INTERNATIONAL ASPECTS OF A POWER-TO-X ROADMAP

A report prepared for the World Energy Council Germany

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The Weltenergierat - Deutschland e. V., based in Berlin, represents the German energy system in the network of the World Energy Council. Among its member are over 60 companies and associations. The council looks at the entire energy spectrum with a fact-based eye in order to promote a better understanding of energy issues and solutions from a global perspective.

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EXECUTIVE SUMMARY

The global energy system needs to fundamentally transform towards carbon-neutral energy sources over the next decades to meet the long term goals set in the Paris Agreement – to keep the increase in global average temperature to well below 2 °C above pre-industrial levels. National governments around the world have committed to highly ambitious goals to reduce greenhouse gases (GHG, including CO_2) in the years to come. The Federal German Government has set the goal to reduce GHG emissions by 80% to 95% by 2050 compared to 1990s levels. Reaching this goal entails a massive change in the supply and utilisation of energy as we know it today.

The increasing use of renewable energies will be a key element for the global energy transformation – alongside improving energy efficiencies. There are numerous ways to deploy renewable energy: directly in end-user applications (biomass, solar panels, geothermal etc. in heating), as electricity (e.g. in electric cars, heat pumps etc.) or as synthetic fuels produced from renewable energies.

In this study, we focus on the latter – synthetic fuels generated from renewable electricity (Power-to-X or PtX), i.e. renewable or "green" fuels.[1] These include green products such as hydrogen[2], ammonia, methane, methanol, diesel, gasoline, and kerosene. The renewable fuels can be deployed across all sectors – such as transport, heating, industry, power generation – and replace conventional fuels from hydrocarbons as the primary energy source and feedstock.

The aim of this study is to develop a dedicated roadmap for establishing a global PtX industry over the course of the next decades. We explain the need for international PtX production and trade on a global scale, explore potential PtX producing and exporting countries around the world and identify major pillars and milestones of a roadmap towards a global PtX market.

The final recommendations of the three pillars of the PtX roadmap are:

- Enhance and support the scaling up of PtX technologies and plant sizes to achieve significant cost savings, paving the way for international trade;
- Create a level playing field for PtX and conventional fuels rewarding the carbon-neutral character of these green synthetic fuels, thereby ensuring reliable demand structures and spurring the growth of the global PtX market; and
- Facilitate an adequate framework for investments via binding and non-binding policy measures, including cooperations and standards for trade.

Finally, complex interdependencies between these core pillars and accompanying recommendations require a coordinated approach to develop a global PtX market.

The main results of the study are summarised as follows.

[1] Unless explicitly stated otherwise, references to PtX or synthetic fuels in the remainder of this study refer exclusively to renewable, i.e. green, products.

[2] Hydrogen is produced via water electrolysis and is therefore not synthesised. In the context of this study, however, we count hydrogen as part of the categorisation of synthetic fuels (for simplicity).

PtX is a necessary element of the global energy transition

PtX will be an integral part of the transformation towards a low carbon energy system. In many countries it will accompany the other key elements carrying this change – the direct use of renewable energy and the direct use of renewable electricity. Green PtX complements these solutions due to a number of reasons.

- **Lack of alternatives:** In some sectors, fuels with high energy density are required for logistical reasons. This applies in large parts to the aviation and shipping industries, for example, but equally to specific high-temperature industrial or chemical processes. PtX fuels provide, in addition to biofuels, the technically feasible solutions to achieve the necessary CO_2-reductions required in these applications.
- **Storability improves security of supply:** The future renewable energy system in Europe will require large scale energy storages, e.g. for shifting renewable power generation from summer to the winter season for heating purposes. PtX products are well placed for this seasonal storage of electricity and the flexibility of PtX products will therefore improve the security of supply.
- **Immediate demand potential:** Most synthetic fuels, including synthetic methane, diesel, gasoline, kerosene and others, can immediately be used in existing appliances and infrastructure. CO_2-reductions can take place within a short timeframe without waiting for lengthy replacements of end-user applications to other technologies. This is especially relevant for the heating sector (using existing heating facilities) and in the transport sector (prolonged use of combustion engines).
- **Strengthened acceptance:** The public acceptance of new infrastructure developments impacting the environment and landscape is limited. Creating the option to use existing energy infrastructure via PtX, such as gas pipelines, can help to overcome public concerns.
- **Cost considerations**: Renewable fuels allow in many cases to save costs due to the option to use existing infrastructures such as gas pipelines, filling stations and storage facilities. Also, the usage of existing and affordable end-user application such as low-cost condensing boilers reduce the need of significant infrastructure investments.

Imports of green synthetic fuels and the development of a global PtX market support the energy transition

The energy transition in Germany will require substantial imports of green fuels from abroad for various reasons.

- **Cost advantages through import**: PtX produced in those regions of the world that demonstrate favourable site conditions for renewable energies (PV, wind) is significantly cheaper than PtX produced in Europe (e.g. Germany) – even considering transportation costs.
- **Availability of sites for RES-E**: The availability of sites for generating electricity from renewable energy sources (RES-E) is limited in many European countries, e.g. in Germany – especially regarding wind, but also biomass. This

may be reinforced by environmental constraints in some countries, such as landscape protection and maritime protection. The expectation is therefore that a substantial share of the renewable energy consumed in Europe/Germany must be imported.

- **Transportability of PtX is comparatively strong:** For importing larger capacities of renewable energy, chemical energy carriers (including PtX) are the first choice: large scale international infrastructure exists and the transportation costs for long distances are relatively low.
- **Global PtX trade supports economic growth and welfare:** Imports and exports of energy are common, strengthening international trade relationships, cooperations and political ties. International trade facilitates political stability and welfare. Exporting countries can benefit from investments and growth, importing countries can benefit from lower energy costs. Furthermore, countries that export technologies and equipment (plants and installations), such as Germany, benefit from ramping up the market.

A global market for PtX can be huge in size in the long term – driving substantial investments in PtX plants and infrastructure

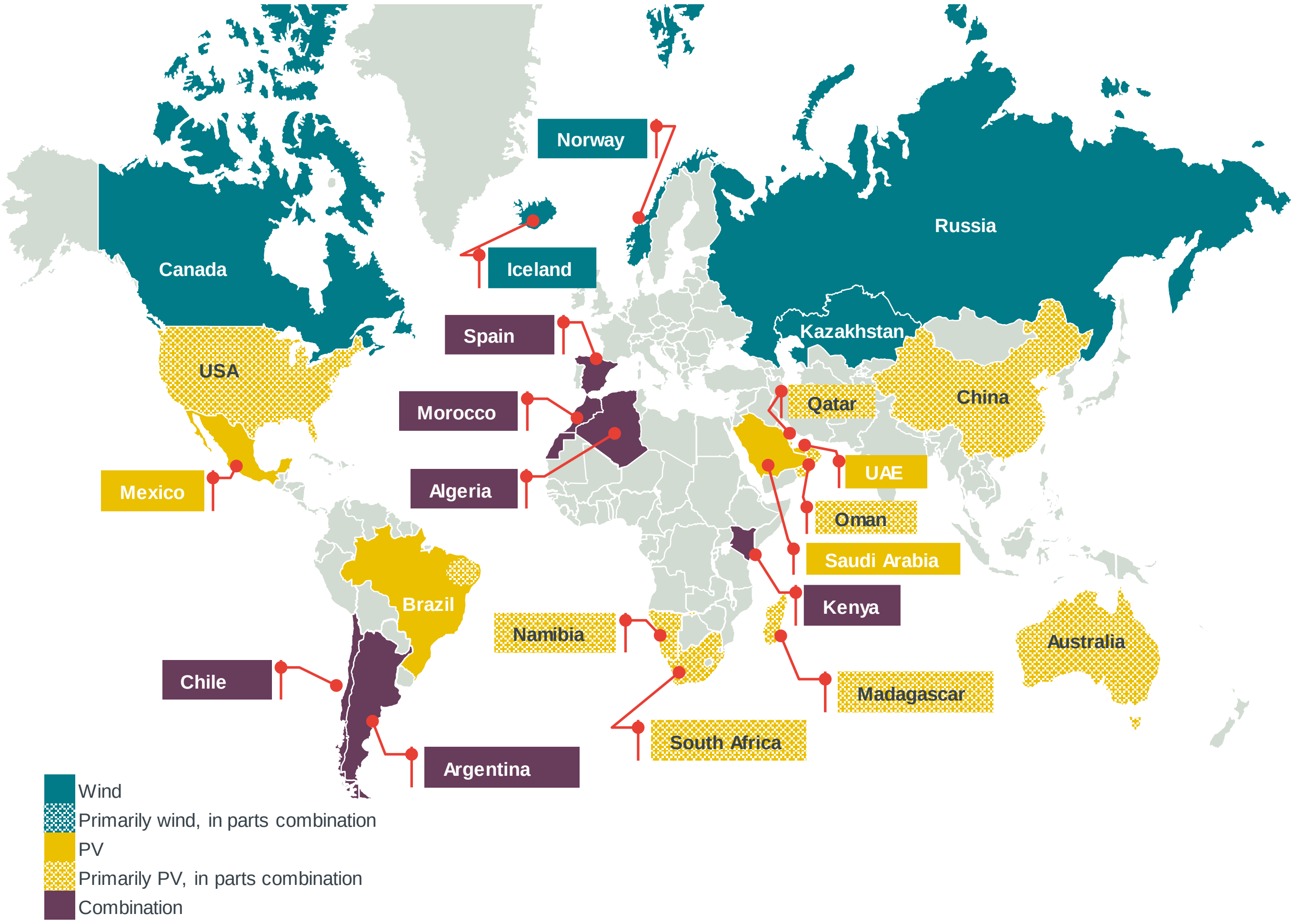
Indicative estimations illustrate that a mature global market for green synthetic fuels can easily demand between 10,000 to 20,000 TWh/a in the long term (2050 and beyond). This corresponds to around 50% of today's global demand for crude oil. The required capacity for water electrolysers (producing hydrogen) alone can reach between 3,000 to 6,000 GW.

A future global PtX market will be sizeable as even a partial materialisation of this indicative global PtX market potential requires significant investments in PtX technologies and plants over the next decades. These investments will need an adequate framework and early action, paving the way towards a global PtX industry.

There is a large number of potential PtX producing countries, however, whether and when they enter the market depends on individual motivations

A global PtX market could be supplied by many potential PtX producing countries. The spread of these countries across the world illustrates the diversity of potential suppliers and shows that the demanded volumes can be provided. Countries and regions with favourable conditions for renewable energies and high technical potential for producing power from renewable energy sources are strong candidates for PtX production and exports (see Figure 1).

Figure 1 Snapshot of the variety and diversity of potential PtX producing countries



Source: Frontier Economics

Note: Illustrative presentation of the strongest RES potentials only; not an extensive list of all countries.

Each country will have an individual story and diverse incentives as to why it would choose to play a part in a global PtX market and at which stage it might be ready and willing to enter. Indicatively, we identify certain categories of "PtX types" according to the countries' current stage of engagement with PtX, their possible motivations to produce synthetic fuels and their potential role in a global market.

We identify "frontrunners" (e.g. Norway), "hidden champions" (e.g. Chile), "hyped potentials" (e.g. Morocco), "converters" (e.g. Saudi Arabia), "giants" (e.g. Australia) and "uncertain candidates" (e.g. China) (Figure 2). The countries are analysed in more depth for illustrative purposes and were selected as representatives for a group of other countries with similar characteristics and PtX potentials. Similarly, the allocation of these candidate countries to a specific type is not necessarily fixed and confined, and elements of other types might also apply. Equally, some countries may be categorised in a number of types as they are not mutually exclusive and may complement each other.

Figure 2 Types of possible PtX producers/exporters and selected example country

Type	PtX motivation and readiness	Selected example
Frontrunners	▪ PtX already on countries (energy) political radar ▪ Export potential and PtX readiness evident ▪ Uncomplicated international trade partner ➢ Especially favourable in early stages of market penetration	Norway
Hidden Champions	▪ Fundamentally unexplored RES potential ▪ Largely mature, but often underestimated, (energy) political framework with sufficiently strong institutions ➢ PtX could readily become a serious topic if facilitated appropriately	Chile
Giants	▪ Abundant resource availability: massive land areas paired with often extensive RES power ▪ PtX readiness not necessarily precondition, may require facilitation ➢ Provide order of PtX magnitudes demanded in mature market	Australia
Hyped Potentials	▪ At centre of PtX debate in Europe with strong PtX potential ▪ Energy partnerships with Europe foster political support ➢ Potential to lead technology development; may depend strongly on solid political facilitation	Morocco
Converters	▪ Global long term conversion from fossil to green energy sources ▪ PtX to diversify portfolio as alternative long-term growth strategy ➢ Strong motivation for PtX export technology development; may requires political facilitation and partnership with the EU/DE	Saudi Arabia
Uncertain Candidates	▪ Partially unexplored RES potentials, possibly paired with ambitious national climate change policies ▪ PtX export in competition with growing national energy demand ➢ PtX export motivation and potential unclear – may drive PtX technology development, however export uncertain	China

Source: Frontier Economics.

Note: The PtX types and the allocation of a possible candidate country within each category serve as starting point to identify possible PtX development strategies; not a concise list and readily alterable.

The roadmap towards a global PtX industry is based on three pillars: Scaling up technology, creating markets/demand and facilitating investment/supply

Global markets for the trade of synthetic fuels will only develop if both supply and demand mature at relatively similar rates over time. The following core pillars build the framework to develop and establish and international PtX market and trade:

- **Pillar 'Technologies' – technological roadmap for building up a large scale PtX industry.** A global market for PtX will require further technological upscaling and cost reductions. Additionally, the initialisation of a global PtX market can be supported by complementing technologies such as "blue" hydrogen (e.g. based on steam reforming of natural gas) or – temporarily – capturing of CO_2 from biomass and/or industrial processes (required for synthetic fuels with carbon content).

- **Pillar 'Markets and Demand' – roadmap for building up markets and reliable demand structures.** Synthetic fuels will have to find their markets to ensure the financing of investments. There will be no substantial PtX industry if consumers do not buy and pay for green PtX. Therefore, the environmental value of PtX must be transferred into monetary terms in countries importing synthetic fuels (e.g. Europe/Germany).
- **Pillar 'Investments and Supply' – roadmap for building up a favourable investment frameworks to secure PtX supply.** The PtX industry needs to be build up in both producing and exporting countries and the framework for investments in PtX plants must be appropriate to attract the necessary global investments. For realising investments in potential PtX exporting countries, international cooperations can be key.

The pillars are interlinked and should be developed simultaneously.

Pillar 'Technologies': Scaling up technologies for significant cost savings

Technology development needs large scale projects and greater numbers of installations to standardise manufacturing of applications and processes. Cost reductions require considerable learning effects and efficiency improvements of PtX technologies. The key drivers to achieve these technological improvements and cost savings are therefore:

- Scaling up plant unit sizes – various studies show that investment costs fall with increasing plant unit size.
- Scaling up manufacturing processes – to standardise the production of installations in standardised modular units. For this, significant growth in the market size for the installations is required.

In addition, at least in the short and medium term, the development of a global PtX market can benefit from low-cost technologies that can complement PtX, such as

- "blue hydrogen" (hydrogen produced from steam reforming of natural gas with carbon capture and storage (CCS)); and
- and carbon capture from lower-cost sources (such as industrial emissions and biomass instead of direct air capture).

Although there are already a number of active PtX projects around the world, only very few (and no large scale) international projects based on renewable energies currently exist demonstrating the feasibility and technical capability of PtX exports across the value chain. Synthetic fuels are currently produced on a smaller scale and in some cases, the electricity is taken from the public electricity grid. Furthermore, today's PtX pilot and demonstration projects are built for local niche markets. Therefore, larger scale integrated pilot projects to demonstrate the viability of PtX exports to Europe based on renewable power can be the next step towards developing an international PtX market.

Pillar 'Demand and Markets': Policies reflecting the green value of PtX

To establish a global market for PtX, it is key that investors can secure the financing of their projects and find long term markets for their products. In this context, this implies that green synthetic fuels must be demanded by customers at a price that covers cost and reflects the value of its carbon-neutrality. Without an adequate demand market and without customers willing to buy the product, investments in PtX technologies and facilities cannot be expected to take place in the longer term – neither inside nor outside Europe.

To support the establishment of PtX markets, the following steps could be envisaged by policy makers:

- In the short term, **support for pilot and demonstration projects** is required: PtX projects will require public support to get financed if the regulatory framework does not incentivise the willingness-to-pay for the green value of PtX. The first plants that offer large scale synthetic fuels generation will require much greater funding than subsequent plants.
- **Regulations of energy markets** should be adapted in a way that R&D and investments in PtX technologies and plants are not obstructed: taxes and levies should be structured in a way that synthetic fuels are not in a position of disadvantage. For example, electricity used for PtX production could be (partly) exempted from energy taxes and levies in the shorter term.
- Market growth can be supported through **targeted policy measures for creating markets in specific sectors and segments,** e.g. by crediting PtX against renewable energy and CO_2-reduction targets/obligations. Another option would be to permit PtX offsetting for the emission thresholds**:** PtX should be an element of renewable energy policy on an equal footing.
- In the long term, a **level playing field for CO_2-reduction technologies including green PtX** needs to be created on a global scale**:** green PtX should compete with other CO_2-reduction technologies on equal terms in the long term.

Pillar 'Investment and Supply': Framework for investment and international policies

Significant investments in PtX technologies and plants in producing countries will be essential to develop a global PtX industry and a market. These investments require an adequate political framework. To improve the investment conditions for green PtX, energy policy makers (e.g. in Europe/Germany) should aim to further improve the green with (potential) PtX exporting countries. These improvements could include:

- Intensifying **the (non-binding) cooperations** with energy exporting countries and increasing the number of states/regions with an energy partnership. A PtX industry can support both climate change policy in importing countries (e.g. Europe/Germany) and the development of economies and energy systems in the exporting countries.

- Pushing for **legally binding Energy Agreements/Treaties** can be a stepwise approach for an improved investment climate. PtX should be part of the political agenda of multilateral negotiations such as UNFCC conferences as well as energy and climate agreements. The Energy Charter Treaty could be promoted with an increasing number of states as only around 50 countries have so far signed and ratified the treaty – this would be an important step in the right direction.
- **Standards for PtX imports** and the establishment of **regional / global monitoring and certification schemes** to guarantee that sustainability and social standards are met. This can raise the trust in global PtX markets and ensures that the green value of PtX can be captured on a global scale.
- Evaluating **financial support to mitigate risks** – governments and state authorities can (temporarily) support investments in green PtX in foreign countries. This aims at lowering potential financial barriers related to country risks, e.g. by granting state guarantees or specific loans.
- **Strategic diplomatic support** can foster the establishment of relevant relationships and set up first projects.

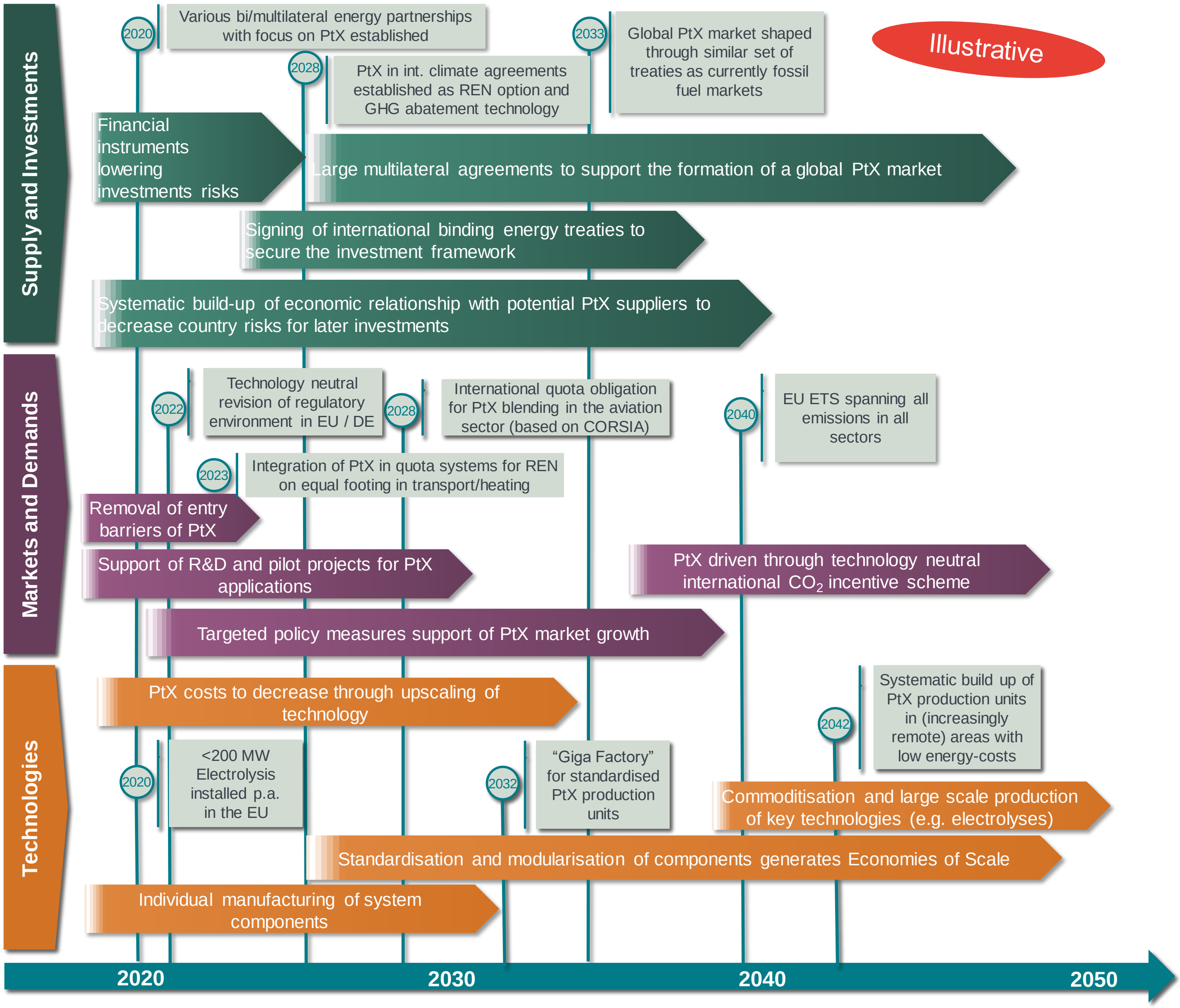
Timing and complex interdependencies require a coordinated approach to developing an international PtX market

In addition to the necessary steps outlined within each pillar, there is a need for coordinated action across the development stages of each pillar. Policy makers therefore need to facilitate and support the development in all areas in parallel (see Figure 3):

- The development and scaling up of the required technologies could be facilitated through direct R&D support. More importantly, creating early opportunities and business cases can help to develop, apply and test the required applications in pilot project and niche markets.
- Effective climate change policies and/or suitable incentives (e.g. crediting of PtX on renewable energy and/or CO_2-targets) will ensure the validation and certification of PtX products and support the market development.
- Investments in production capacities should be fostered through a general favourable investment environment and a prospect for future business models.

