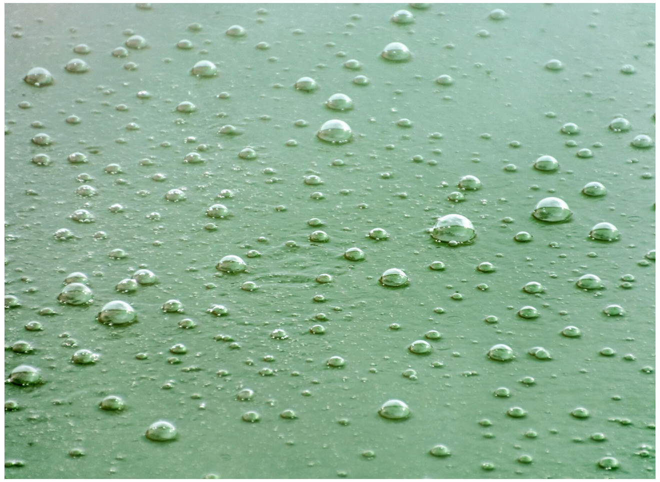
Open full table in browser:
https://explore.frontier-economics.com/story/roadmap-to-hydrogen/page/6/2

SO...WHAT'S THE BEST OPTION?

It depends. We have considered these options in the context of enabling an early market for hydrogen in the UK, where FOAK investments are needed, and there are some specific target sectors for consumption (primarily in industry). Under these conditions, we found that the best support option in the near term is likely to be a contractual producer subsidy model, combined with a subsidy to incentivise users to switch.

But in other contexts, where the focus is getting demand off the ground, an end user subsidy might work better. In Germany, Carbon Contracts for Differences (CCfDs) are intended to be introduced for energy-intensive industrial companies. The idea is that CCfDs give the demand side a reliable basis on which to invest, alongside incentives to attain the carbon reduction targets. Creating a stable demand for hydrogen should have a positive impact on the supply side. Other actions that can help stimulate demand and make hydrogen production investable in the near term include:

- **Grid blending with natural gas**: This could provide a stable demand source as hydrogen production is getting off the ground, with the potential to deliver demand certainty for investors and less disruption for customers. But it needs to start soon to be worthwhile, and issues like billing need to be resolved.
- **Investigating storage**: The role of storage, and identifying the type of storage that has most value, needs further work – it could play an important role alongside grid blending to further reduce demand risk.
- **Imposing standards**: Requiring gas turbines and boilers to be hydrogen ready would reduce the risk of them becoming stranded assets, and would provide ready-made markets for hydrogen.



EXPLORE OUR WORK IN THIS AREA:

The future of low carbon hydrogen production

A market-based approach to decarbonising the gas sector

Crediting system for renewable fuels in EU emission standards for road transport

HYDROGEN INFRASTRUCTURE

Transitioning to new systems

TO PLAY ITS PART IN DECARBONISATION, HYDROGEN NEEDS TO GET FROM WHERE IT IS MADE TO WHERE IT IS NEEDED.

Today, this is achieved via a combination of road transport and privately owned pipelines, including grids connecting a few closely located producers and industrial consumers (for example in Belgium and the Netherlands).

But more infrastructure will be needed to create a market for hydrogen on a national or European scale. We are likely to see a mix of:

- **Blending** hydrogen with natural gas in existing infrastructure.
- **Repurposing** existing natural gas infrastructure to dedicate it to hydrogen.
- **Rolling out** new, dedicated hydrogen infrastructure.

These approaches may be adopted simultaneously. Alternatively, some regions may opt for blending hydrogen as a stepping stone on the way to dedicated hydrogen infrastructure.

Whatever the approach, there are two important challenges to address:

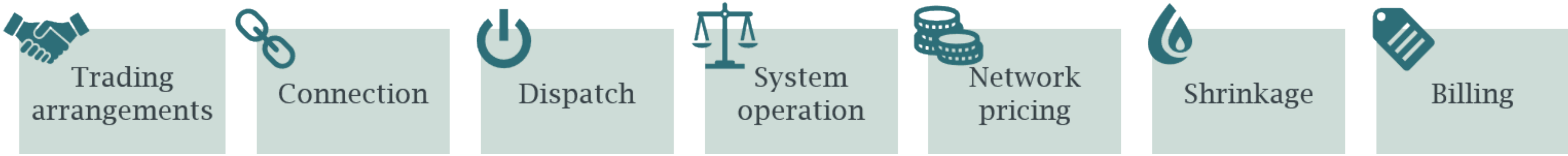
1. **The commercial framework for hydrogen**: Making efficient use of existing infrastructure, and ensuring a balance between supply and demand (both at an overall level in the gas system, and in particular parts of the network).
2. **Hydrogen infrastructure regulation**: Ensuring the right pipelines are delivered, in the right places, and that they can be accessed by those who need them, to support cost-effective delivery of hydrogen.

CHALLENGE 1: COMMERCIAL FRAMEWORK

In many ways, the commercial framework for dedicated hydrogen infrastructure could operate along similar lines to that in place today for natural gas. Blending, however, raises specific challenges:

- How to keep the hydrogen blend within the blend limit?
- How to manage specific gas quality requirements of certain user types, e.g. if a natural gas filling station for vehicles is connected to the gas network?
- How to ensure that blending does not lead to lock-in effects that prevent the full replacement of natural gas by carbon-neutral energies in the long term?
- How to strike a balance between the benefits of cross-border trading (blended) gases and the need to ensure the right quality of domestic gas supplies?

There are seven elements of the commercial framework that need to be considered, whatever the approach to transportation:



Some of the relevant considerations under each of the seven building blocks are outlined here:

COMPONENT	CONSIDERATIONS
Trading arrangements	Arrangements for trading energy and settling imbalances will need to be in place.
Connections	A regime will be needed to enable the connection of hydrogen production facilities.
Dispatch	Dispatch (i.e. injection of hydrogen into the grid) must be managed under both a hydrogen-dedicated network and blended system. Under a blended system, this will need to ensure that the maximum blend is not breached at any time.

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CHALLENGE 2: INFRASTRUCTURE REGULATION

Two key aspects of regulation are:

1. **Incentivising** the right level of hydrogen infrastructure at the right time, in the right places and at the lowest cost.
2. **Enabling competition** in hydrogen production, trading and sales by granting non-discriminatory access to hydrogen infrastructure.

EU regulation in natural gas and electricity markets has been very successful with regards to the second point, and there are good reasons to apply this proven regulatory framework to hydrogen infrastructure.

However, the starting point for hydrogen is different to that of electricity and gas. The bulk of electricity and gas infrastructure had already been built when regulation was introduced in the late 1990s, so the regulatory framework was not created to incentivise the development of new infrastructure.

In fact, since the introduction of regulation, many major investments have been made under a regulatory exemption, where investors need to prove that they would not undertake the investments if the asset were not exempted from regulation.

By contrast, the hydrogen infrastructure that might be required in the future is still to be built or repurposed, and the associated upfront investment costs will be significant.

If the regulatory framework is similar to that of gas and electricity, securing finance will be difficult. If grid operators can only earn money from hydrogen user tariffs, there will be few, if any, users during the construction phase. Subsequent growth in the user base may also be uncertain, while tariff regulation and limitations to long-term capacity contracting impose asymmetric risks for investors.

There are several options to deal with this, with any consideration needing to be linked into the wider discussion of government support in chapter 3. In the event that subsidies are required, the following options must be considered:

- **Direct state financing** to support infrastructure investments – though this would be a departure from typical practice and would lead to tricky state aid questions.
- Allowing network operators to **cross-subsidise** upfront financing, using income from natural gas user tariffs, to overcome the challenge of limited hydrogen users in the ramp-up phase. This, however, deviates from the ideal of cost-reflectiveness and poses controversial distributional questions (e.g. why should a small residential natural gas consumer pay for the infrastructure of large industrial hydrogen consumers?).
- **Step-wise introduction of regulatory elements**, where more interventional

elements (such as tariff regulation) are activated only as the maturity of the hydrogen infrastructure increases – although this imposes regulatory uncertainty for investors.

- Enabling the opportunity for investors to build or repurpose dedicated hydrogen infrastructure assets under a **temporary exemption** from regulation. This avoids asymmetric risks and grants investment certainty, but may result in a late actual application of infrastructure regulation, if most yet-to-be-built assets receive a 20-year exemption from regulation.