With increasing maturity and growth of the PtX market, policy should aim towards international integration and move from more technology-specific policies towards a more generic approach to provide a level playing field for all carbon-neutral technologies, including PtX.

Figure 3 The three pillars of an international PtX roadmap



Source: Frontier Economics

1 INTRODUCTION: WE DEVELOP A ROADMAP TOWARDS A GLOBAL PTX MARKET

In the following, we

- describe the background and the key questions of the study;
- characterise the synthetic fuels (Power-to-X or PtX) that are at the heart of this study; and
- explain the structure of the report.

1.1 Background

The global energy system needs to fundamentally transform towards carbon-neutral energy sources over the next decades to meet the long term goals set in the Paris Agreement – to keep the increase in global average temperature to well below 2 C above pre-industrial levels. National governments around the world have committed to highly ambitious goals to reduce greenhouse gases (GHG, including CO_2) in the years to come. The Federal German Government has set the goal to reduce GHG emissions by 80% to 95% until 2050 compared to 1990s levels. Reaching this goal entails a massive change in the supply and utilisation of energy as we know it today.

The energy transition towards carbon-neutrality is based on a number of key elements such as

- increasing the efficiencies of energy applications;
- boosting the supply of renewable energy sources (RES); and
- deploying other forms of carbon-neutral technologies, such as nuclear power or carbon capture and storage (CCS).

The increasing use of renewable energies will be a key element for the global energy transformation – alongside improving energy efficiencies.[3] There are numerous ways to deploy renewable energy: directly in end-user applications (e.g. biomass, solar panels, geothermal in heating), as electricity (e.g. in electric cars or heat pumps) or as synthetic fuels produced from renewable energies.

In this study, we focus on synthetic fuels produced from renewable electricity (Power-to-X or PtX), i.e. renewable or “green” liquid or gaseous fuels.[4] These include green products such as hydrogen[5], ammonia, methane, methanol, diesel, gasoline, and kerosene. The renewable fuels can be deployed across all sectors –

[3] The use of other forms of carbon-neutral technologies, such as nuclear power or carbon capture and storage (CCS), may only apply to some countries and its use may be limited (see Section 4.1.1).

[4] In the context of the focus of this study, PtX does not include Power-to-Heat. Unless explicitly stated otherwise, references to PtX or synthetic fuels in the remainder of this study refer exclusively to renewable, i.e. green, fuels.

[5] Hydrogen is produced via water electrolysis and is therefore not synthesised. In the context of this study, however, we count hydrogen as part of the categorisation of synthetic fuels (for simplicity).

such as transport, heating, industry, power generation – and replace conventional fuels from hydrocarbons as the primary energy source and feedstock.

The aim of the study is to develop a dedicated **roadmap for establishing a global PtX industry** over the course of the next decades. We analyse the following questions:

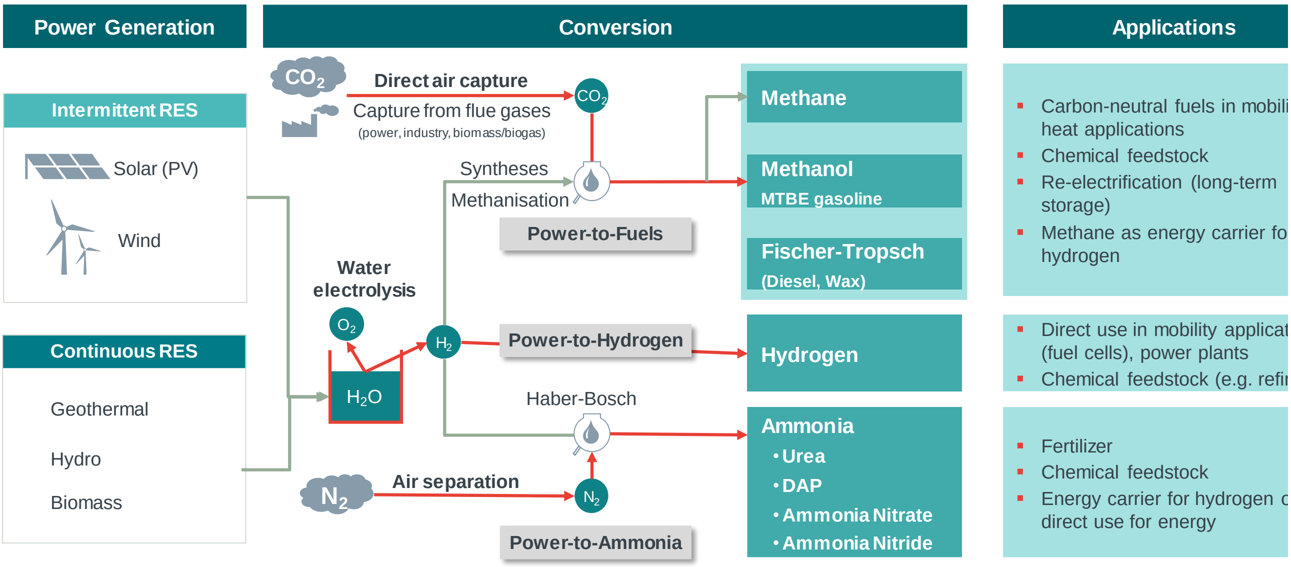
- What are the benefits of PtX in the energy transition and why is international trade of PtX beneficial?
- Which market size might a global PtX market achieve in the long term?
- Which countries could be high potentials for PtX production and export? How can these countries be differentiated, what are the motivations for the countries to enter to the PtX market as suppliers and what are the perspectives? For this, we analyse a sample of selected countries in greater detail.
- What are the main drivers for the establishment of a global PtX market, what are the obstacles?
- How could policy makers support the establishment of a global PtX market?
- How could a roadmap towards 2050 look like for ramping up a global PtX market?

1.2 The focus of this study is on PtX

In this study, we focus on synthetic fuels, i.e. liquids and gases produced from renewable electricity (Power-to-X or PtX) (Figure 4):

- **Hydrogen** can be used directly in energy appliances (e.g. power plants), in mobility applications (e.g. fuel cells) and as chemical feedstock (e.g. refinery).
- **Synthetic methane** can be fed directly into an existing grid for natural gas and can be used in mobility, industry and heat applications.
- **Synthetic liquid fuels** (e.g. methanol, gasoline, kerosene, diesel and heating oil) can be used directly in the same applications as fossil liquid fuels.
- **Ammonia** (and secondary products such as Urea, DAP) can be used, for example, in the fertiliser industry. Ammonia can also serve as an energy carrier of hydrogen to enable transportation.

Figure 4 Power-to-X: Conversion of renewable power into various forms of chemical energy carriers



Source: Based on Siemens

Note: In the context of the focus of this study, PtX does not include Power-to-Heat.

In this study, we assume that hydrogen is produced via water electrolyses[6], where water is decomposed into oxygen (O_2) and hydrogen (H_2) using electricity. We further assume that the electricity is generated from renewable energies such as PV, wind, geothermal, hydro or biomass.

The hydrogen can either be directly used in end-user energy appliances (power plants, fuel cells, heat appliances etc.) or can be further converted in a second-stage process to synthetic fuels. The options are

- synthetic liquid fuels incorporating CO_2 which are produced either via
  - Methanol synthesis (possibly plus upgrading); or
  - Fischer-Tropsch synthesis (possibly plus upgrading); or
- synthetic methane incorporating CO_2 via the process of methanisation; or
- ammonia via the Haber-Bosch process.

For synthetic fuels such as methane, diesel, heating oil, gasoline, kerosene etc., CO_2 is required as an input factor alongside hydrogen. The CO_2 can be captured directly from the air, from biomass/biogas or from flue gases from the industry. The nitrogen that is required for the production of ammonia is separated from the air.

1.3 Structure of the report

The report is structured as follows:

[6] Hydrogen can also be produced from e.g. natural gas or other fossil fuels. In this case, the carbon (CO_2) is separated from the hydrogen via steam reforming. However, to keep the hydrogen production carbon-neutral, the CO_2 has to be captured and stored in the ground (CCS) – this hydrogen is referred to as “blue hydrogen”. We will discuss this option as complementary technology for PtX further in Section 4.1.1.

- **Section 2**: We explain the benefits of PtX in the energy transition towards carbon-neutrality as complementary to other energy options (e.g. direct usage of renewable electricity via battery systems) and explore the benefits of international PtX trade. Additionally, we indicatively estimate the potential global PtX market size in the long term.
- **Section 3**: We examine countries worldwide that could be high potentials for producing PtX, and shed light on their possible motivations and levels of readiness to build up a new industry and to enter an international PtX market as suppliers/exporters. To illustrate the varying motivations and levels of readiness, we analyse a sample of six selected countries in greater detail. We also explain incentives for the import of PtX from these countries, e.g. from the perspective of the EU or Germany.
- **Section 4**: We analyse the three main pillars of a roadmap towards a global PtX industry. These are technology development and scale up, creating PtX markets as well as demand and providing an adequate investment framework to secure supply. We also discuss how policy makers could support the establishment of a global PtX market, e.g. by intensifying cooperations and political treaties/agreements.
- **Section 5**: We summarise the roadmap and highlight interlinkages between the three core pillars analysed in the previous section. Furthermore, we provide a list of potential next steps on the political agenda.

2 PTX WILL BE A KEY ELEMENT FOR THE TRANSITION OF ENERGY SYSTEMS TOWARDS CARBON-NEUTRALITY

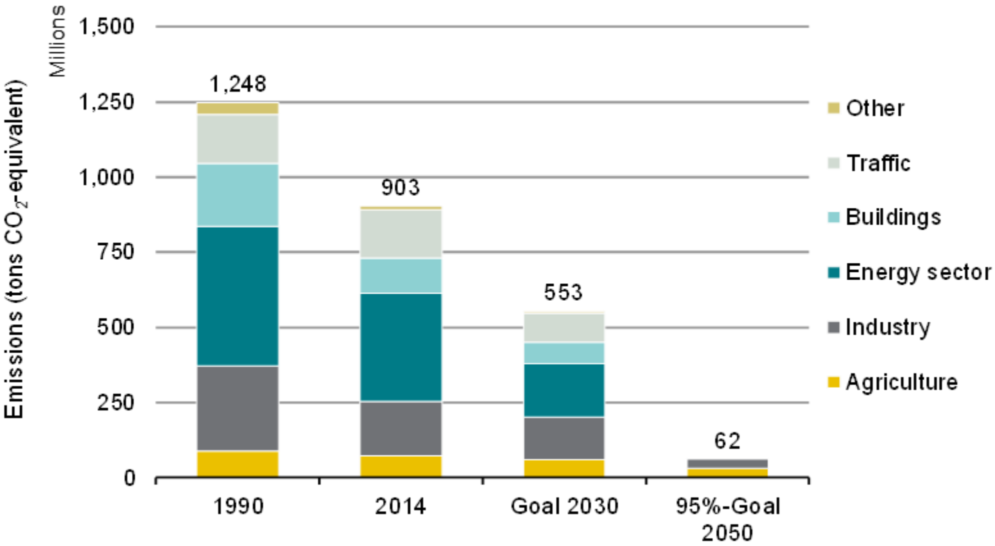
In the following, we analyse the potential future role of PtX for the transition of the global energy system towards carbon-neutrality. In this context, we

- explain the benefits of PtX as an important element of the future energy mix in complementation to other carbon neutral fuels as well as the direct use of renewable electricity (e.g. E-mobility, electric heat pumps) and direct use of renewable energies in final applications (solar panels, geothermal, biomass for heating etc.) (Section 2.1);
- explain the benefits of international PtX production and trade for importing and exporting countries (Section 2.2); and
- estimate a potential indicative size of a future global PtX demand in the long term in order to get a sense for the magnitude of investments required to establish a larger scale global PtX market (Section 2.3).

2.1 Ambitious climate targets require a “de-fossilisation” in all major sectors

As stated in the previous section, agreed climate change goals across the world – but especially in Europe – are very ambitious. In order to reach these goals, it will be essential that all energy consuming sectors reduce GHG-emissions over the next decades, including power generation (energy), transport, industry and buildings (Figure 5). In many countries, major reductions of GHG-emissions have so far been limited to the power sector and the industry (and to a lower extend to the heating of buildings), however, especially emissions from the transport sector have not yet been reduced to a larger extend as mobility demand and freight transport have significantly increased

Figure 5 Greenhouse gas emissions in Germany across sectors



Source: Frontier Economics (historical values based on information from the Federal Environmental Agency: National greenhouse gas inventory 2017, final status 04/2017).

While the power sector can reduce CO_2 emissions by switching from fossil-fuels emitting CO_2 (coal, natural gas, oil products) to other generation technologies such as renewables, nuclear and carbon capture and storage (CCS), the GHG-abatement in the other sectors (transport, heating, industry, agriculture) has to be based on a mix of instruments such as:

- Increasing energy efficiency (e.g. energy saving by insulation, efficiency improvements of combustion engines etc.);
- Direct usage of solid, liquid or gaseous renewable energies in end-user applications (e.g. heating with biomass, geothermal or solar panels etc.);
- Application of CCS (carbon capture and storage) or CCU (carbon capture and usage);
- Increasing direct usage of electricity from renewables (e.g. conversion of industrial processes to electricity, e-mobility in the transport sector, electric heat pumps or direct electricity heating in the heating sector); and
- Indirect usage of renewable energy via PtX.

Due to technical reasons, there are certain constraints to these alternative sources: the efficiency increase in end-user applications shows thermodynamic limitations, the direct usage of renewables has limited availability and CCU/CCS have limited availability of storages and uses for CO_2. Further limitations to the direct use of electricity in some sectors include technical constraints, cost considerations and infrastructure concerns, including the timing and acceptance to build required infrastructure – as we will explain in the following. Nonetheless, increasing the direct use of electricity will form a core pillar of the energy transition in any case.

Therefore, a broad mix of measures to reduce carbon related emissions will be key for the energy transition – all of the options listed above will be essential. PtX will play an important role in this context since the other options are subject to limitations in a number of circumstances. We will explain the benefits of PtX in this context in the following in more detail.

2.1.1 Some sectors will require green synthetic fuels for decarbonisation

An important characteristic of chemical energy sources is their high energy density. This applies in particular to liquid fuels, but also to gases, such as methane and hydrogen. Not least because of this basic chemical/physical property, around 70% of final energy consumption in Germany is currently based on chemical energy sources. It is therefore very difficult, if not even impossible, for some sectors to replace these types of energy carriers. This holds for some parts of the chemical industry (e.g. some high temperature processes) as well as some parts of the transport sector (e.g. long distance aviation, shipping, road transport etc.).[7]

In addition, certain technical solutions that currently exist are often unfeasible: for example, installing heat pumps in existing buildings frequently requires an extensive refitting to adjust installed heating systems to function on the low-flow temperatures that are required for an efficient operation of heat pumps (in some cases even a refitting is impracticable). Technology improvements are in development to solve such technical hurdles, but there are not yet widely available. In these cases, synthetic fuels are needed if fossil fuels shall be replaced at least in the short and medium term.

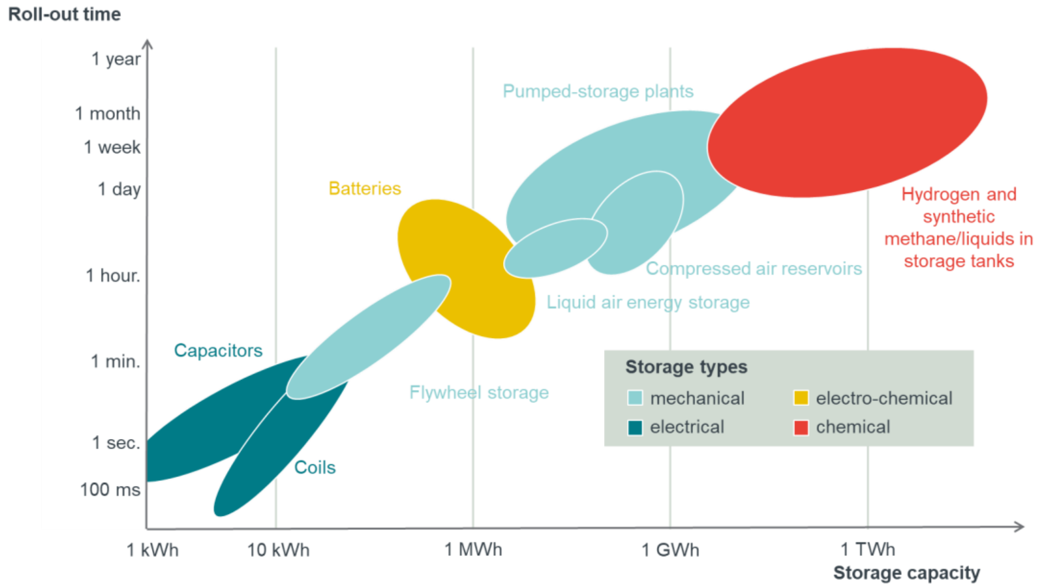
2.1.2 An electricity system based solely on renewables will need massive storing of energy – this requires chemical fuels

Power is increasingly produced from renewable energy sources in Europe, in particular from wind and photovoltaic. This fundamental development makes energy storage indispensable because wind and sun are only capable of providing fluctuating energy. This applies at short notice, i.e. within or between individual days and over weeks, as well as seasonally, i.e. over several months (e.g. from summer to winter for heating).

Electricity can efficiently be stored for seconds, hours, days and weeks e.g. in batteries and pumped hydro storages (Figure 6). However, there is a lack of viable affordable solutions for seasonal electricity storage to date. In contrast, due to their energy density, synthetic fuels and hydrogen are well placed for seasonal storage of renewable energy. PtX will therefore inevitably become a central part of the transition towards a system in which renewable energy production has to be stored in large volumes and over a long period of time (seasons).

[7] U.a. Prognos et al (2018): Status und Perspektiven flüssiger Energieträger in der Energiewende.

Figure 6 Technologies to economically store energy will require PtX



Source: Frontier Economics based on Sterner et al. (2014), and own analyses. Also see WEC (2016).

Additionally, huge storage capacities for oil and gas are already available. For example in Germany, existing facilities for storing liquid fuels have a volume of more than 535 TWh (this corresponds to around 42% of annual demand for oil, 62% of annual demand for the main fuel products gasoline, diesel and heating oil[8] or 90% of the gross electricity consumption[9]). Gas storage capacities in the existing facilities in Germany are around 260 TWh (this corresponds to more than 33% of annual gas demand).[10] In comparison, the volume of all German power storage systems[11] is only about 0.04 TWh. The electricity storage capacity of all German power plants is therefore currently sufficient to serve the average electricity demand for 41 minutes. [12]

2.1.3 A key benefit of PtX is the option to use existing infrastructure and applications, and this has positive effects on costs

As explained in Section 1.2, PtX products can be synthetic liquid fuels such as diesel, heating oil, gasoline, kerosene, methanol and synthetic gases such as hydrogen or methane. A major advantage of some of these synthetic fuels is that they can be fed into the current energy system with existing infrastructure and that

8 Federal Office of Economics and Export Control (BAFA): Mineral oil data for the Federal Republic of Germany (December 2017).

9 The gross electricity consumption of Germany in 2017 added up to almost 600 TWh. Arbeitsgemeinschaft Energiebilanzen e.V. (2018), p. 28.

10 Primary energy consumption gas 2016: 2.804 PJ (according to https://www.bmwi.de/Redaktion/DE/Infografiken/Energie/energie-primaerverbrauch.html).

11 The indicated capacities are based almost exclusively on pumped storage power plants. There is no systematic statistic of the capacities of battery storages, but even based on optimistic estimates these provide only a single-digit GWh capacity and are therefore negligible.

12 Based on an annual electricity demand of 521 TWh.

most end-user applications do not have to be exchanged before the end of their technical lifetime.