EXPLORE OUR WORK IN THIS AREA:

EU-level policy action to facilitate low-carbon gases

A commercial framework to facilitate hydrogen blending

A co-ordinated EU approach for managing different types of gases in the gas system

Regulating dedicated hydrogen networks

Import of hydrogen and low-carbon gas to Europe: The role of LNG terminals

UK Committee on Climate Change publishes Frontier report on the future of gas regulation

THE GLOBAL MARKET

Understanding trade in green hydrogen

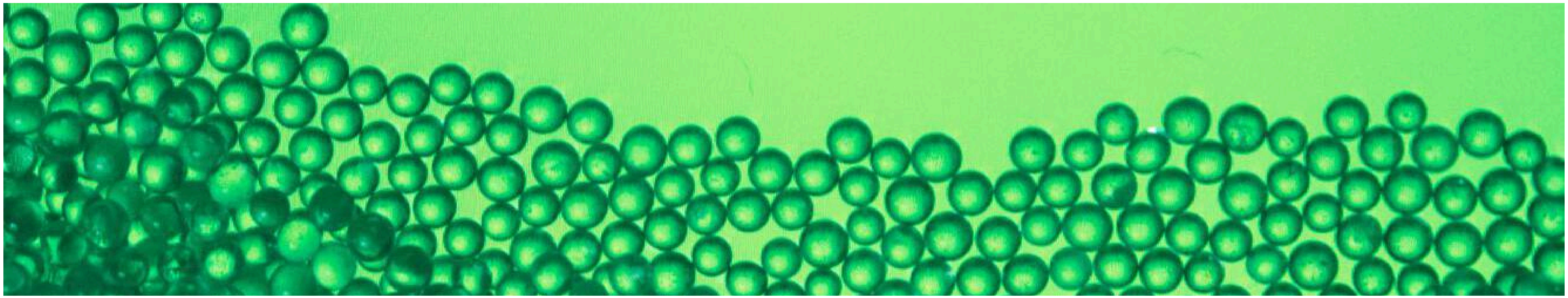
GLOBAL TRADE OF GREEN HYDROGEN WILL PLAY AN IMPORTANT ROLE IN ACHIEVING DECARBONISATION TARGETS.

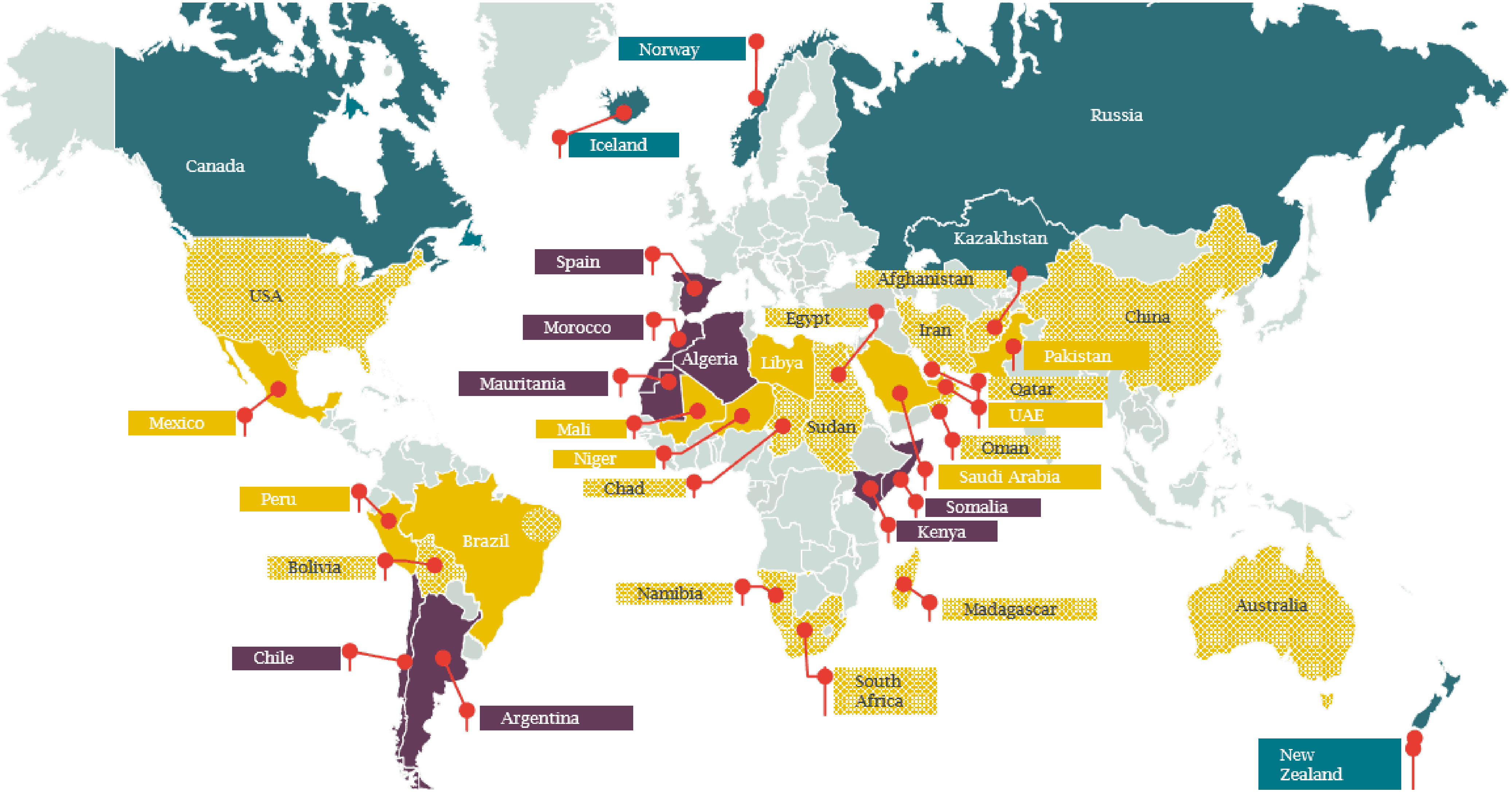
A global market will be vital to meeting demand

By 2050, global demand for hydrogen and other forms of electricity-to-fuel conversion (known as Power-to-X) could amount to 20,000 TWh per year or more. International trade will play an important part in meeting that demand – which will be particularly high in Asia and Europe – in a cost-efficient way.

Countries with significant hydrogen production potential are spread right across the world, from South America to Australia. Many countries would become new energy suppliers on the global market, leading to a more diversified portfolio of energy-supplying countries than, for example, for petroleum products.

Wind
Primarily wind, also PV-wind-hybrid in parts
PV
Primarily PV, also PV-wind-hybrid in parts
PV-wind-hybrid





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Qatar
Mexico
UAE
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Sudan
Oman
Niger
Saudi Arabia
Chad
Peru
Somalia
Kenya
Brazil
Bolivia
Namibia
Madagascar
Australia
Chile
South
Africa
Argentina
New
Zealand

Enabling a global market requires action in three main areas:

1. Establish the international business case.

Since green hydrogen competes directly with the fossil-fuel 'grey' alternatives on the market, investment projects are unlikely to be economically viable without additional measures. These issues were largely discussed in chapter 3, although it is also important to recognise that country-specific risks of financing projects in exporting countries will also need to be tackled. This may require international cooperation and coordination along the value chain.

2. Build coordinated infrastructure.

It's crucial that investment in infrastructure is coordinated between exporting and importing countries, to avoid incompatibilities and bottlenecks in transportation. This is true for transportation via shipping as well as via pipelines.

Issues with the timing of infrastructure investments must also be resolved – retrofitting natural gas pipelines is only possible when they are no longer needed for gas. And the optimal level of scaling and financing of first infrastructure investments must be determined.

3. Create a certification system.

A certification system is necessary to ensure that imported hydrogen is accountable to decarbonisation or renewable energy targets in the consumer countries.

As a first step, participating entities must agree on the sustainability criteria to be certified. These could include:

- Green energy sourcing
- Additionality of the green energy used
- Further environmental criteria, such as sustainable use of land and water
- Sustainable transport to the destination country
- Social criteria, such as fair wages.