Using existing energy infrastructure and applications can have a variety of benefits as it allows, inter alia, for

- cost savings;
- increased acceptance of the energy transition;
- faster energy transformation.

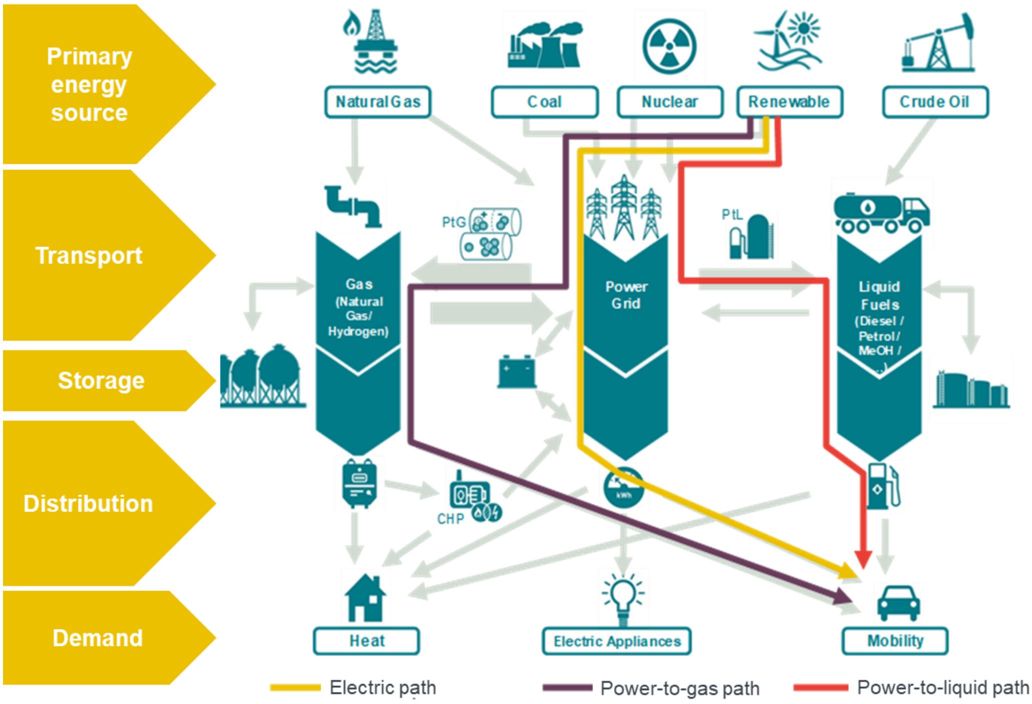
Realising cost savings

Cost savings can be realised when using the current infrastructure as compared to a situation in which for example alternative grids have to be built or expanded in order to deliver green energy to the customers. For example, full electrification of the energy system would imply a massive investment in new electricity grid infrastructure (both transport and distribution) and new end-user applications.

Therefore, when assessing cost advantages / disadvantages of PtX compared to other carbon-neutral energy options, the costs and benefits of each technology have to be analysed…

- …on the basis of the actual situation of the energy system, including existing infrastructure, installed applications etc. (“brownfield” instead of “greenfield” assessment;
- …for each individual sector and end-user applications and the different circumstances of using the energy (e.g. long distance vs. short distance transport);
- …along the whole value chain, from energy production via transport, storage, distribution, storage to the end-user applications (Figure 7).

Figure 7 Value chain for energy supply from generation to the final customer (example for mobility)



Source: Frontier Economics

When comparing the costs of PtX with those of alternative energy sources such as biofuels or direct usage of electricity, the following benefits and costs have to be taken into account:

- Benefits, such as those from
  - applying existing infrastructure such as gas and oil pipelines, filling stations, storage facilities, etc.; and
  - using existing and more affordable end-application technologies such as low-cost condensing boilers vs. expensive heat pumps for heating purposes in existing buildings.
- Additional costs, such as
  - investments in plants, e.g.
    - water electrolysers (to produce hydrogen);
    - plants for the second-stage conversion, including methanisation (producing synthetic methane), Fischer-Tropsch or methanol syntheses (producing synthetic liquid fuels); and
    - plants to extract CO_2 from concentred sources (e.g. the cement industry) or from the atmospheric air (Direct Air Capture);
  - renewable energy facilities that have to be additionally build due to conversion losses when producing synthetic fuels.

In the public debate, the economic viability of synthetic fuels is mostly limited to conversion losses. However, a holistic assessment of the economic viability of PtX covers investments and expansions for generation, conversion, storage, distribution, infrastructure and end-user appliances as outlined above.

In this context, various studies[13] recently aim to answer the question which energy system is suitable to achieve a long term energy transition towards an exclusive use of renewable energy sources and what the according cost would be. Although the results differ in detail depending on the assumptions and the underlying parameters, there is a consensus that an energy system using a mixture of electrification and chemical energy carriers shows clear cost advantages over a the exclusive use of direct electrification.

In a study for the German gas transmission network operators (FNB Gas), we, Frontier Economics, show that an energy mix using PtX (gaseous and liquid) can save about 250 billion euros until 2050 in investments as compared to a far-reaching electrification in Germany.[14] A recently published study by dena estimates even higher savings of up to 600 billion euros, inter alia through PtX, if cost advantages of imports are used simultaneously.[15]

Facilitating the wider acceptance of the energy transition

The success of the energy transition towards climate neutrality also depends crucially on the broad support of society – accommodating this consideration of acceptance involves evaluating various technologies.

The development of new infrastructure for switching energy consumption to carbon neutral energies such as green electricity requires a significant expansion of the current electricity grid infrastructure. For example, comprehensive electrification will require considerable grid expansion: In the study by Frontier economics and RWTH Aachen regarding the benefits of using existing gas infrastructure,[16] it is estimated that a comprehensive electrification would require more than doubling the length of electric circuits in the high-voltage grid, equating to around 30-35 additional electricity pylon links from north to south throughout Germany. This requirements represent a huge challenge regarding acceptance in society:

- The need to significantly expand the electricity transmission network has been known for many years. While the majority of Germany's population sees the energy transition as very positive and supports it, concrete electricity network expansion projects regularly encounter significant opposition in the affected regions.
- As a result, many major projects involved in the expansion of the electricity network have been significantly delayed in recent years. Several legislative attempts to accelerate network expansion have been unsuccessful to date, including the adoption of the Energy Line Extension Act (EnLAG) in 2009 and the Network Expansion Acceleration Act (NABEG) in 2011. Delays in expanding the electricity network increasingly cause congestions that are usually solved by costly redispatch (network operators to call for electricity

[13] Inter alia Frontier Economics et al (2017): The importance of the gas infrastructure for Germany's energy transition; Dena (2018): dena-Leitstudie Integrierte Energiewende.

[14] Frontier Economics et al (2017): The importance of the gas infrastructure for Germany's energy transition.

[15] Dena (2018): dena-Leitstudie Integrierte Energiewende.

[16] Frontier Economics et al (2017): The importance of the gas infrastructure for Germany's energy transition.

generation plants and consumers to reduce or increase their generation or consumption of electricity).

Using existing transportation infrastructure for gas and liquid fuels can help to alleviate potential congestions from a lack of building new energy infrastructure. For example, in the study by Frontier Economics and RWTH Aachen on German gas infrastructure cited above[17], it is estimated that using the gas network may avoid the need to expand the electricity network by several thousands of kilometres of transmission lines as well as distribution lines between 2030 and 2050. In addition, conventional service stations could be used for synthetic fuels also in future, which are numerous (14,500 stations, also the following figures are always for Germany)[18] e.g. compared to hydrogen filling stations (51 in Germany)[19]. Finally, existing mobile non-pipeline logistics for liquid fuels can be used more flexibly, e.g. in rural areas or even with changing energy needs (for example through energy-based refurbishments or with a changing population density).

Furthermore, PtX can help to increase the acceptance of green fuels amongst end-users. If nothing else, the slow modernisation of the heating sector shows that existing obstacles to changing consumers' behaviour – having to abandon usual habits and accustomed end-user devices – should not be underestimated, particularly while change is often associated with high investment costs. A lack of acceptance for such measures could be an obstacle for the energy transition in the same way as an opposition to network expansion is. The use of climate-neutral synthetic fuels in existing and known end-user applications can therefore facilitate wider acceptance in the society.

Accelerating the speed of the energy transformation

Finally, the use of existing infrastructure and end-user applications allows for a fast introduction of green PtX – at least in niche markets – in the short to medium term. For example, to date,

- renewable liquid fuels, such as diesel, kerosene, heating oil, ammonia etc., can be blended with fossil liquid fuel products. They could, from a technical perspective, even replace fossil liquid fuels altogether without any changes in infrastructure, engines or heating boilers.
- renewable gases, such as synthetic methane and (to a limited extend) hydrogen can be used in existing grids for natural gases without major changes to infrastructure or burners/boilers. However, for a system based on pure hydrogen, existing infrastructure has to be tested and upgraded and new infrastructure and end-user applications may need to be installed.[20]

Therefore, the scaling up the production of synthetic fuels is ready to begin from an infrastructure and end-user perspective – however an adequate supply side and the necessary incentives to use these synthetic fuels are still missing (see Section 4).

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[17] Frontier Economics et al (2017): The importance of the gas infrastructure for Germany's energy transition.

[18] Mineralölwirtschaftsverband, available at https://www.mwv.de/statistiken/tankstellenbestand/, last downloaded 01/10/2018.

[19] H2 MOBILITY Deutschland GmbH & Co. KG, available at https://h2.live/, last downloaded 01/10/2018.

[20] DVGW (2011).

2.2 Meeting the ambitious climate change targets will require significant energy imports – including PtX

In order to meet the ambitious climate targets, renewable energy use and generation will accelerate strongly. Accommodating for this increasing demand, Europe/Germany's face a number of challenges with a system carried by renewable energies. As a consequence, significant amounts of the renewable energy will have to imported from abroad. Furthering the scale of renewable energy imports in turn will require the use of chemical energy carriers such as green synthetic fuels, as these carry various benefits in terms of transportation, storage and use of existing infrastructure (see also preceding section).

In general, we expect that in the long term, a mix of local PtX production/consumption and international trade will arise. International trade of PtX is beneficial for the importing countries, primarily due to cost savings and increased diversity of energy imports. Benefits for and motivations of potential PtX exporting countries are analysed in Section 3.

2.2.1 Renewable energy will have to be imported in order to accommodate accelerating demand

At the moment, Germany covers about two thirds of its primary energy supply through imports.[21] Since Germany's energy demand is expected to be at least 75% of current demand in 2050 – even if the highest energy efficiency targets are achieved – the question as to how to meet this demand remains. Due to Germany's long term climate protection goals (reducing CO_2 by up to 95% until 2050 compared to 1990 levels), most energy demand will have to be supplied by renewable energies. This is reinforced by Germany's decision to opt out of nuclear power production and by the limited potential to use fossil fuels with CCS/CCU One factor which limits this is substantial public resistance against CCS.

Indicative calculations illustrate the challenges that a system carried by renewable energies imposes on the electricity system in Germany, if the future power demand in transport, heating, industry etc. picks up due to de-carbonisation. The approximate RES-capacity required to serve this demand can be illustrated in an exemplary calculation:

- According to publicly available studies, German electricity demand is expected to expand substantially in the long term (2040/50). However, estimations for electricity demand vary significantly between sources (and the underlying assumptions), ranging from around 630 TWh/a[22] up to 3,000 TWh/a[23]. This compares to an electricity demand of around 600 TWh today.[24]

[21] AG Energiebilanzen.

[22] BCG, Prognos (2018), p. 246.

[23] Range from literature review by the Renwebles Energies Ageny (Agentur für Erneuerbare Energien (AEE), 2016, p.4). Quatschning (2016) projects 3,120 TWh/a without efficiency measures.

[24] Arbeitsgemeinschaft Energiebilanzen e.V. (2018), p. 28.

- If electricity demand was assumed to rise to around 1,000 TWh/a, then up to 600 GW of renewable generation capacity would be required.[25] However, only approximately 57 GW of on- and offshore wind capacity and 44 GW of PV are currently installed. Therefore today's RES capacities would have to increase by a factor of up to six.

These necessary expansions of renewable facilities and the required accompanying infrastructure (networks – without PtX – plus storage facilities) are likely to encounter increasing resistance within Germany. Even if from a technical perspective sufficient sites capable of accommodating renewable energy installations exist in Germany, it is doubtful whether they can be exploited to their potential, given the expected opposition of nearby residents. This ties in directly with the widespread disputes that arise when wind turbines are installed on land – and not only in Germany, but across many countries in Europe. It is therefore expected that renewable energy will have to be imported if the energy transformation is to be successful when faced with weakening public acceptance.

2.2.2 Boosting the scale of renewable energy imports will require chemical energy carriers facilitating PtX

If it proves impossible to meet the renewable energy demand within Germany/Europe autonomously, renewable energy will have to be imported on a larger scale in the future. There are a number of options for importing renewable energies, however, the potential of some of them is limited:

- Import of **biomass, biogas or biogenic fuels**: Europe/Germany already imports biomass, biogas and biogenic fuels (such as ethanol) and import volumes are expected to grow further in the future. Due to limitations in the availability of these fuels (e.g. land usage for biofuels is in competition with food production), however, import growth may be limited in the long term.
- Import of **electricity from renewables by transmission** (AC/DC): Current interconnection capacities for electricity are limited, and the expansion of the electricity grid is relatively expensive, especially for very long distances such as from North Africa to central Europe. Those very large scale projects have failed to be realised so far – amongst other things due to costs (e.g. the Desertec project which aimed at exporting renewable electricity from North Africa to Europe by direct transmission lines).

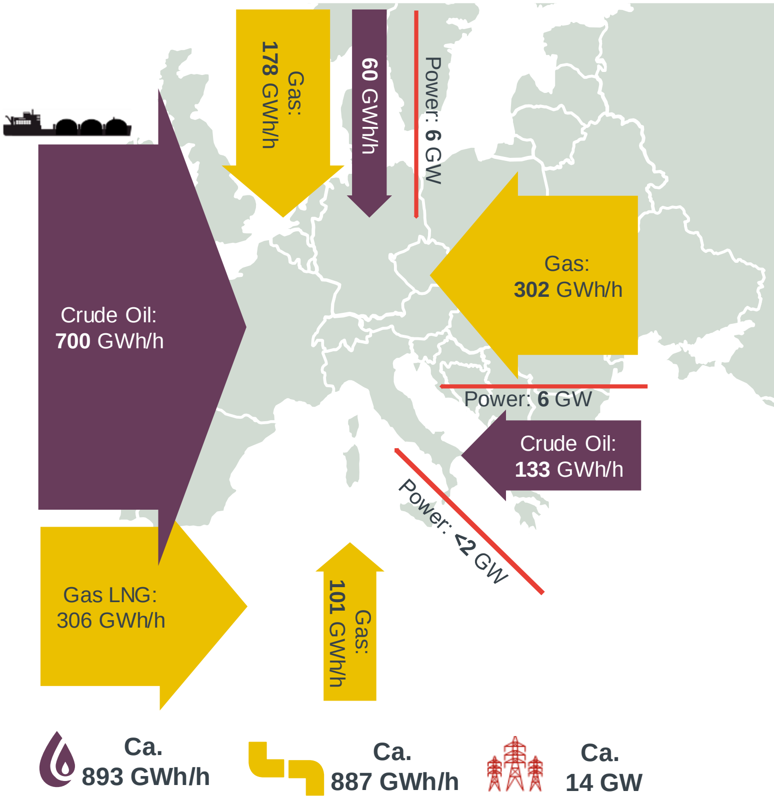
Imports of biomass, biogas or biogenic fuels as well as renewable electricity to Germany/Europe can be expected to increase in future, however are limited in terms of total volumes. In contrast, synthetic fuels are well placed as chemical energy carriers to transport large volumes of renewable energy to Europe:

- Even for long distances, **transportation costs** for these synthetic fuels are relatively low, so distances play only a minor role in this context. The transportation of liquid fuels (such as crude oil and oil products) and gases (such as methane) is well-established.

[25] Assuming average full load hours of around 1,670 full load hours per year (FLH/a) across a variety of renewable electricity technologies including PV (In Germany around 950 FLH/a), wind onshore (inland around 1,800 FLH/a) and wind offshore (around 4,000 FLH/a).

- A fully developed **European import infrastructure** for synthetic liquid fuels and methane already exists (Figure 8). In capacity terms, Europe's existing gas and oil infrastructure is well positioned: the combined installed capacities of gas and oil import pipelines amount to almost 1,800 GW as opposed to only 14 GW of electricity import capacity via transmission lines – meaning transmission lines are a mere 3% of the pipelines.
- Imported renewable synthetic fuels can be fed directly into the **existing infrastructure in Europe/Germany** (transport, distribution, storage etc.) which helps mitigate the restrictions on grid expansion and strengthens the acceptance of the energy transition (see Section 2.1.3).

Figure 8 Existing European oil and gas import infrastructure



Source: Frontier Economics

Note: Figures concerning transport capacities for gas/liquids are in GWh/h equivalent to volume measures (e.g. m³/h). These are comparable with the typical measurement unit GW for electricity.

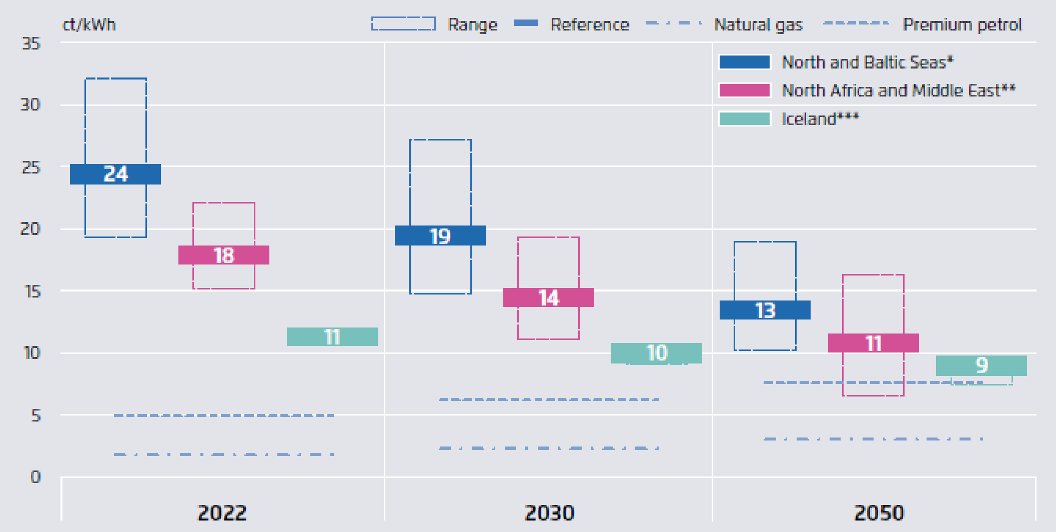
2.2.3 International PtX trade will help to accommodate the costs of the energy transition and can diversify import portfolio

In the medium to long term, the success of the energy transition will depend on renewable energies being made available at the lowest cost possible. Many regions worldwide pave the way to tap into renewable energies, such as sun, wind, water and biomass, in a far more cost effective way in terms of production than in Central Europe. Converted into synthetic fuels, they can be transported in liquid and gaseous form at proportionally low costs to Europe, capitalising on the existing pipeline, transhipment, interim storage and tanker infrastructure.

In the study by Frontier Economics for the Agora Energie- und Verkehrswende, we show that overseas locations such as North Africa, the Middle East or Iceland, can by far outperform domestic outlets in terms of producing synthetic methane and liquid fuels at low costs (Figure 9). For example, in the short term, synthetic methane and liquid fuels can be imported at 18 ct/kWh via PV and PV-wind-hybrids in North Africa and the Middle East as compared to a local production at 24 ct/kWh on the basis of offshore wind

generation in the North and Baltic Sea – an import cost advantage of 27%. In 2030, the cost advantage remains almost the same at around 26%, and even until 2050 synthetic methane and liquid fuels can still be imported 20% at cheaper from North Africa and the Middle east.[26]

Figure 9 International comparison of PtX production cost (synthetic methane and liquid fuels)



Note: Prices of natural gas and premium petrol are based on average values from scenarios by the World Bank and the IEA. Other cost reductions for PtG / PtL may result from advancements in PV, from battery storage that increases full load hours, and from especially large electrolysis facilities. Cost increases may result from higher cost of capital due to higher country risks.

* Offshore wind power
** PV and PV / wind systems
*** Geothermal / hydropower (total potential limited to 50 terawatt hours)

Note: 10 cents per kilowatt hour is equivalent to around 90 cents per liter of liquid fuel.

Source: Frontier Economics, in: Agora Verkehrswende and Agora Energiewende (2018).

Note: Without network charges and distribution cost.
PtX production cost in in North Africa and the Middle East include transportation cost to Europe.

An illustrative calculation demonstrates the magnitude of the possible savings:

- In 2030, based on the savings potential outlined above (around 5 ct/kWh)[27] and Germanys current total energy imports of around 2,600 TWh/a,[28] the yearly savings could be as high as 130 billion euros.

[26] The %-differences are precisely calculated based on the underlying figures including various decimals, and differences to %-results calculated from numbers in Figure 9 arise due to rounding.

[27] Cost difference in 2030: 19 ct/kWh based on offshore wind generation in the North and Baltic Sea vs. 14 ct/kWh via PV and PV-wind-hybrids in North Africa and the Middle East.

[28] AG Energiebilanzen

- Around 2040/2050, based on an average cost advantage of between 3-4 ct/kWh and assuming half of Germany's current energy imports (i.e. 1,300 TWh/a), yearly savings could still amount to between 39-52 billion euros.

The achieved cost savings through imports would benefit the German industry and consumers and could strengthen the acceptance of climate protection efforts: by limiting the overall burden on the one hand, and during the transition process where (at given costs) a more favourable PtX production abroad could provide considerably more climate-neutral fuels on the other.

At the same time, a global PtX market can help to diversify energy imports. Currently, Europe and Germany import energy – especially oil and gas – from a limited number of countries of origin. World markets for these fossil fuels are dominated by a few suppliers. In contrast, synthetic fuels can be imported from a variety of countries that have favourable site conditions for renewable energies and appropriate area availabilities. We illustrate in Section 3 that there is a wide range of countries worldwide that demonstrate favourable conditions for renewable energies and for the production of PtX.

2.3 A future global PtX market will rise to a significant size

In this section, we provide a rough estimate of a future global PtX market. The results demonstrate that global demand for synthetic fuels could be as large as 20,000 TWh by 2050 and beyond. This would correspond to about half of today's global demand for crude oil or eight times the current final energy demand in Germany. While these rough estimates are to be understood as a first approximation and orientation towards possible dimensions of a global PtX market, the order of magnitude of these global demand figures demonstrate that this new international industry can be very large in size in the long term.

The estimation of the potential global PtX demand assumes shares of synthetic fuels and hydrogen in regional and sectoral energy markets. We further substantiate our results with a complementary PtX market estimation, which analyses the PtX market from a different angle, assessing the impact of global climate targets on the decarbonisation of overall energy demand and how much of these CO_2 reductions might be covered by PtX (see Annex A.1)[29].

2.3.1 The global PtX demand could amount to 20,000 TWh in 2050 and beyond

In order to derive possible magnitudes of global PtX demand in 2050 and beyond, we assume different PtX shares to be used in the individual energy consuming sectors across the world. For this, we apply a 3-step approach (Figure 10):

[29] Available at https://www.weltenergierat.de/ptxstudie/.

- **Step 1 – Reference to established global energy demand forecasts** by the OECD/IEA in the „World Energy Outlook 2016" (New Policies Scenario) by sector and by region for the year 2040.[30]
- **Step 2 – Assumptions of percentage shares of PtX of final energy demand** in 2050 by sector. These shares are based on the expectation and practicability of end-user applications (e.g. reasonable PtX share in aviation vs. households) and have been discussed with experts of the World Energy Council. As the PtX shares of long term energy demand (i.e. in 2050) are speculative, we look at three different scenarios:
  - The **high case** assumes PtX shares in final energy demand from different studies for the European markets.[31] As we assume the share of PtX on a global scale to be lower than for Europe, we regard this scenario as an absolute upper bound for a future PtX market size.
  - The **reference case** is more conservative. PtX is applied when electrification and the use of direct renewable energy may reach limits:
    - PtX shares range from moderate 10% to 20% in sectors where renewable electricity and green fuels other than PtX are expected to be the dominating energy sources (e.g. individual road transport[32], rail transport, households, industry[33]).
    - In other sectors, such as maritime transport and aviation, the PtX shares are estimated between 50% and 70%, as decarbonisation is more difficult without green synthetic fuels. For example, in the aviation sector, especially on long-haul flights, synthetic fuels will be required due to the high energy density.
  - The **low case** assumes that other low carbon energy options such as the direct use of renewable energies, "blue" hydrogen/fuels and electricity from renewables take a larger share of the energy market than in the reference case.

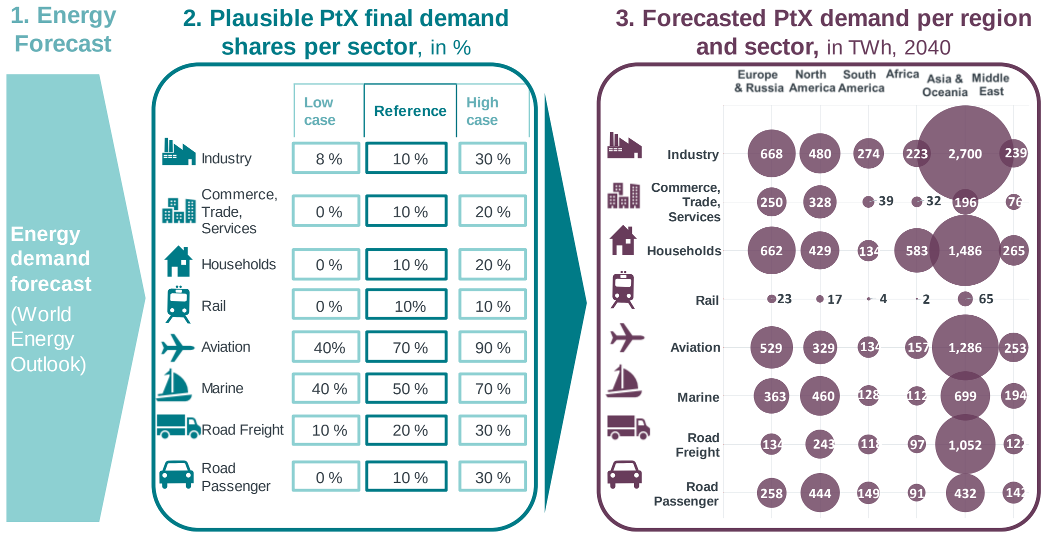
[30] IEA forecast final energy demand for 2040. We use these forecasts nevertheless for our rough estimate of 2050 PtX shares.

[31] Dena (2017), E-fuels study – the potential of electricity based fuels for low emission transport in the EU.

[32] We do not assume 100 % electrification for road transport because of long-distance passenger and freight transport: electric engines have limited reach and it is doubtable that electric infrastructure can be rolled out to all outskirts.

[33] We do not assume 100 % electrification for buildings and industry, because although efficient technologies such as heat pumps in buildings and low-temperature industry or electrification of high-temperature industry can be pushed - it will come to technical and acceptance limits.

Figure 10 Global PtX demand estimation by sector for 2050, in%



Source: Frontier based on IEA, World Energy Outlook 2016, New Policies scenario

Note: Reference case

- **Step 3 – Combining the assumed PtX shares by sector with energy demand forecasts** provides the regional PtX demand by sector for 2050 and beyond. The aggregation of these regional/sectoral PtX demand estimations yields the global demand for PtX.

Based on these assumptions, the global PtX demand could reach an order of magnitude of 10,000 TWh to 41,000 TWh in the long term (Figure 11). Even though the approach is based on a rough assessment and expert speculation and cannot be regarded as a model-based market demand forecast, it illustrates that a future global market for PtX can easily be very large in size in 2050 and beyond. The complementary PtX analysis substantiates our estimate (see Annex A.1).

Figure 11 Range of potential global PtX demand

Source: Frontier Economics

2.3.2 Global PtX market requires the installation of massive PtX capacities

A worldwide PtX demand in the order of magnitude derived above will require substantial capacities of electrolysers and PtX conversion plants. A simple calculation illustrates the requirements: assuming a PtX production of 20,000 TWh per year it can be roughly calculated that around 8,000 GW of installed PtX capacity would be required worldwide until 2050. In this calculation, the majority of about 6,000 GW is electrolyser capacity for the production of hydrogen, and about

2,000 GW are required for plants for the second-stage processes, such as methanisation or Fischer-Tropsch/methanol synthesis. In this illustration, we assume that

- the load factor of electrolyser capacity is around 4.000 h/a (based on an assumed load factor of renewable energy supplies of around 4000 hours which corresponds e.g. with combined wind/PV installations in North Africa; no installation of batteries assumed);
- the load factor of the plants for the synthesis processes (methanisation, Fischer-Tropsch, Methanol synthesis plus upgrading) is 8,000 h/a (assuming the storage of hydrogen);
- the conversion efficiency of electrolysers and synthesis plants is assumed at 80% each by 2050; and
- the mix of PtX fuels is 50% gases (25% hydrogen, 25% methane) and 50% synthetic liquids.

Moreover, we assume that all hydrogen considered in this estimation is produced from RES (i.e. wind and solar) via water electrolysis and is therefore green. Hydrogen can, however, also be produced via steam reforming (e.g. from natural gas) (see Section 4.1.1). Therefore, the estimations above can be regarded to be at the upper end of potential capacity requirements for electrolysers and synthetisation plants.

However, even if the indicative global market potential for PtX materialises only in parts (e.g. between 3,000 to 6,000 GW of electrolysis), there will be massive investments in PtX technologies and plants required during the next decades. These investments will need an adequate framework to pave the way towards a global PtX industry.

2.4 Summary: A global PtX market will be an integral part of the energy transition and of significant size

In summary, green Power-to-X is – in complementation to direct RES electricity or direct use of renewable energies – a key technology for achieving the goals of climate policy due to a number of reasons such as

- **Multifunctional alternative:** In some sectors, fuels with high energy density are required due to logistics. This holds e.g. for aviation and shipping industry (at least in major parts of the sectors), but also for some high temperature chemical processes. Without PtX fuels, it will be technically difficult to achieve the CO_2 abatement required in these applications.
- **Storability:** The future renewable energy system in Europe will require large scale energy storages, e.g. for shifting renewable power generation from summer to the winter season for heating purposes. PtX products are well placed for seasonal storage of electricity.
- **Immediate demand potential:** Synthetic fuels such as synthetic methane, diesel, heating oil, gasoline, Heating Oil, kerosene etc. can immediately be used in existing appliances. This means that CO_2 abatement can take place in

a short timeframe without waiting for longer term transitions of end-user applications to other technologies. This is relevant for e.g. for heating of existing buildings, but also e.g. for the transport sector (E-mobility e.g. needs time for the creation of the charging infrastructure and the establishment of the e-car fleet).

- **Acceptance:** The public acceptance of new built of infrastructures with environmental and landscape impact (e.g. long distance electricity transmission lines) is limited – conversely, the usage of existing energy infrastructures like gas pipeline etc. can help to overcome public resistance.
- **Costs**: Synthetic fuels from renewable energies allow in many cases to save investment costs in Germany/Europe due to the option to use existing infrastructures such as gas pipelines, filling stations, storage facilities, mobile transport logistic etc., and using existing and more affordable application technologies such as low-cost condensing boilers.

Furthermore, the energy transition in Germany/Europe will require substantial imports of green fuels from outside Europe due to

- **Cost savings via imports**: PtX produced in world regions with favourable site conditions for renewable energies (wind, PV) are significantly cheaper than the same fuels produced inside e.g. Germany. In order to keep costs of the energy transition as low as possible these potentials should be used.
- **Availability of sites for RES-E**: The availability of sites for renewable energies (especially wind) is limited or subject to environmental constraints (landscape protection, maritime protection) in many countries, e.g. Germany. Therefore, it can be expected that a substantial share of renewable energy supply has to be imported.
- **Transportability of PtX fuels as an advantage:** For importing renewable energies at a larger scale, chemical energy carriers are the first choice: large scale international infrastructure exists, and the costs of transport represent a minor share of the energy cost.

Given this the global market for PtX will be sizeable. Even if the indicative global market potential for PtX materialises only in parts there will be massive investments in PtX technologies and plants required during the next decades. These investments will need an adequate framework to pave the way towards a global PtX industry. We will revert to this in the following sections.

3 THE RANGE OF POTENTIAL PTX EXPORTING COUNTRIES IS BROAD AND INCENTIVES FOR TRADE VARY

In the previous chapters, we examined the need for Power-to-X in the course of the transition towards a carbon neutral energy system and the benefits from international production and trade of PtX. In the following, we explore potential PtX exporting countries in more detail. In this context, we discuss

- The requirements to identify potential PtX producers/exporters worldwide and a selection of the countries with strong PtX potentials (Section 3.1);
- Varying motivations and incentives for countries to produce and trade PtX, as well as their readiness to adjust to an emerging industry – categorised in different "types" of potential PtX producers/exporters, including example country case studies illustrating each "type" to provide insights on how each country's PtX path might unfold (Section 3.2); and

3.1 Potential PtX producing/exporting countries require a combination of various factors

In order to capture the benefits of international production and trade of PtX and realise investments in PtX facilities and infrastructures, potential PtX exporting countries need to fulfil a number of requirements. These can be sub-divided into "hard" and "soft" factors (Figure 12).

The hard factors relate to the countries' resource abundance or constraints and are largely independent of human or political influence and hardly modifiable by political intervention. The soft factors, however, relate to a country's political stability and energy framework and may be influenced through (energy) political facilitation, at a minimum in the medium to long term.

The **hard factors** comprise:

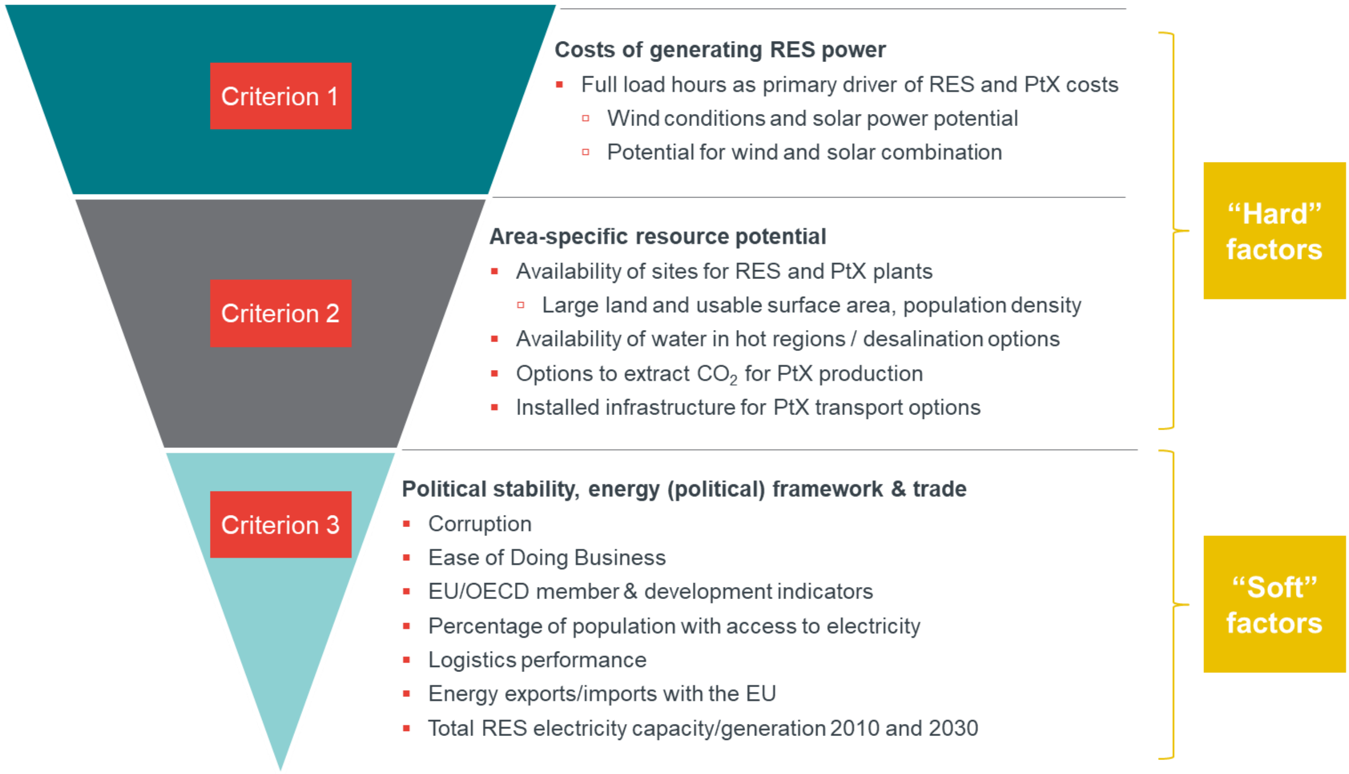
- *Criterion 1*: The costs of generating RES power as the main input to PtX production, primarily driven by full load hours of installed capacities.
- *Criterion 2*: Additional area-specific resource potentials or constraints, such as surface area or availability of water.

The **soft factors** are characterised as follows:

- *Criterion 3*: Further factors beyond the natural resource potential, such as a country's political stability, its development status and the embedded energy framework.

The hard factors, i.e. the first two criteria, serve as primary filter to identify potential PtX production locations worldwide, however the soft factors are equally imperative to provide support for the establishment of a new PtX industry. Therefore, we explore all three criteria individually in the next section.

Figure 12 Overview of "hard" and "soft" factors for identifying potential PtX producer



Source: Frontier Economics

Note: A detailed presentation of criteria two and three can be found in the data tables in a separate annex document, available at https://www.weltenergierat.de/ptxstudie/.

3.1.1 Criterion 1: Many countries proof promising for PtX production and/or export in terms of RES costs

The key determinant for potential prime PtX locations is the cost of renewable energy as the main input factor for PtX production: The higher the hours of use of renewable energy plants, the lower the resulting electricity costs to produce PtX (see Section 4.1.2 for a discussion of the cost drivers). In addition, the load factor of electricity from renewable energies determines the utilisation of the conversion plants – this is a fundamental cost factor in PtX production due to the high capital intensity of the plants[34]. Potentials regarding wind energy, incident solar radiation, hydro or geothermal power are key catalysts that make renewable energies feasible in terms of their technical/physical capabilities in the various countries.

Based on this criterion of RES potential and cost, there are a large number of countries that could produce and export PtX in the future. This can be illustrated by heat maps which demonstrate wind and solar power worldwide.[35]

[34] Agora Verkehrswende, Agora Energiewende und Frontier Economics (2018).

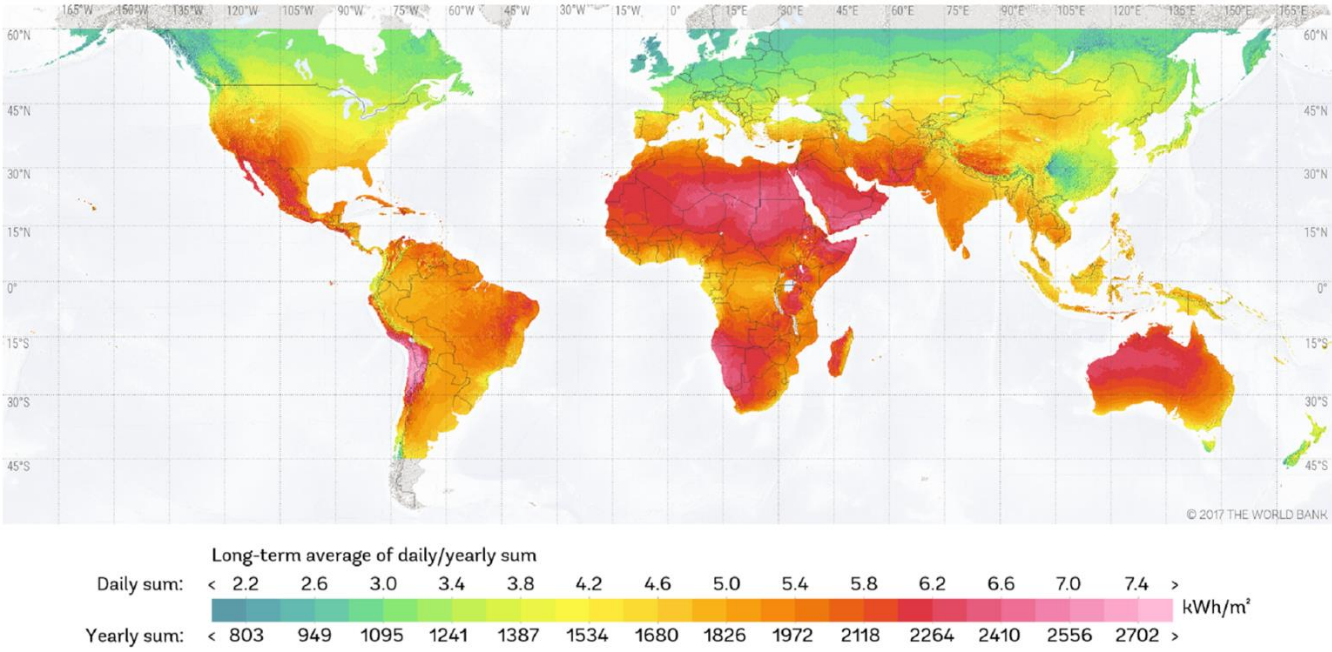
[35] This study primarily focusses on PV and wind power potentials. Nonetheless, the potential of hydro (e.g. Norway) and geothermal energies (e.g. Iceland) add to the global availability of renewables for PtX production.

Photovoltaic potential

Many countries show very favourable conditions for PV renewable energy and naturally, the potential for PV is especially concentrated in countries relatively close to the equator (Figure 13):

- Almost the entire African continent, all countries in the Middle East and Australia show highly favourable PV conditions.
- The US, many countries in Central and South America and parts of Central Asia also show strong PV potentials.