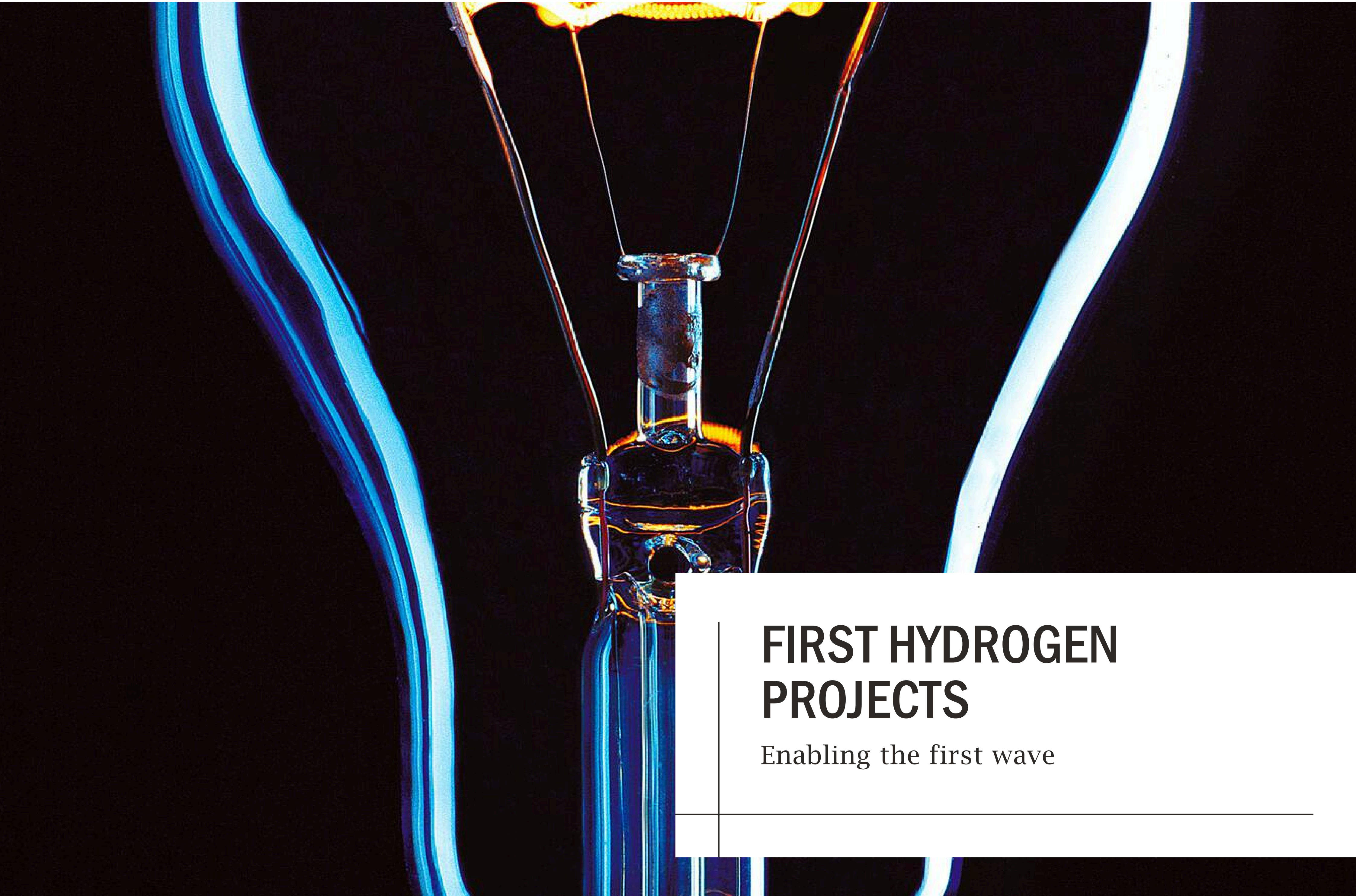
Once this has been done, practical issues will need to be clarified – what is the regional and temporal scope of the system, and which entities are involved?