Figure 13 Worldwide solar irradiation map



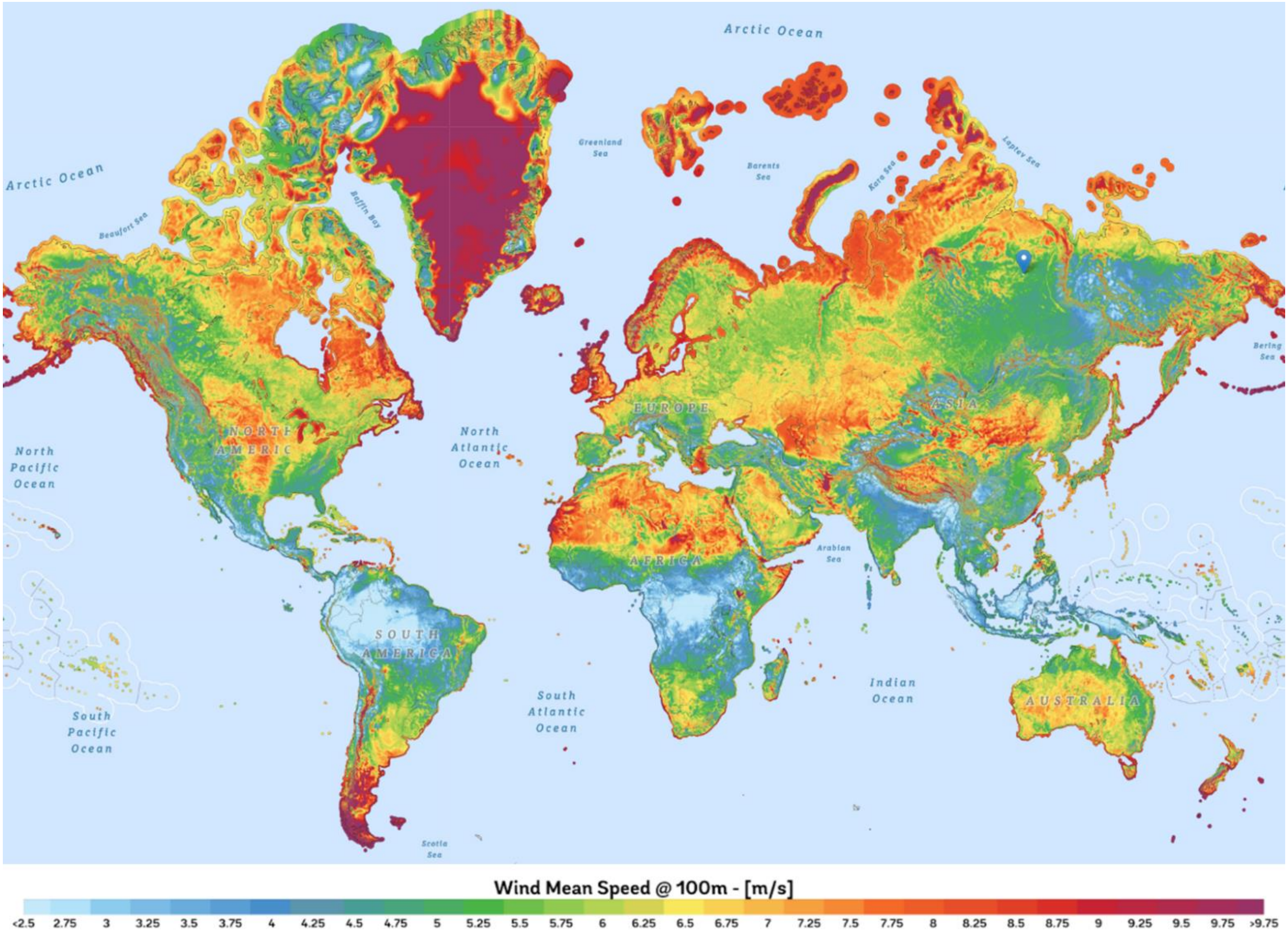
Source: World Bank Group, http://globalsolaratlas.info/

Note: Global Horrizontal Irradiation (GHI) – [kWh/m^2].

Wind speed potential

Favourable climate conditions for wind alongside coastal lines (on- and offshore power) are spread more widely across the globe than those for PV, and countries very close to the equator show less favourable conditions than those located north and south of the equator (Figure 14). In addition, many elevated regions around the world show strong wind speed potentials inland.

Figure 14 Worldwide wind speed map



Source: World Bank Group, https://www.globalwindatlas.info/

Note: Wind Mean Speed @100m – [m/s]; Scale ranges from light blue (<2.5 m/s) to dark red (≥ 9.75 m/s).

Hybrid power potential

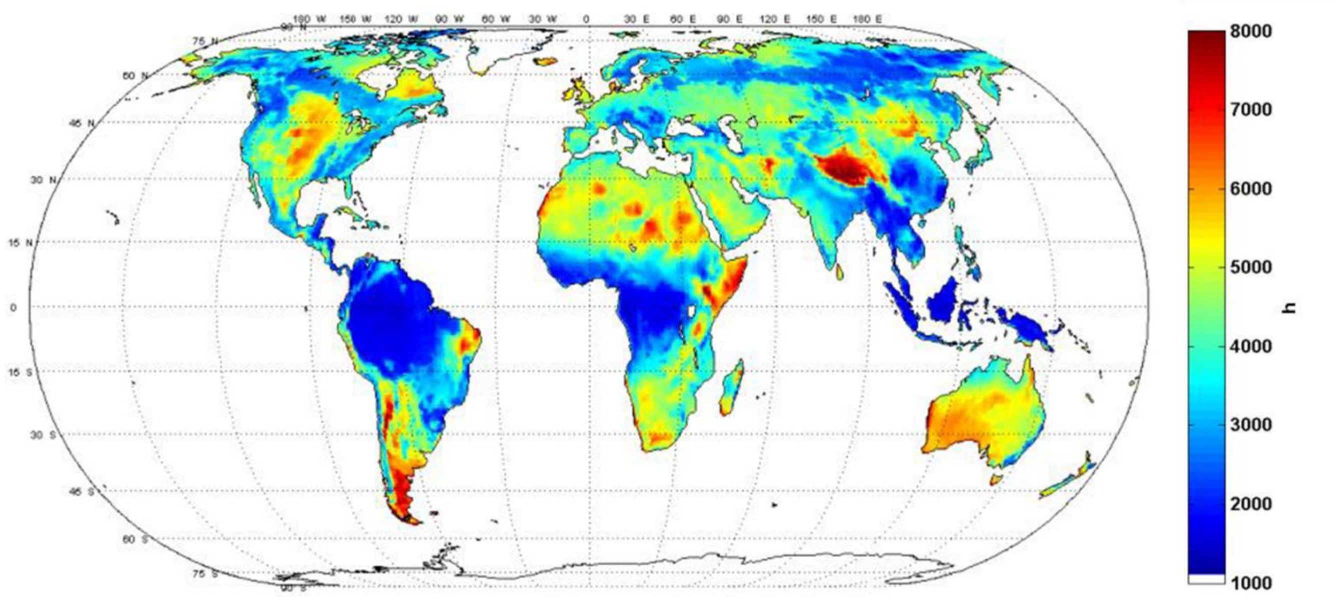
As previously discussed, the primary driver for low RES cost is high full load hour potential. In terms of costs, the combination of PV and wind power production is most favourable since load factors of combined plants are substantially higher than for sites focussed on single technologies.[36] Locations that allow for a combination of PV and wind are therefore of particular interest as wind resources tend to complement solar resources.

Favourable PV-wind-hybrid condition spread around the globe (Figure 15):

- The MENA region and South Africa as well as Somalia and Kenya;
- The southern continent of Latin America, especially in the parts of the Andes mountain ranges;
- Australia and parts of Canada, the US and central Asia, especially in the region of the Himalaya mountain range.

[36] Agora Verkehrswende, Agora Energiewende und Frontier Economics (2018).

Figure 15 **World's hybrid PV-Wind power plant cumulative full load hour map in 2030**



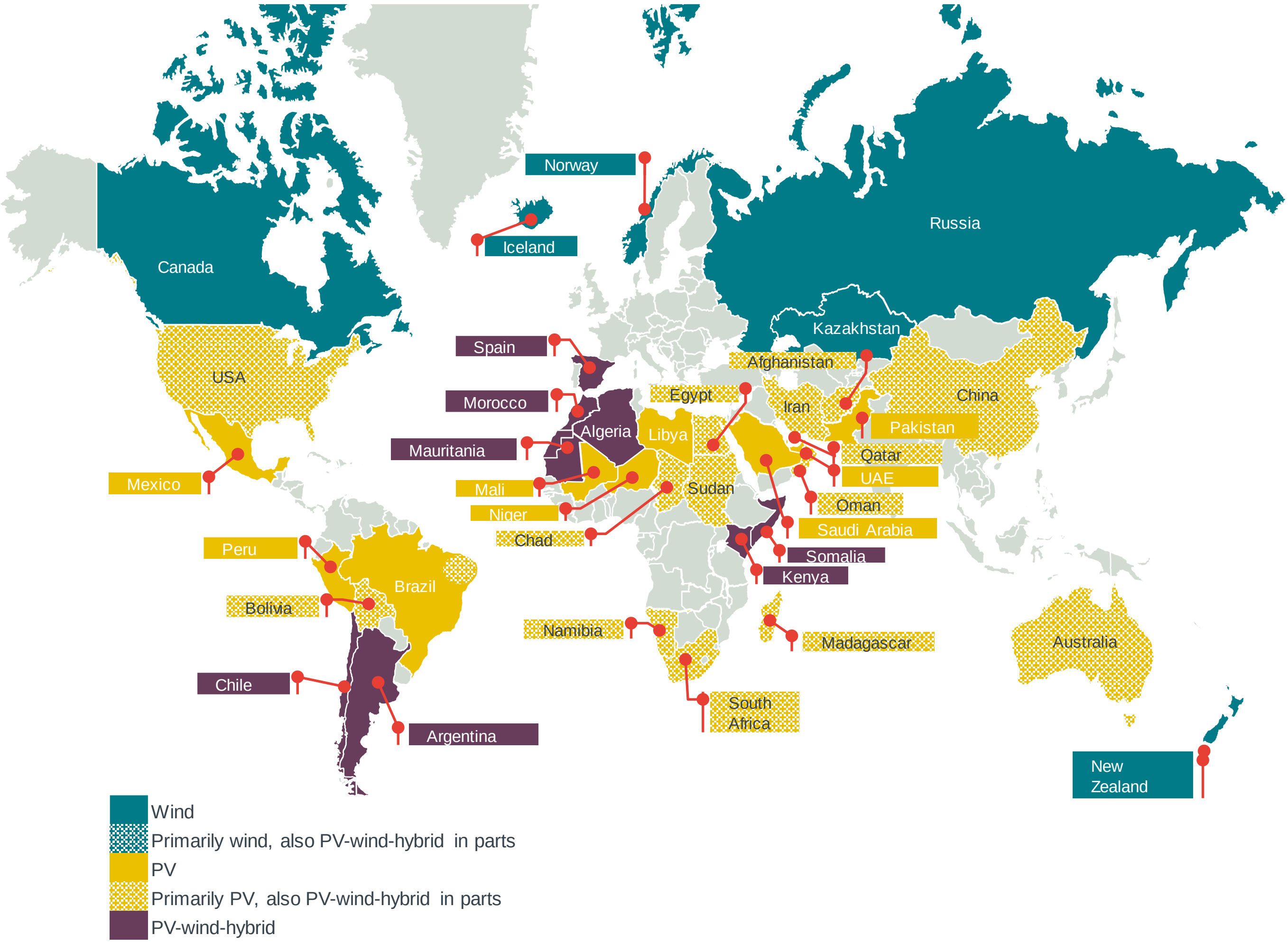
Source: Fasihi et al (2017).

Conclusion: We identify many countries with strong RES potential as main input to PtX production

Figure 16 shows a map of selected countries that demonstrate some of the strongest PV and wind potentials worldwide, also including the PV-wind-hydro potential. We identify these countries as amongst those most favourable for setting up a global PtX industry in terms of their low costs of generating renewable electricity as the main input into the PtX production (see Section 4.1.2 for a discussion of the main PtX production cost drivers).

This is only a snapshot of the world's strongest candidates in terms of costs, focused only on countries with the highest RES potential – and the number of identified countries is considerably large. Consequently, a worldwide future PtX market could be very diverse in its supply structure, especially given that countries with slightly less favourable RES cost conditions can be able to participate in PtX world trade as well.

Figure 16 Snapshot of the world's strongest RES potentials



Source: Frontier Economics

Note: Illustrative presentation of the strongest RES potentials only; not an extensive list of all countries.

3.1.2 Criterion 2: Area specific resource potential as additional "hard" selection criteria

Alongside the RES cost considerations as key location determinant, we have considered additional resource requirements and constraints as essential prerequisite to determine prime PtX locations.

These additional resource requirements include:

- **Availability of sites for RES (and PtX plants)** – potential PtX exporting countries require huge capacities of renewable energies as input to the PtX production with corresponding vast space requirements. In addition, plants are also required for other parts of the PtX value chain, such as the water electrolysis, conversion processes (methanisation, Fischer-Tropsch/methanol synthesis), Direct Air Capture or seawater desalination.[37] The feasibility of installing these plants operably depends primarily on:

[37] For example, the total plant has a size in the large scale production of PtL by Nordic Blue Crude (20 MW_{el} and production of 10 million litres of synthetic fuel per year) occupies 40,000 m² (see

  - Availability of sufficiently large land and surface area;
  - Roughness and surface topography, e.g. high elevation in mountainous areas or shifting sand dunes in deserts are not suitable for large installations;
  - Climatic conditions, e.g. year-long freezing temperatures or extreme winds;
  - Population density; and
  - No critical competition with alternative forms of use, e.g. agriculture or settlement.
- **Availability of water** – the production of hydrogen via electrolysis is a first step across almost all PtX technologies and water electrolysis requires water as a key input. Accordingly, the availability of water is essential and for countries in very hot and arid regions water may not be readily available.[38] At a minimum, these countries should have access to a coastline to ensure that water can be obtained via saltwater desalination plants.
- **Availability/recoverability of CO_2** – a key input to the production of synthetic methane or liquid fuels is CO_2. In the long term, CO_2 will have to be extracted from the air via Direct Air Capture (DAC) technology. In the short and medium term, the CO_2 may be extracted from other (less expensive) CO_2 sources – e.g. from biomass or industrial processes (including temporarily accepted as well as unavoidable CO_2 emissions) [39] – which can additionally support the creation of a PtX industry.
- **Potential of transport options** – PtX fuels must be transported from the production country to Europe and depending on the source of energy, transport via ship or pipeline is a necessary requirement. A mature energy industry (e.g. oil and gas industry) and an existing energy export infrastructure (oil and gas pipelines[40] and LNG terminals for the liquefaction of gas etc.) facilitate the development of a PtX export industry.

In addition to these criteria as the focus of our study, there are other factors that could be investigated in further research, such as the levelized cost of energy (LCOE) which also include capital expenditure and operating and maintenance costs. These costs may vary greatly depending on the economic and political stability, existent infrastructures and on the availability of personal and know-how to build and maintain facilities on-site.

http://nordicbluecrude.no/). The direct air capture (DAC) plant will be located in the same location. In general, for extracting around 5,000 kg CO_2 per day from the air, an area of 181 m² is needed only for the collectors, any auxiliary equipment is not yet included (see https://www.sunfire.de/de/unternehmen/presse/detail/erste-kommerzielle-blue-crude-produktion-entsteht-in-norwegen and http://www.climeworks.com/our-products/).

[38] The World Energy Council (World Energy Scenarios, (2016) provides a worldwide heat map of the countries' water stress. See https://www.worldenergy.org/wp-content/uploads/2016/10/World-Energy-Scenarios-2016_Full-report.pdf

[39] The European Commission Joint Research Centre provides a worldwide heat map of the countries' tons of CO_2 equivalent emission per capita in 2012. See http://edgar.jrc.ec.europa.eu/overview.php?v=CO2andGHG1970-2016&dst=GHGpc

[40] Harvard Centre for Geographic Analysis provides a worldwide map of gas and oil pipeline infrastructure. See https://worldmap.harvard.edu/maps/pipelines1

3.1.3 Criterion 3: Large scale investments in a new PtX industry require an adequate “soft” factor framework

For the establishment of a PtX export industry and to enable large scale investments (which are common in major international projects, e.g. in the energy industry or with infrastructure expansions), the political environment must also be suitably designed. We have considered the following “soft” aspects as vital:

- **Political stability**[41] – corruption is a major obstacle to democracy and the rule of law. In a democratic system, offices and institutions lose their legitimacy when they are misused for private advantage. This is harmful in established democracies, but even more so in newly emerging ones. It is extremely challenging to develop accountable political leadership in a corrupt climate and to develop new industries. Corruption also hinders the development of fair market structures and distorts competition, which in turn deters domestic and international investment.
- **Development indicators**[42] – the state of economic and political development of a country strongly influences its readiness to engage with a newly emerging industry. Heavily indebted poor countries and/or fragile countries suffering from conflicts may lack the necessary framework and stability to create a new industry (at least in the short to medium term) – probably even with political and financial support from abroad. On the other hand, countries that are politically close to the EU/Germany, such as OECD members, are of particular interest.
- **Business environment**[43] – aspects of business regulation and their implications for firm establishment and operations are decisive factors for investment and the successful development of new industries.
- **Energy infrastructure and logistics**[44] **criteria** – The existence of a developed energy industry such as an existing oil and gas industry, developed electricity infrastructure and renewable electricity generation facilities support the development of a PtX industry due to experience and knowledge of the workforce. Combined with its performance in terms of logistics, these factors provide an understanding of the readiness of the current energy industry and logistics to adjust to an emerging PtX industry.[45]
- **Trade relationship with EU/Germany**[46] – exports or imports to or from the EU are a good indicator for an already functioning international trade relationship and provide a strong base for any future possible PtX trade.

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41 The Corruption Perception Index 2017 (Transparency International) ranks 180 countries and territories by their perceived levels of public sector corruption according to experts and businesspeople, on a scale from 0 to 100, where 0 is highly corrupt and 100 is very clean. See https://www.transparency.org/news/feature/corruption_perceptions_index_2017

42 World Bank Development Indicators: Heavily indebted poor countries (HIPC) and Fragile and conflict affected situations.

43 The Ease of Doing Business Index (World Bank) ranks economies on their ease of doing business, on a scale from 1 to 190. A high ease of doing business ranking means the regulatory environment is more conducive to the starting and operation of a local firm. See http://www.doingbusiness.org/rankings

44 World Bank Indicator: Logistics performance.

46 European Commission, available at http://ec.europa.eu/trade/policy/countries-and-regions/, and Simoes, Hidalgo (2011), available at https://atlas.media.mit.edu/en/profile/country/.

Soft factors can change over time and are strongly influenced by the political setting which permanently develops. Countries which currently fail to meet the soft criteria for large scale investments in PtX might therefore be able to meet those in the nearer future if the framework is modified, and vice versa. Obviously, any future change in soft factors is speculative from today's perspective.

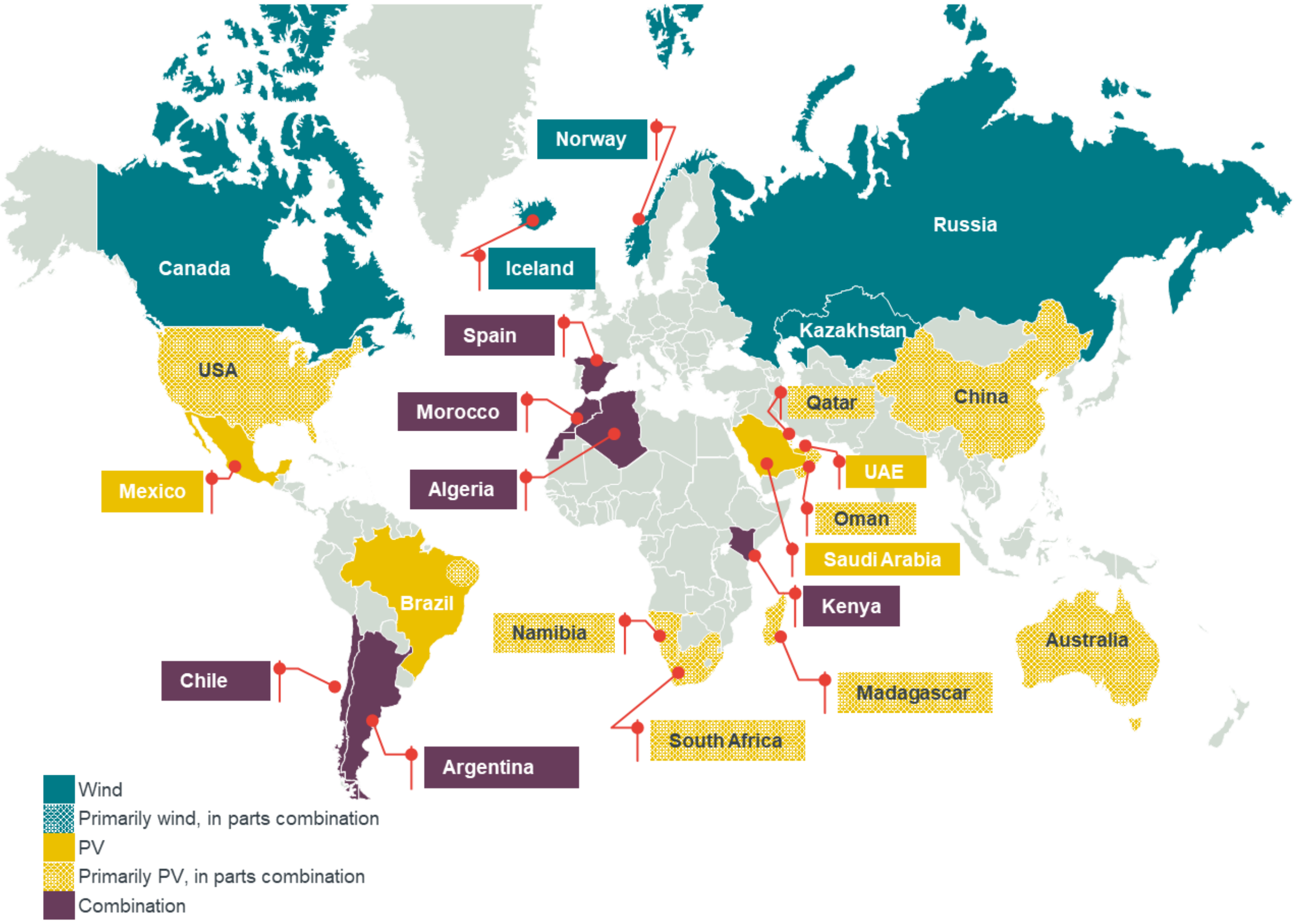
3.1.4 Intermediate conclusion: Various countries demonstrate strong PtX potential

Accounting for the analysed aspects from both hard and soft PtX location factors (i.e. based on the countries' resource abundance and the political stability and energy framework), we have identified 23 countries that demonstrate strong potential for PtX production (Figure 17).[47]

It has to be noted that the selection of countries is neither complete nor constant over time: For example, there may be vast RES potentials on a regional basis in certain countries that are not included in this list, which may be captured for PtX production and export. Furthermore a number of countries may not be identified as high potentials for political reasons (e.g. Somalia), however, the assessment can change over time with the development of the political environment. Consequently, the following map provides an indicative evaluation of countries from today's perspective.

[47] A detailed description of the individual criteria considered for all countries is presented in a separate annex document, available at https://www.weltenergierat.de/ptxstudie/.

Figure 17 Strongest potential PtX producer worldwide



Source: Frontier Economics

Note: Illustrative presentation of the strongest RES potentials only; not an extensive list of all countries.

3.2 Potential PtX suppliers vary in terms of incentives and readiness to adjust

As outlined in the previous section, a vast number of countries across the globe demonstrate a strong potential to produce PtX. To disentangle this large group of possible suppliers, it is crucial to identify underlying incentives for establishing a national PtX industry and for (possibly) exporting PtX products – individual backgrounds and how each profile favours renewable energy may play an important role here. Which motivations build the foundation for creating a PtX industry and which potential barriers have to be overcome to get the candidates ready to produce and export PtX?

The understanding of underlying incentives and the level of readiness is a crucial factor to decide the ultimate PtX potential to produce and to export for individual countries. Exploring these elements is a basic prerequisite, in line with the previously described hard and soft criteria. Given that these elements vary across different countries and are fundamentally interlinked and need to be analysed in conjunction, we explore these criteria only for a handful of countries that we select as example case studies that stand representative for other groups of countries. Notwithstanding, these criteria are very relevant to deciding the definitive PtX potential to produce and to export.

3.2.1 Basic prerequisite criteria defining the potential motivation and level of PtX readiness

For discussing the characteristics of the individual countries and to identify “types” that are representative for groups of countries, we address potential drivers and obstacles for a further establishment and implementation of a PtX industry:

- **Attitude of governments towards renewable energies** – Governments of potential exporting countries that are open-minded with regard to Renewable Energies (e.g. based on Renewable Energy National Energy Programs), may also favor the development of a PtX industry. Strong RES targets might imply early involvement in developing PtX technology, such as at the R&D and market introduction phases.
- **Fundamental export orientation of the economy –** Economies with a strong export orientation and with corresponding technical and cost-related capabilities for PtX could support the development of PtX. These countries may already have the relevant multilateral and bilateral trade agreements in place, which are also relevant for the export of PtX.
- **Share of fossil fuel exports in national income** – Countries which today finance a high proportion of their economic output or household through the export of fossil fuels may choose to replace fossil energy exports by synthetic fuels due to the necessary "defossilisation" of global energy demand. In this case, setting up a corresponding PtX export industry serves as a "hedge" against the sales risks in the area of fossil fuels. These countries could lead the development stages of PtX technology, but will also be capable to take part in the scale up (and potentially) mass-market phase.
- **Perspectives for economic development** – PtX technologies would allow countries with large renewable energy potential but without significant energy exports to enter the circle of energy exporters and tap into a new source of revenue. This could be attractive especially for less developed countries. Developing a new PtX industry can increase social welfare and prosperity and reduce the pressure for migration.
- **Potential energy exports vs. domestic energy demand** – Large scale exports of synthetic fuels produced from renewable energy can only take place in the long term if the renewable energy potentials or expected renewable energy production volumes exceed domestic energy requirements. Countries with high growth in energy demand but limited renewable resources cannot be expected to be large scale PtX exporters in the short to medium term. Limited growth in local energy demand and high current renewable penetration in energy supply can therefore be a positive factor for establishing a PtX export industry – and vice versa.

3.2.2 Typology of groups of potential PtX producers/exporters

Naturally, each country will have an individual story and diverse underlying incentives to take part in a developing PtX market as outlined across the varying criteria in the previous section. The potential suppliers are at different levels of readiness and willingness to participate and to enter this market. However, for illustrative purposes and to provide a concept on how these countries might be clustered with regard to their part in a global PtX market, we identify several types of "PtX stories" using the criteria defined previously.

For each of these types, we provide a selected example of a country that may fall within each of these categories, and is considered representative for a wider group of potential suppliers (Figure 18).

Figure 18 Types of possible PtX producers/exporters and example country

Type	PtX motivation and readiness	Selected example
Frontrunners	▪ PtX already on countries (energy) political radar ▪ Export potential and PtX readiness evident ▪ Uncomplicated international trade partner ➢ Especially favourable in early stages of market penetration	Norway
Hidden Champions	▪ Fundamentally unexplored RES potential ▪ Largely mature, but often underestimated, (energy) political framework with sufficiently strong institutions ➢ PtX could readily become a serious topic if facilitated appropriately	Chile
Giants	▪ Abundant resource availability: massive land areas paired with often extensive RES power ▪ PtX readiness not necessarily precondition, may require facilitation ➢ Provide order of PtX magnitudes demanded in mature market	Australia
Hyped Potentials	▪ At centre of PtX debate in Europe with strong PtX potential ▪ Energy partnerships with Europe foster political support ➢ Potential to lead technology development; may depend strongly on solid political facilitation	Morocco
Converters	▪ Global long term conversion from fossil to green energy sources ▪ PtX to diversify portfolio as alternative long-term growth strategy ➢ Strong motivation for PtX export technology development; may requires political facilitation and partnership with the EU/DE	Saudi Arabia
Uncertain Candidates	▪ Partially unexplored RES potentials, possibly paired with ambitious national climate change policies ▪ PtX export in competition with growing national energy demand ➢ PtX export motivation and potential unclear – may drive PtX technology development, however export uncertain	China

Source: Frontier Economics

Note: The PtX types and the allocation of a possible candidate country within each category serve as starting point to identify possible PtX development strategies; not a concise list and readily alterable.

PtX types in Figure 18 showcase illustrative country profiles of potential PtX producers and exporters and are therefore not to be considered as a comprehensive list of all possible categorisations of countries.

In the following section, we illustrate the positions and motivations of potential PtX producing or exporting countries in more depth by using the example cases.

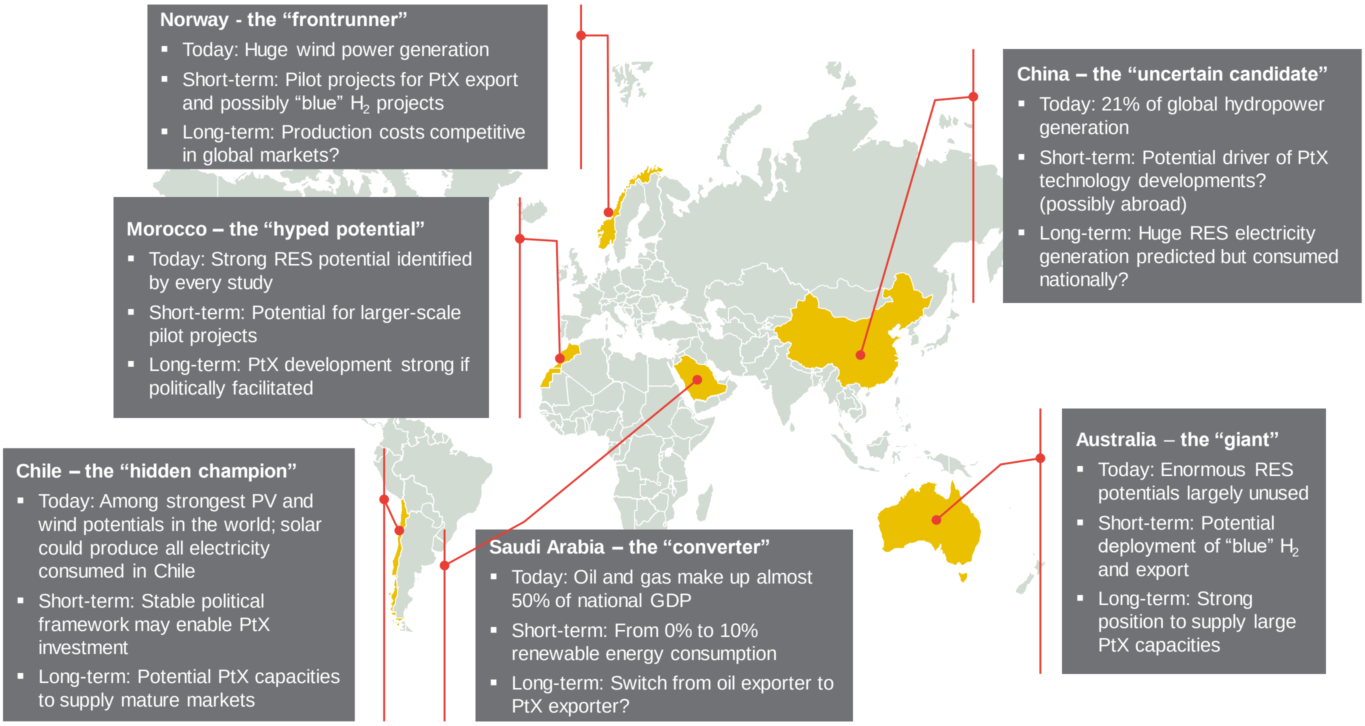
3.3 Exploring the country case studies provides insight how each country's PtX story might unfold

To support the understanding of the different PtX types and the underlying motivational story of every country, the study builds on specific case studies with selected example countries shown in Figure 19:

1. Norway – the "*frontrunner*";
2. Chile – the "*hidden champion*";
3. Morocco – the "*hyped potential*";
4. Saudi Arabia – the "*converter*";
5. Australia – the "*giant*"; and
6. China – the "*uncertain candidate*".

The in-depth case study of these example countries can be found in ANNEX B.

Figure 19 Selected case study examples from each "type" of PtX story



Source: Frontier Economics

Note: The in-depth case studies of these example countries can be found in ANNEX B.

The countries are selected as examples to illustrate the different types and each country stands representative for a group of countries with similar characteristics and PtX potentials. Similarly, the allocation of candidate countries across the types is not necessarily fixed and confined. Elements of other types might also apply to countries allocated within others types, and some countries fall in a number of categories as they are not mutually exclusive and may complement each other, for example:

- Chile is identified as a “hidden champion”, but elements of a “frontrunner” also apply, e.g. PtX already being on the political energy agenda.
- Australia is selected as an example for a “giant”, however, currently first PtX projects for exporting hydrogen to Japan and South Korea are in planning stages (element of a “frontrunner”), and future PtX exports could replace current national income from exports of coal (element of a “converter”)
- Saudi Arabia is categorised as a "converter" today with a possible long term strategy of exporting PtX and strong incentives to invest in technologies of the future, but may show elements of a “frontrunner” with the potential to lead early phases of market penetration if certain conditions in the political framework are altered faster than expected.
- With support from industrialised nations, a “hyped potential” such as Morocco may also quickly enter the initial market penetration phase and/or become a “frontrunner”.

3.3.1 Norway – the frontrunner: PtX is already on the radar and export potential evident on short term

Frontrunners demonstrate largely undeveloped Renewable Energy potential and ambitious climate targets. They show enhanced PtX awareness and interest, e.g. with Pilot Projects currently in testing to develop PtX technologies. Their closeness to Europe – geographically, culturally and in terms of trade relationships – guarantee that they are uncomplicated potential PtX trade partners. These countries could be in the lead in the market implementation phase of PtX, fostering the development of PtX technology. When it comes to long term sustainable supply of large PtX capacities once the market has matured and world trade is established, it may depend on the countries’ PtX capacity potential of whether they will remain a key player in the long term.

CASE STUDY INSIGHTS: NORWAY

Huge PtX potential through largely unexplored on- and offshore wind energy and PtX would fit well with the ambitious climate targets

In all parts of Norway, the wind speed levels are among the highest in Europe. Besides onshore wind farms also numerous offshore wind farms could be installed. However, the current electricity generation is primarily based on hydro (97%, 2016). The other 3% stems from gas (2%) and wind (1%).[48] At the end of 2016, installed wind generation capacity totalled only 838 MW (1,162 MW in 2017)[49], and production of wind-generated electricity was 2.1 TWh. Accordingly, a large amount of the potential seems to be unused, for example Wind Europe (2017) envisages 11 GW of installed capacity in Norway in 2030. Norway is also well positioned to generate very high full load-hours using a combination of both wind power and annual storage power reservoirs. PtX would also fit well within the ambitious Norwegian climate targets, which include for example the aim to be carbon neutral in 2030.[50]

Strong position not just to produce, but to become a PtX exporter – and sound infrastructure is already in place

Norway has sufficient RES to meet the domestic demand in most years and is usually already a net energy exporter.[51] With an expected increase of wind generation capacity in the future, Norway will likely have enough excess electricity generated from RES to produce and export PtX. Norway might also be incentivised to prepare a transition of its economy towards alternative export strategies to diversify the portfolio, such as exporting green energy via PtX, as it currently exports large amounts of fossil oil and gas.[52]

Norway already has sound infrastructure in place to produce and export PtX, particularly hydrogen, methane or synthetic liquid fuels: gas pipelines lead all the way to mainland Europe and liquefaction terminals for LNG and harbours for liquid products could serve for additional exports.[53]

Norway has the potential to be a frontrunner and lead the early market introduction phase in terms of PtX development and trade

The topic of PtX is already on Norway's (energy) political agenda and considerations to produce PtX are quite advanced with pilot projects currently in testing. Nordic Blue Crude, for instance, plans a first production site for synthetic liquid fuels for use in cars in the south of the country (Porsgrunn) with 10 million litres being produced per year from 2020.[54] Norway also regards hydrogen generation in the North Sea based on natural gas and combined with CCS as a classic PtX development strategy with export potential to other countries, e.g. to

[48] Statistics Norway, available at https://www.ssb.no/en/energi-og-industri/statistikker/elektrisitet/aar, last downloaded 03/09/2018.

[49] Wind Europe (2018).

[50] See Climate Action Tracker, available at https://climateactiontracker.org/countries/norway/pledges-and-targets/, last downloaded 27/08/2018.

[51] IEA (2017a), p. 100.

[52] Ministry of Petroleum and Energy and the Norwegian Petroleum Directorate, available at https://www.norskpetroleum.no/en/production-and-exports/the-oil-and-gas-pipeline-system/, last downloaded 27/08/2019.

[53] For more information on the oil and gas pipeline system see homepage of Ministry of Petroleum and Energy and the Norwegian Petroleum Directorate, available at https://www.norskpetroleum.no/en/production-and-exports/the-oil-and-gas-pipeline-system/, last downloaded 27/08/2019.

[54] The renewable electricity is generated from hydropower and H_2 is produced via water electrolysis. CO_2 is extracted from the air via Direct Air Capture technology. For further project information, see http://nordicbluecrude.no/, last downloaded 05/07/2018, and Manager Magazin (2017), available at http://www.manager-magazin.de/unternehmen/autoindustrie/norwegen-investoren-bauen-fabrik-fuer-wunder-diesel-a-1156215.html.

the UK. This may prepare the infrastructure for green and "blue" hydrogen (see also Section 4.1.1 regarding "blue" hydrogen). Norway is part of the European Economic Area and guarantees an uncomplicated trade relationship with ideal investment conditions.

This implies that Norway has the potential to be in the lead in the early phases of market penetration, fostering PtX development and leading PtX trade. When it comes to long term sustainable supply of large PtX capacities that will be demanded worldwide once the market has matured, it may depend on the countries' PtX capacity potential of whether they will remain a key player in the long term.

The detailed country study on Norway can be found in Annex B.1.[55]

3.3.2 Chile – the hidden champion: Largely unexplored RES potential paired with strong (energy) political environment

Countries categorised as hidden champions, like Chile, typically demonstrate fundamentally unexplored RES potential with strong climate change targets. Paired with a largely mature (energy) political framework and sufficiently strong institutions – that are often underestimated in the general perception of Latin American countries – PtX could immediately become a serious topic if facilitated appropriately. These countries may well be in the lead in the market penetration phase, fostering the development of PtX technology.

CASE STUDY INSIGHTS: CHILE

Chile has fundamentally unexplored RES potential, but already strong existing infrastructure and appropriate ambitious climate targets

Chile shows very strong PV or Wind potential in the far north or south with combinations possible in parts of the country as well. RES energy was virtually non-existent before 2014 but has steadily increased since. Installed capacities still only amount to around 3.5 GW in 2017.[56] The remaining RES potential is vast, estimated at 1,800 GW in the north.[57] The north is dominated by the copper mining industry where currently the focus is still on coal as a source of energy, but supply contracts are about to run out, and the Energy companies are keen to transform towards RES as a long term strategy, which would bring RES into full swing.

Climate objectives are ambitious demonstrating the countries direction: The target is to generate 70% of electricity from RES in 2030 and 90% in 2050. Chile also has existing infrastructure of gas and oil pipelines that connect all mayor cities and potential PtX production sites. Various harbours, both in the very north and the south, are qualified for transporting liquid fuels.

[55] Available at https://www.weltenergierat.de/ptxstudie/.

[56] See http://resourceirena.irena.org/gateway/countrySearch/?countryCode=CHL

[57] Ministry of Energy Chile, GIZ (2014), p. 7.

Chile has sufficiently strong institutions – its “hidden” strength is often underrated – which are further supported by foreign facilitation

Chile by far outperforms most of its neighbouring countries in terms of its stability of institutions with both the corruption index[58] and the ease of doing business index[59] being very strong – even compared to some European countries. In the past four years, strong development of RES has also been driven by foreign assistance (e.g. projects supported by GIZ). Direct cooperation with TSOs and ministries further supports the strength of the (energy) political framework.

Chile is currently a net energy importer, however there is still definite potential for Chile to become a PtX exporter

Chile imports large amounts of its national energy use, up to almost 80% over the past decade. Chile may therefore be incentivised to decrease its energy import dependence by focussing on meeting an increasing share of demand by domestic (renewable) production, however, due to its strong market orientation, PtX exports are nevertheless conceivable, particularly as RES costs for PtX production can be expected to be exceptionally low.

PtX is already a hot topic in Chile, and Hydrogen pilot projects are already planned

PtX is already on the country’s agenda and especially Hydrogen is a widely discussed topic amongst the key players in Chile’s energy markets. The debate is only at the beginning with private-sector initiatives at the starting point, however, the government is now starting to set the scene and the first major conferences on PtX are currently taking place. According to regional PtX experts, there are already two hydrogen projects underway in Chile, paving the way for PtX production and export.

The detailed country study on Chile can be found in Annex B.2.

3.3.3 Morocco – the hyped potential: Potential at centre of PtX debate in Europe and incentives to develop technologies

Countries categorised as hyped potentials, e.g. Morocco, are already at the centre of the PtX debate in Europe as potential PtX exporters. While they have large PtX potentials and are (generally) committed to climate targets, the (energy) political framework indicates that it might require more PtX facilitation, e.g. by initiating the PtX topic on a wider scale and by sensitising political leaders and decision makers. For example, if countries are currently net energy importers, especially importing fossil gases and fuels, PtX exports might not be on the political agenda in the short to medium term. However, if markets for green PtX e.g. in Europe are willing to pay for the green property of synthetically produced fuels from renewable energy,

[58] Transparency International, available at https://www.transparency.org/news/feature/corruption_perceptions_index_2017#table, last downloaded 25/09/2018.

[59] The World Bank, Doing Business, available at http://www.doingbusiness.org/rankings, last downloaded 25/09/2018.

then countries may export PtX regardless, and continue to import fossil oil and gas.[60]

CASE STUDY INSIGHTS: MOROCCO

Morocco shows strong RES potential with renewable development targets, and parts of necessary infrastructure already exist

Morocco shows strong solar potentials across the entirety of the country, with the option for installing PV-wind-hydro combinations – wind also has strong potentials (especially in the southern region and along the coastline). Morocco is committed to developing RES and compared to other MENA countries, Morocco was one of the first countries investing in RES. In early 2016, Morocco's electricity production capacity for wind added up to almost 750 MW and the first 160 MW of solar generation (CSP) were launched.[61] Morocco strives for a fast rise: in 2020, production capacity of solar and wind energy will probably reach 2 GW[62] each and the target for 2030 is an amount of 52% RES of total electricity generation capacity[63]. Morocco has large CO_2 emitting industries[64], such as cement, iron and steel, and seawater desalination plants along the coastline can be constructed to provide necessary (and sparse) water resources. A gas pipeline from the northern part of Morocco to Europe and several harbours qualified for liquid products are already in place. However, a PtX industry may require large infrastructure investments to connect to the existent grid (especially in the southern region) as there are no pipelines or harbours currently installed, but some gas pipeline extensions to a planned LNG import terminal in Jorf Lasfar are already envisaged[65].