EXPLORE OUR WORK IN THIS AREA:

Frontier presents Power-to-X Study commissioned by World Energy Council Germany

Jens Perner presents Frontier study on costs of imported synthetic heating and fuel in Berlin

frontier economics



FIRST HYDROGEN PROJECTS

Enabling the first wave

NOW THAT WE KNOW HYDROGEN HAS A ROLE TO PLAY, WE NEED TO ENABLE THE FIRST HYDROGEN PROJECTS TO HAPPEN.

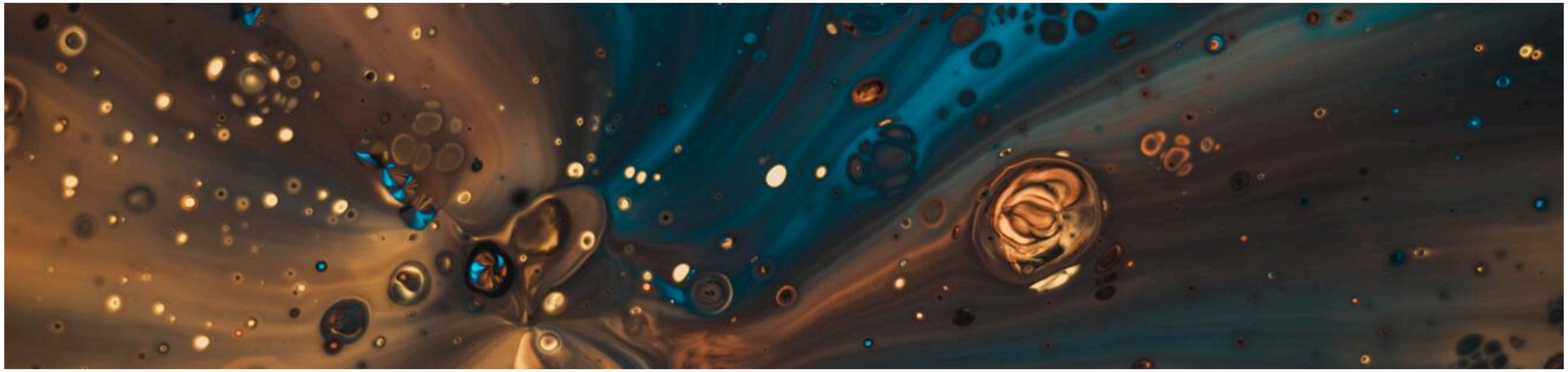
This means developing the contractual and regulatory infrastructure that would support a first wave of hydrogen projects. But this is a complex task. Even for a basic project, the following must be covered:

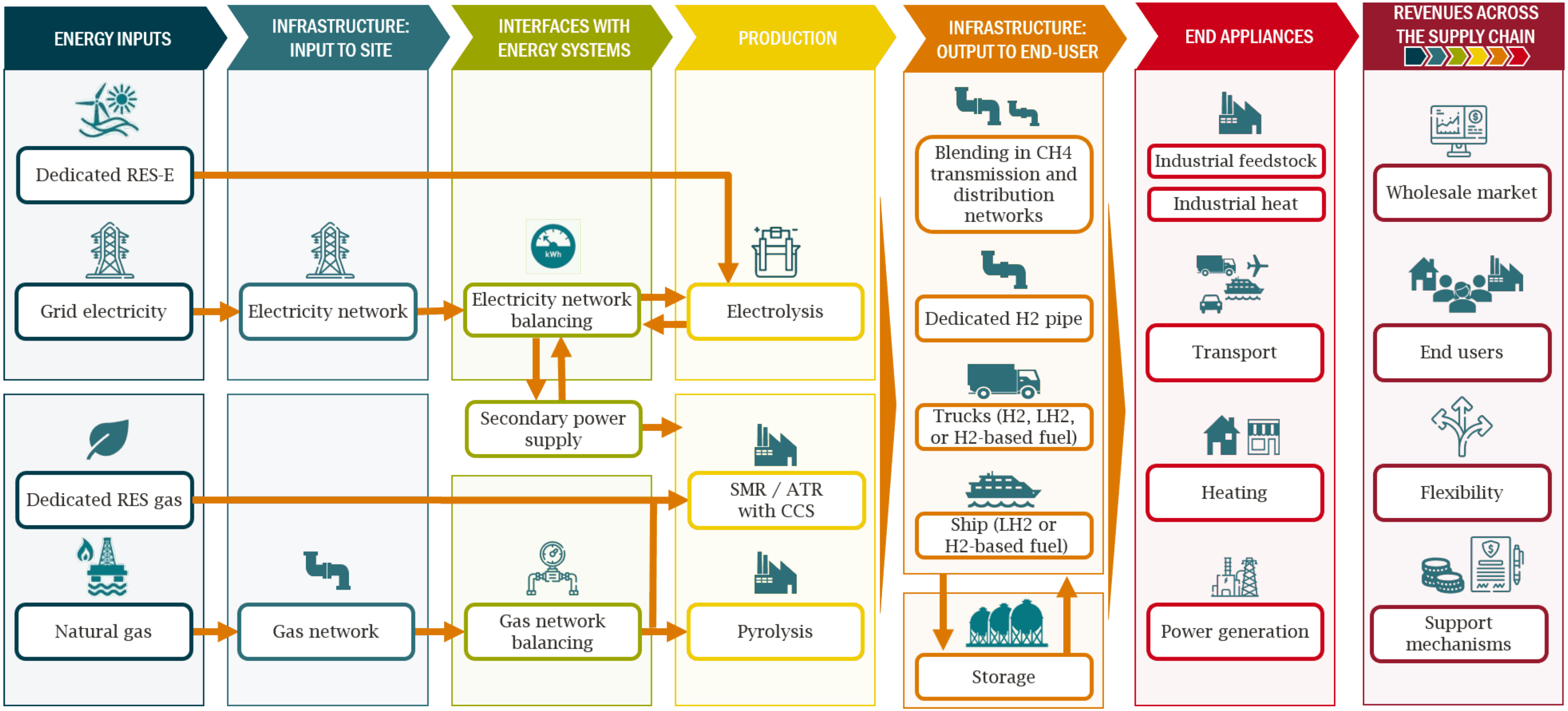
- **Energy inputs** – electricity (dedicated renewable electricity or electricity from the grid) or gas (dedicated renewable gas or natural gas from the network).
- **Physical infrastructure** – for the inputs, the hydrogen produced and, in the case of blue hydrogen, the resulting CO2.
- **Interfaces with the energy systems** – for issues such as balancing supply and demand of gas and/or electricity.

BRINGING TOGETHER MULTIPLE STAKEHOLDERS

For any scheme to reach a final investment decision, numerous stakeholders will need to agree: producers, suppliers, infrastructure providers, customers and, at least in the beginning, governments providing public support.

For all these parties to work together, several arrangements must be in place: contracts among different stakeholders, any required regulation of the infrastructure and the form of the public support.




ENERGY INPUTS
INFRASTRUCTURE: INPUT TO SITE
INTERFACES WITH ENERGY SYSTEMS
PRODUCTION
INFRASTRUCTURE: OUTPUT TO END-USER
END APPLIANCES
REVENUES ACROSS THE SUPPLY CHAIN
Dedicated RES-E
Grid electricity
Dedicated RES gas
Natural gas
Electricity network
Gas network
kWh
Electricity network balancing
Secondary power supply
Gas network balancing
Electrolysis
SMR / ATR with CCS
Pyrolysis
Blending in CH4 transmission and distribution networks
Dedicated H2 pipe
Trucks (H2, LH2, or H2-based fuel)
Ship (LH2 or H2-based fuel)
Storage
Industrial feedstock
Industrial heat
Transport
Heating
Power generation
Wholesale market
End users
Flexibility
Support mechanisms

ALLOCATING RISKS

A key element of these arrangements will be how they allocate risks. Doing so effectively, and reducing developer cost of capital, will be an important part of ensuring the investability and affordability of early projects.

The main risks that investors will be keen to see managed effectively are:

- Development phase:
  - Coordinating commitment
  - Coordinating operational start.
- Operational:
  - Commodity risk
  - Demand risk
  - Network cost risk
  - Infrastructure availability risk.

You can read more about these risks in a UK context, including how they might be mitigated and allocated efficiently, in Frontier's recent joint paper with Dentons.

EXPLORE OUR WORK IN THIS AREA:

Making early hydrogen projects investable

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ROADMAP TO HYDROGEN

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