Morocco and Europe already have a strong economic and energy-specific partnerships, even if investment climate may be diverse

The relationship between the EU and Morocco is well-established and strong. The free trade area between Morocco and the EU was introduced almost two decades ago and bilateral partnerships also foster the development of renewable energy and accompanying technology, such the German-Moroccan Energy Partnership (PAREMA) since 2012[66] that focuses on the integration of RE energies into the power grids, energy efficiency and the funding of climate protection projects. German financial cooperation commitments in the energy sector in Morocco add up to over one billion Euro, with the main partners KfW for financial cooperation

[60] In the end, the green PtX does not have to be exported physically in all cases. The fuels could be consumed in the countries of origin, however, the green property of the fuel could be traded to Europe and paid by the customers to fulfil e.g. REN obligations in industrialised countries.

[61] Steinbacher (2019), p. 188.

[62] U.S. Department of State, available at https://www.export.gov/article?id=Morocco-Energy, last downloaded 27/08/2018.

[63] Climate Action Tracker, available at https://climateactiontracker.org/countries/morocco/pledges-and-targets/, last downloaded 28/08/2018.

[64] See https://www.industryabout.com/industrial-maps, last downloaded 05/07/2018.

[65] See https://www.reuters.com/article/morocco-lng/update-1-morocco-preparing-tender-for-45-bln-lng-project-minister-idUSL8N1WH485, last downloaded 01/10/2018.

[66] Commissioned by BMWi. See Federal Ministry for Economic Affairs and Energy (2017), pp. 26 f. and https://www.giz.de/en/worldwide/57157.html

and GIZ in the domain of technical assistance.[67] For instance, the KfW – as well as other European actors – is also involved in the prominent large scale solar project in Ouarzazate.[68]

Morocco is a net energy importer and may strive for PtX to cover its significant national energy requirements – depending on market prices

Morocco is currently highly dependent on energy imports and national electricity demand is rising. This burdens the country's economic budget and leads to high uncertainties concerning security of supply, which were important drivers for the establishment of the national energy strategy in 2009.[69] In order to be able to produce PtX sustainably, i.e. without importing large quantities of fossil fuels at the same time to meet national demand, large investments in RES capacity are required. It may therefore be possible that Morocco is incentivised to focus on meeting national demand rather than to export it (if both are sold at competitive prices), at least in the short to medium term. If, however, market participants abroad are willing to pay for the green property of synthetically produced fuels from renewable energy, then Morocco may export PtX regardless, even in the short term, and could continue to import fossil oil and gas.

Morocco may be incentivised to lead initial market phases with (energy) political facilitation from EU/DE, potentially supporting future PtX export

Combining domestic energy demand with excellent meteorological site conditions, Morocco could be highly motivated to quickly start building large scale PtX plants in its own country. PtX technology transfer into the country can accelerate and due to the existing technology know-how and energy partnerships, Germany could play a key role today as a technology partner for these projects in Morocco. Within an existing project cooperation to develop solutions for a sustainable fertilizer industry [70], there is already a pilot plant in Leuna (Germany) and a plant in the Green Energy Park in Ben Guerir (west Morocco), which is the largest test field and research platform for photovoltaic modules and systems in Africa. This project and Morocco's general interest in hydrogen and ammonia could be regarded a first step towards a strong PtX future. Depending on the speed of the progress with regard to the scale up of RES and PtX production structures, Morocco's medium to long term energy political agenda could focus on PtX exports on a larger scale (especially if prices become more competitive during the market saturation phase). In the long term, PtX could be regarded a very interesting and sustainable value creation perspective for Morocco.

The detailed country study on Morocco can be found in Annex B.3.

[67] Steinbacher (2019), p. 195.

[68] BMZ, BMU (2014), available at http://www.bmz.de/20141222-1, last downloaded 05/09/2018.

[69] Chentouf and Allouch (2018), p. 5.

[70] The OCP Group in Morocco and the Fraunhofer Institute for Microstructure of Materials and Systems IMWS in Germany signed a cooperation agreement to develop solutions for a sustainable fertilizer industry. This includes the production of green hydrogen (PtG) and green ammonia (PtC).

3.3.4 Saudi Arabia – the converter: Diversifying fossil fuel-based export portfolio via PtX as potential long term growth strategy

Countries categorised as converters, e.g. Saudi Arabia, typically export large quantities of fossil energy. In the medium to long term, these countries must fear that their prosperity may deteriorate in the face of a tightened climate policy, as fossil fuels are increasingly being pushed out of the global arena in the "post-fossil age", if climate protection is to be seriously pursued. The global climate goals will inevitably require a long term conversion of fossil energy sources to green energies. Synthetic fuels could provide these countries with an alternative long term growth prospect and at least offset some of the expected losses in fossil fuel sales. This would drive structural change in these countries and may dissolve areas of tension for exporting countries.

Due to their well-developed existing oil and gas infrastructure (export infrastructure for fossils) and strong potential incentives for exporting PtX, a speedy transformation to PtX production and export logistics is plausible – if facilitated adequately. For such a transformation to be successful, forming energy partnerships with EU/DE is a strong starting point to reach technological advances and the scale up of the PtX industry.

CASE STUDY INSIGHTS: SAUDI ARABIA

Strong PtX potential in numerous locations paired with a strong position in energy enable Saudi Arabia to be a huge global PtX exporter

Saudi Arabia shows strong PtX potential – abundant and extensive RES availability and vast surface areas combined with low population density – however the total installed wind and solar capacity is only around 90 MW in 2017, carried almost exclusively by Photovoltaic.[71] Numerous locations could be used for PtX production, especially in close proximity to the coastline and to the harbours, both to allow for water as input to the process being extracted from saltwater desalination plants and to make use of available infrastructure at the harbours, especially for exporting synthetic fuels.

In addition to the country's large PtX potential, Saudi Arabia is effectively one of the world's strongest net exporter of energy – the country exports roughly three times as much energy as it consumes.[72] The potential for PtX is not limited by local demand and Saudi Arabia is therefore well positioned to become a PtX exporter and a supplier on the world stage.

High dependence on oil exports – diversifying export portfolio via PtX as potential long term growth strategy for Saudi Arabia

Saudi Arabia's economy heavily relies on the oil sector: Saudi Arabia is the 2nd biggest oil producer worldwide (2017) and between 25-50% of national GDP over

[71] See http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=19

[72] Brookings based on data from BP Statistical Review of World Energy 2014 and IEA.

the last ten years were associated with oil rents[73]. In the medium to long term, Saudi Arabia might fear that the basis of its prosperity could be withdrawn in the face of a tightened climate policy – in 2016 King Salman presented a Renewable Energies "Vision 2030" with the aim to diversify the economy to be less dependent on the revenues of its oil production. Synthetic fuels could provide Saudi Arabia with an alternative long term growth prospect, and Saudi Arabia might develop serious interest in becoming a "converter".

Some hesitation remains: actual implementation of "Visions 2030" uncertain, and PtX may require international political facilitation

In 2016, King Salman committed to installing 9.5 GW Renewable Energy in its "Vision 2030" – however this target is much lower than the announced 23.9 GW by 2020 by King Abdullah in 2010. The slow progress raises uncertainty around actual implementation: Experiences from historic announcements show that pure (industry-) political ambitions do not necessarily secure the actual implementation. Political facilitation from international partners and energy project cooperations with the EU/DE may therefore be key for a successful emergence of PtX in Saudi Arabia.

Is Saudi Arabia ready to consider PtX?

Due to the excellent resource availability, the well-developed existing oil and gas infrastructure and strong potential incentives for exporting PtX, a speedy transformation to PtX production and export logistics is plausible – if facilitated adequately. For such a transformation to be successful, Saudi Arabia's economic power and the existing technological know-how could serve as an important starting point, also for forming energy partnerships with EU/DE.

The detailed country study on Saudi Arabia can be found in Annex B.4.

3.3.5 Australia – the giant: Enormous PtX capacity potential due to vast arable land area paired with extensive RES potential

Countries categorised as giants, e.g. Australia (but also Saudi Arabia), typically show abundant resource availability – particularly massive land areas paired with extensive RES power. This makes these countries disproportionately strong potential players in the market. If coupled with PtX readiness, these countries could not only serve the order of magnitudes demanded in a mature market, but also lead the technological development.

CASE STUDY INSIGHTS: AUSTRALIA

[73] World Bank Indicator: Oil rents (% of GDP), available at https://data.worldbank.org/indicator/NY.GDP.PETR.RT.ZS?locations=SA, last downloaded 28/09/2018.

Vast RES potential paired with existing infrastructure for PtX make Australia an outstanding candidate

Australia is the sixth-largest country in the world and almost all areas of the country are rich in solar power potential. In addition, there are some locations for wind farms close to the coast, making a combination of wind and solar power possible. In combination with a low population density[74] and a suitable orography, the potential of producing electricity from RES is huge and – with only about 5 GW of wind and larger solar power systems[75] – mainly undeveloped.

Strong position not just to produce, but to become a PtX exporter – however uncertain whether Europe is a realistic trade partner

Australia's economy is based on the export of fossil fuels (especially coal[76] and LNG[77]) and Australia is a net energy exporter since the 1970ies – exporting almost twice as much as total national energy use[78]. Diversifying the export portfolio by shifting towards exporting PtX could represent a good option for remaining economically strong in a future climate-neutral global economy. Australia is also already involved in several hydrogen projects, inter alia in a project with Japan which aims at testing the logistics for exporting hydrogen – the ambitions are very much directed towards developing PtX options as demand from abroad grows.

Energy importers in Asia, such as Japan or South Korea, already show a strong interest in future imports of PtX – mainly hydrogen – from Australia. Japan and Australia currently develop a large scale international hydrogen supply chain project, envisaging a demonstration plant in 2020. This project is based on exporting "blue hydrogen" (i.e. extracting hydrogen from brown coal, combined with CCS) via liquefied H_2 carrier.[79] Japan's clearly defined hydrogen plan, utilising renewable energy via PtX as their target for around 2040, may also drive the scaling up of PtX technology in Australia. However, it is uncertain whether Australia would realistically export to far-away destinations such as Europe if demand is sufficiently strong in closer regions like Japan.

National RES development needs stronger governmental facilitation and the Energy Partnership with Germany may help

Australia has comparatively weak renewable energy and climate targets and the current government undergoes a governmental crisis with urgent and sensible reforms being stopped near completion.[80] There is currently no clear strategy for

[74] Australia is with only 3.2 people per km² one of the least populated countries in the world. See World Bank Databank, Indicator: Population density (people per sq. km of land area).

[75] Clean Energy Council (2018, p. 53 and 56).

[76] U.S. Energy Information Administration (2015), available at https://www.eia.gov/beta/international/rankings/#?cy=2015&pid=7&aid=4, last downloaded 14/08/2018.

[77] Statista (2016), available at https://www.statista.com/statistics/264771/top-countries-based-on-natural-gas-production/, last downloaded 14/08/2018 for production and Statista (2017), available at https://www.statista.com/statistics/274528/major-exporting-countries-of-lng/, last downloaded 14/08/2018 for export of LNG.

[78] World Bank Indicator 'Energy imports, net (% of energy use)'.

[79] Ohira, E. (2018)

[80] See https://www.theguardian.com/australia-news/2018/aug/23/australia-in-crisis-as-prime-minister-faces-down-coup-attempt-by-bullies

reducing CO_2 emissions and these would require governmental facilitation introducing a strong incentive framework if the aim is to reduce LNG production – possibly in favour of producing synthetic gases (e.g. methane).

The recently developed Energy Partnership with Germany in 2017 provides a central platform for institutionalised energy policy dialogue between Germany and Australia. The aim is to incentivise investment in technologies to allow both countries to attain energy and climate targets which may help Australia facilitate RES development.

The giant Australia may well become a world key player in the long term, but possibly also in the early phases of market introduction

It is apparent that Australia has the potential to become a key player due to its disproportionately vast renewable resource potential. At the moment, PtX is not yet on top of mind of (energy) political discussions, however, hydrogen production has become more important last year due to the "low emissions technology roadmap"[81]. If the government starts facilitating these initiatives, the export of hydrogen may well be a prospect of the near-future. Likewise, if demand continues to grow from abroad, as is demonstrated from Japan and Korea, market forces will likely drive PtX production as export would proof profitable (at the start the export of Hydrogen).

The detailed country study on Australia can be found in Annex B.5.

3.3.6 China – the uncertain candidate: Projected RES generation and technology interest forms strong base for PtX production, but export incentives are ambiguous

Countries categorised as uncertain candidates, e.g. China, typically demonstrate partially unexplored RES potentials and PtX may seem an attractive investment given ambitious national climate change policies. The energy strategy of these countries is currently not fully transparent, and PtX production vs. export might be under competition from rapidly growing national energy demand. However, incentives to develop PtX technologies might be strong to secure production and (possibly) import of RE via PtX from abroad.

CASE STUDY INSIGHTS: CHINA

China shows huge and still unexplored RES potential and PtX could be attractive given its climate targets

China shows huge RES potential: the technical wind potential is estimated at 2,500 GW and the solar potential at 500 GW.[82] This is true despite the fact that a large area demonstrating some of the strongest wind and solar power potentials is set on the rocky steep walls of the Himalaya, which impedes the construction of wind

[81] See https://www.csiro.au/en/Do-business/Futures/Reports/Low-Emissions-Technology-Roadmap

[82] According to IRENA (2014), p. 47.

and solar plants. Currently installed total wind and solar capacity in 2017 alone add up to 295 GW[83] – massive projected capacities are still unexploited. However, wind rejection rates are quite high (between 2010 and 2016 about 10%) and increased in 2016 due to absence of an adequate networks.[84]

Coal currently plays a major role in supplying national energy demand[85] and with the Paris agreement ratified, China should have an incentive to reduce its coal dependency and to increase its supply of green energy.

Developing PtX technology could be on China's strategic agenda, and existing energy partnership may reinforce the development

Economic development remains a top priority for China, and technological know-how is on the country's political agenda. China's strategy is to become a high technology country, which means exploring PtX could fit to its political agenda. PtX is a topic that is discussed within China's energy framework and PtX pilot projects may already be underway.

Various energy partnerships with Germany may also facilitate the development of PtX technology with China, such as the Sino-German Energy Partnership since (2007). The partnership aims to support China with the liberalisation of the energy market as key for the Chinese energy transition with a strong focus on renewables and energy efficiency.

Uncertainty remains: China might lead PtX technology development, however PtX export in competition with growing national energy demand

China is the world's largest energy user[86] and IRENA projects that China's energy consumption will even grow considerably in the future[87] due to economic growth and energy demand from transport and residents. To cover the large and increasing national energy demand over the last 10 years, China heavily imported energy from abroad[88]. Given the import dependency and China's strategy to reduce the dependency, although RES capacity is likely to increase hugely in the near future, it is uncertain whether China will be prepared to export any green energy in the short and medium term. It can be expected that China is a potential candidate for PtX exports in the long term when domestic energy demand can be served by domestic supply.

Growth strategies in the energy sector could support PtX technology development and infrastructure/production abroad

However, China might be incentivised to drive the development of PtX technology, especially e.g. through partnerships with the EU/DE in order to meet climate

83 IRENA, available at http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=19, last downloaded 08/08/2018.

84 Zhang et al. (2016).

85 IRENA (2014), p. 98.

86 IRENA (2014), p. 1, and Enerdata (2018): Global Energy Statistical Yearbook, available at https://yearbook.enerdata.net/, last downloaded 09/08/2018.

87 IRENA (2014), p. 31.

88 World Bank Indicator 'Energy imports, net (% of energy use)'.

change targets and growing national energy demands.

China has in the past shown geographically expansive growth strategies in the energy sector (e.g. large investment in UK nuclear power plant at Hinkley point in southern England by Chinese General Nuclear Power Group (CGN), a state-run Chinese energy company)[89]. China is currently heavily investing in its economic relations with Africa, financing large scale projects in infrastructure, securing energy supply, thereby securing access to natural resources.[90] The 2018 Forum on China-Africa Cooperation (FOCAC) summit[91] was held in Beijing this month and leaders from almost 50 African states attended to discuss a wide range of topics - from enhanced Sino-African military ties, health agreements, and academic exchanges. However, a key announcement was a financing package of $60 billion for African states to build infrastructure.[92]

China might use its position to set up PtX production sites in African countries (such as Morocco or Algeria), to develop the technology and build up comprehensive know-how. In later stages, the knowledge could be transferred to other countries including China itself for building up a PtX production and export infrastructures to supply domestic as well as world markets.

The detailed country study on China can be found in Annex B.6.

89 See https://www.theguardian.com/business/2016/sep/15/hinkley-point-chinese-firm-to-submit-essex-nuclear-plant-plans

90 See, for example, http://www.chinafile.com/library/china-africa-project

91 See http://www.xinhuanet.com/english/2018-08/30/c_137431608.htm

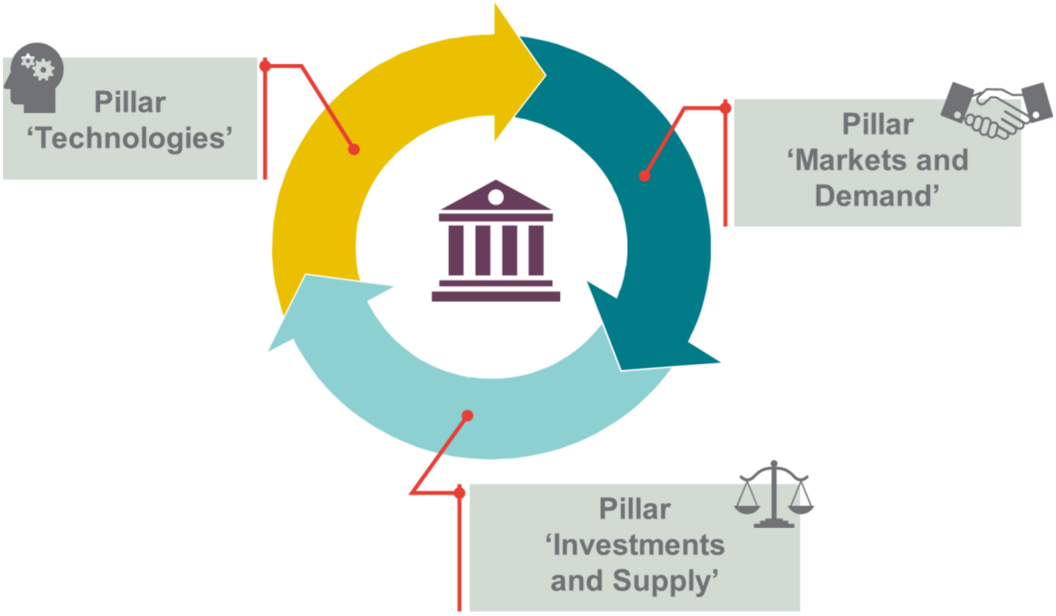
92 See http://www.chinafile.com/library/china-africa-project/should-african-governments-welcome-or-be-wary-of-chinese-infrastructure

4 PTX ROADMAP TOWARDS AN INTERNATIONAL MARKET REQUIRES A SUITABLE FRAMEWORK

Global markets for the trade of synthetic fuels will only develop if both supply and demand mature at relatively similar rates over time. For this, the framework for investments in PtX-plants and international trade of synthetic fuels has to be defined appropriately.

In the following, we analyse the core pillars of a roadmap towards an international PtX market (Figure 20):

Figure 20 Potential pillars as the foundation towards a global PtX market



Source: Frontier Economics

- **Pillar 'Technologies':** Technological roadmap for building up a large scale PtX industry – a global market for PtX will require further technological developments and cost savings. Therefore, the scaling up of the PtX technologies will be key. Furthermore, the creation of a global PtX market can be supported by complementing technologies such as hydrogen from steam reforming (based on natural gas and CCS) or the temporary capturing of CO_2 (required for synthetic fuels with carbon content) from biomass and/or industrial processes.
- **Pillar 'Markets and Demand':** Building up markets and a framework for demand – a market for synthetic fuels needs to be established and facilitated in order to ensure that the product is demanded. The development of a substantial PtX industry will only be successful if consumers are willing to pay for green PtX. Therefore, the green value of PtX has to be transferred into monetary terms in countries importing synthetic fuels (Europe/Germany).

- **Pillar 'Investments and Supply':** Framework for building up a PtX industry in producing and exporting countries – the framework for investments in PtX plants have to be appropriate in order to attract the necessary global investments. International green is key for realising investments in potential PtX exporting countries. In this context, in the short and medium term, Europe/Germany could especially target potential PtX exporting countries which are expected to be frontrunners. However, politics should also pave the way towards exploring the PtX export potential of countries with huge potential in size but more difficult current investment conditions.

In the following, we describe the three pillars in more detail.

4.1 Pillar 'Technologies': Development of a PtX industry requires further technological progress

PtX markets will need both renewable power and PtX technologies (electrolysers, synthesis plants etc.) at low costs. In principle, these technologies are already available, however further technical development and scaling up is required.

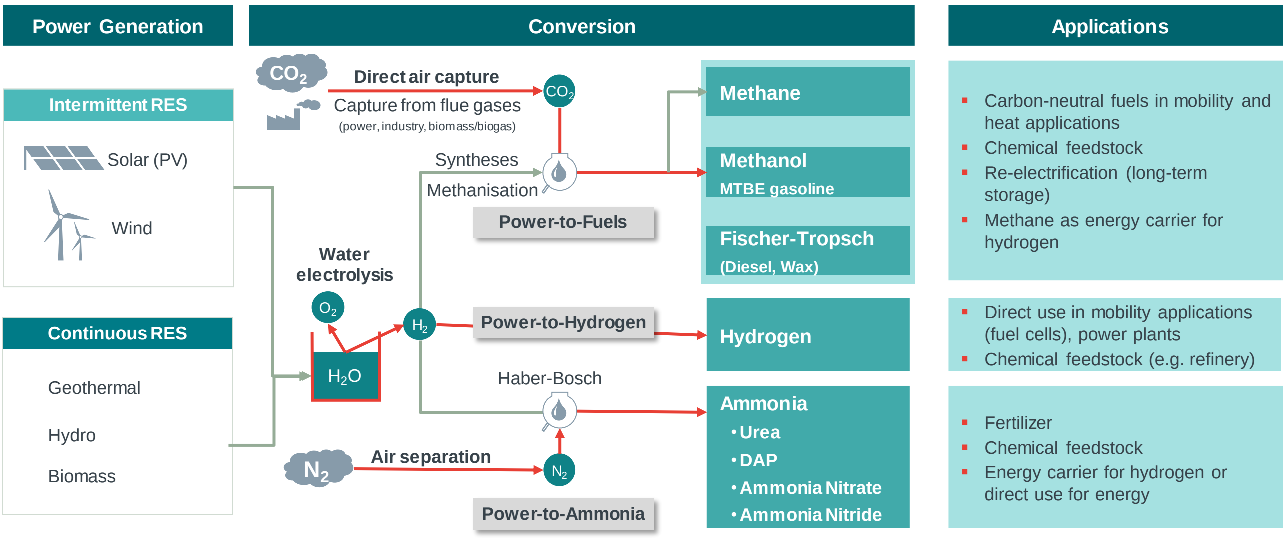
In the following, we will explain the cost structure of producing PtX in more detail and identify requirements for reducing costs further.

4.1.1 PtX technologies and implementation strategies

As explained in Section 1.2, typical products of PtX include (Figure 21):

- Hydrogen – which can be used directly in energy appliances and the mobility sector, e.g. as fuel cells or power plants. Hydrogen is synthetically produced via water electrolysis.
- Synthetic methane – which for example can be fed into an existing grid for natural gas. Methane is synthetically produced via the processes of methanisation.
- Synthetic liquid fuels (e.g. methanol, gasoline, kerosene, diesel, heating oil) – which can be used in the same applications as fossil liquid fuels. Synthetic fuels are produced either via
  - Methanol synthesis (eventually plus upgrading); or
  - Fischer-Tropsch synthesis (eventually plus upgrading).
- Ammonia (and secondary products such as Urea, DAP). Ammonia is produced via the Haber-Bosch process.

Figure 21 Power-to-X: Conversion of renewable power into various forms of chemical energy carriers



Source: Based on Siemens

In the following, we analyse the characteristics of the PtX technologies required to produce these products and discuss the necessary steps in terms of technological advances that are required for a PtX world market to emerge.

PtX production technologies are, in principle, well-known and available

The technologies that are the foundation for producing PtX are already available in principle, however, (still) at considerably high costs. Some of the technologies need substantial further upscaling in order to be “market ready”, i.e. for costs to come down sufficiently so that PtX products can compete in the market. This holds especially for electrolysers as most of the other second-stage conversion processes, e.g. the Fischer-Tropsch and methanol synthesis, are relatively well established and less cost savings are expected for the future for these technologies.

Hydrogen and oxygen are derived from the electrolysis of water using (renewable) energy. Water electrolysis is therefore the base technology for the PtX process as all second-stage conversion methods require hydrogen as a key input (see Figure 21). Water electrolysis can be carried out using low-temperature processes or high-temperature processes (Table 1):

- **Low-temperature processes** are carried out at around 50-80 degrees Celsius and include Alkaline Electrolysis (AEC) and Proton Exchange Membrane Electrolysis (PEMEC). Both technologies are well-established and sold commercially. AEC is the slightly more mature technology which has been in use for decades in various applications and it is a robust but less flexible process than the PEMEC technology. However, the flexibility of operation (power ramps, fast starts / stops of the plant) is becoming increasingly important in conjunction with fluctuating RE where PEMEC is stronger. The PEMEC technology also offers the option of achieving the pressures required for any subsequent synthesis processes (up to 200 bar) more easily than AEC technology. PEMEC still has to be improved in its cost and efficiency position compared to AEC.

- **High-temperature processes** are carried out at 650 to 1,000 degrees Celsius and include Solid Oxide Electrolysis (SOEC). This technology is still in the development phase, but there are a number of pilot projects under way.

Table 1 Electrolyser technologies in competition – comparison of operation characteristics

	Low temperature		High temperature
	Alkaline	**PEM**	**Solid-Oxide**
Operating Temperature	60-80 °C	50-80 °C	650-1,000 °C
Voltage Efficiency	62-82%	67-82%	< 110%
Stack Lifetime	20,000-90,000 h	60,000-90,000 h	< 10,000
Lower dynamic ranged (%)*	10-40%	0-10%	> 30%
Operating pressure	< 20 bar	< 200 bar	< 25 bar
Maturity	Mature	Commercial	Demonstration

Source: Frontier Economics based on Schmidt et al. (2017)

** Minimum operable hydrogen production rate relative to maximum specified production rate.*

An advantage of SOEC compared to low-temperature electrolysis technologies is that the higher temperatures offer the chance to replace a part of the electricity needed for the reaction by heat. In the case of the second-stage conversion processes (methanisation, methanol- or Fischer-Tropsch synthesis), heat is generated as a by-product, which can be used as an input for SOEC electrolysis. However, SOEC needs to be kept warm even in non-operating periods, when renewable energy is not available, and the heat created as a by-product could be needed to cover the additional heat demand. In addition, capturing the CO_2 input for the conversion from the air requires heat input, which may further increase the competition for heat resources.[93]

A fundamental drawback of SOEC is its lack of flexibility compared to low-temperature electrolysis. This impairs the use of SOEC in combination with fluctuating renewable energy as intermittent production requires a storage solution which increases costs significantly.[94] As of today, SOEC also shows fast degradation as compared to a lifetime stack of 20,000 to 90,000 hours for low-temperature technologies (stack lifetime < 10,000 hours).

In the longer term, the SOEC technology is a strong option to significantly increase efficiency. However, this technology is not yet commercially available. The advantage of low-temperature processes is that they are mature technologies and commercially available from a range of suppliers.

[93] Fasihi et al. (2016).

[94] Fasihi et al. (2016).

Green PtX should be based on renewable energies, however, “blue hydrogen” may be part of a roadmap

In this study, we focus on synthetic fuels generated from renewable energies, such as wind, solar, geothermal, hydro or biomass. The intermittency of power generation from wind and solar is a specific challenge for the production of synthetic fuels due to the limited full load hours of these installations. However, at the same time, these technologies provide by far the highest potential for increasing RES-E production. Therefore, we focus to a large extend on power generation from wind and solar in this study.

Energy from RES and water are the main input into the production of green hydrogen via water electrolyses. Green hydrogen is the key product for the future PtX industry, and it can be used in a variety of ways. For example, it can be

- blended with natural gas in existing grids for natural gas. It is currently tested in a number of field projects to which extend hydrogen can be mixed to natural gas without raising technical problems for gas grids, compressors and end applications;
- used directly in a variety of end-user applications (e.g. fuel cells in electric cars and private homes) as well as in power plants; and
- used as in input factor to produce other synthetic fuels such as
  - synthetic methane;
  - synthetic liquid fuels (methanol, diesel, heating oil, gasoline, kerosene, MTBE etc.); and
  - ammonia (including Urea, DAP).

Alternatively, hydrogen can also be produced via steam-methane reforming (from natural gas), which produces hydrogen and CO_2. However, as long as the CO_2 is released into the air, the process is not carbon-neutral and the hydrogen is therefore considered “grey”. In order to sustain carbon-neutrality, the CO_2 separated from the hydrogen has to be captured and stored safely in the ground, e.g. in exhausted natural gas fields (CCS), or used in industrial processes (CCU). This carbon-neutral hydrogen is known as “blue” hydrogen. Actually, most of the hydrogen used worldwide, e.g. in the industry, is produced via the process of steam reforming, and blue hydrogen can therefore serve as catalyser to build up hydrogen economies and to foster global demand in end-user applications and in the industry. Blue hydrogen as an option to produce H_2 can support the establishment of a global PtX (especially hydrogen) industry based on RES-E.

In most cases, steam reforming of methane (from natural gas) including CCS is less costly than producing hydrogen from RES (i.e. wind and solar), however

- the locations of potential storages for CO_2 are restricted to specific areas in the world (e.g. regions with former natural gas production);
- the storage and CCU volumes are limited; and
- CCS is not perceived as a safe technical option to store CO_2 in some countries of the world (e.g. in Germany).

Due to the limitations of blue hydrogen, the long term outlook for a growing market for hydrogen and synthetic fuels is expected to rely on green hydrogen produced via water electrolysis from renewable energy sources.

Establishment of a global PtX industry can thrive on utilisation of existing energy infrastructure and appliances

As previously discussed, the utilisation of PtX fuels can be based either directly on hydrogen or on synthetic fuels which are produced using hydrogen. As of today, it is unclear which mixture of synthetic fuels will be used in a carbon neutral energy future. However, for the process of establishing a global PtX market, some of the key questions are whether

- existing infrastructure can be used to transport and distribute the energy and whether existing energy applications can be used – this is relevant, for example, for synthetic methane, diesel, heating oil, gasoline and kerosene; or
- whether new infrastructure has to be installed and end-user applications have to be converted to the new fuels – this is relevant, for example, for hydrogen, methanol, OME/DME or ammonia.

Hydrogen infrastructure that allows hydrogen to be used in a huge number of small scale applications (e.g. fuel cells in cars or in private homes) does currently not exist in most countries around the world. Therefore,

- either new distribution infrastructure (i.e. a hydrogen pipeline grid) for hydrogen has to be build; or
- existing pipelines (i.e. for natural gas) have to be converted to hydrogen.

Furthermore, end-user applications have to be converted to hydrogen, and distribution infrastructure (e.g. filling stations for electric cars with fuel cells) would have to be built.

JAPANS PLANS TO REALISE A “HYDROGEN SOCIETY”[95]

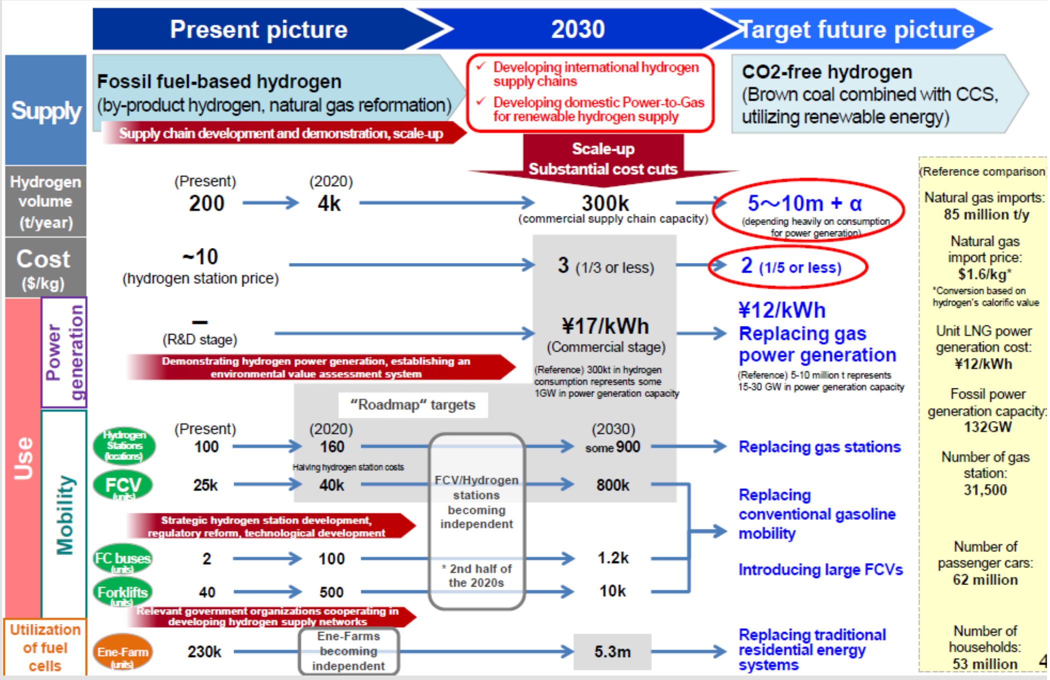
The Japanese government faces structural challenges regarding the country’s energy supply and demand: strong dependence on imports of fossil fuels and a persistently low energy self-sufficiency rate on the one hand and ambitious targets to cut GHG emissions on the other. METI, the Japanese ministry of Economy, Trade and Industry, defines a “hydrogen-based society as a means to an end” (METI, 2017) and recognises its potential as a CO_2-neutral energy source. The government shows clear commitment to expanding its hydrogen technologies and innovations overseas, leading hydrogen initiatives in foreign countries and “creating a new growth industry” (METI, 2017).

Accordingly, METI published its basic hydrogen strategy plan that lays out the vision for a “hydrogen-based society” with targets that public and private sectors should pursue together until 2050 (Figure 22):

- Realising low-cost hydrogen either via CCS inside Japan or by procuring massive amounts of hydrogen from overseas
  - Commercial-scale supply chains by around 2030 to procure 300,000 tons of hydrogen annually and ensure that the cost of hydrogen reaches 30 yen/Nm^3.
- Developing energy carrier technologies to enable efficient hydrogen transportation and storage
  - Liquefied hydrogen supply chain and basic technologies for an organic hydride supply chain by the mid-2020s (commercialisation around 2030)
  - Aim to disseminate methanisation technology that employs CO2-free hydrogen
- Expanding the use of hydrogen from renewable energy and developing technologies for storing surplus power (power-to-gas as promising method)
  - Cost reduction as key point: develop a technology that cuts the unit cost for water electrolysis systems as core power-to-gas equipment to 50,000 yen/kW by 2020
  - Attempt to commercialise power-to-gas systems by around 2032
- Hydrogen power generation can play a major role as a regulated power supply and backup power source; attempt to make hydrogen power generation including environmental values as cost competitive as LNG power generation.
- Hydrogen use in mobility: increase the number of FCVs, FC buses and hydrogen stations in Japan by a significant amount until 2030
  - Promote regulatory reform, technological development, and joint, strategic hydrogen station development by the public and private sectors.
- Potential hydrogen use in industrial processes and heat utilisation
- Utilising fuel cell technologies and innovative technologies

95 METI – Ministry of Economy, Trade and Industry in Japan, see http://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf and the Government of Japan and Bureau of Environment Tokyo Metropolitan Government, see https://www.japan.go.jp/tomodachi/2016/spring2016/tokyo_realize_hydrogen_by_2020.html and http://www.kankyo.metro.tokyo.jp/en/index.html

Figure 22 METI Scenario for basic hydrogen strategy



Source: *METI – Ministry of Economy, Trade and Industry in Japan, see http://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf*

There are various advantages and disadvantages when moving to new energy systems, such as a "hydrogen economy", as compared to relying on existing infrastructure and appliances using green synthetic fuels (see Table 2 below).

Table 2 Comparison: Utilisation of existing infrastructure (e.g. for natural gas, gasoline, diesel) vs. "hydrogen economy"

	Advantages	Disadvantages
Utilisation of green synthetic fuels	▪ Cost savings due to utilisation of existing infrastructure and appliances ▪ Immediate implementation on consumer side possible	▪ Higher costs for conversion facilities (albeit conversion cost only around 15%-17% of total) ▪ Additional energy losses due to conversion ▪ Need for CO_2 as input for fuels production
Establishment of a "hydrogen economy" (including end-user applications, e.g. cars or heating systems for buildings)	▪ No additional conversion of H_2 needed ▪ Less energy losses in conversion ▪ No CO_2 as input required ▪ Applications are relatively efficient (e.g. fuel cells)	▪ Substantial investments in new infrastructure/ conversion of infrastructure required (costs, limitations in acceptance?) ▪ Investments in new applications or conversion of end-user applications at consumer side ▪ International transport with additional significant energy losses due to compression or liquification ▪ Applications such as fuel cells are (still) relatively expensive

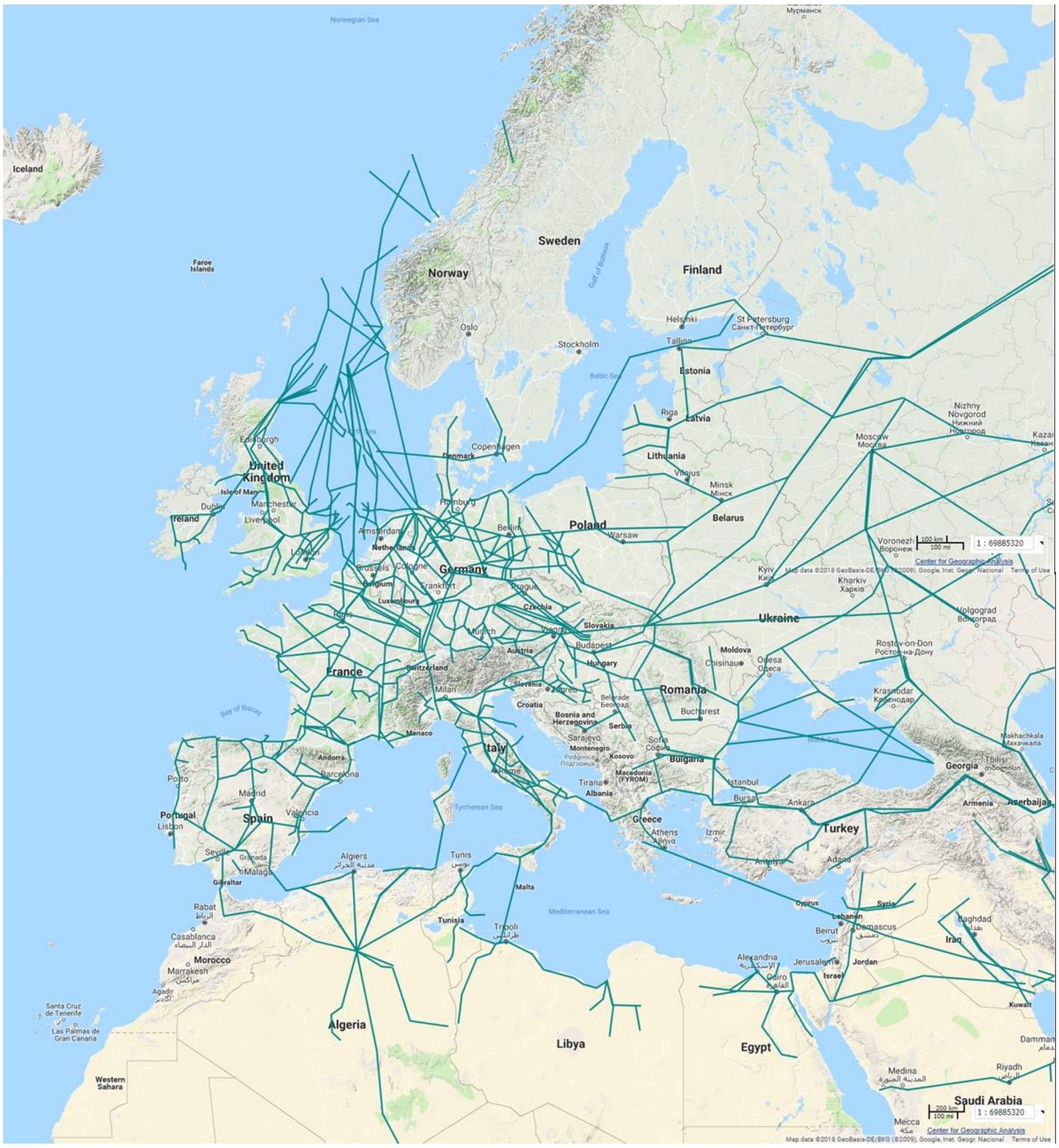
Source: *Frontier Economics*

To simplify the establishment of a PtX market, a stepwise approach can support the use of existing infrastructure while at the same time allowing for a pathway towards a (partial) transformation of the energy system:

- **Phase 1 –** can be implemented today:
  - Utilisation of green hydrogen in industrial processes which currently rely on hydrogen from steam reforming (without CCS).
  - Blending of green hydrogen into existing natural gas grids.
- **Phase 2 –** to be implemented in the medium term (e.g. around 2025-2030):
  - Stepwise conversion of current natural gas grids (locally) to hydrogen (if technically feasible).
  - Local development of new hydrogen infrastructure.
- **Phase 3 –** to be implemented in the long term (e.g. beyond 2030):
  - Development of new large scale hydrogen infrastructure with a large area coverage.

For the utilisation of existing gas grids, major current import pipelines, e.g. from Norway, Russia and North Africa to Europe, could be used to transport green hydrogen. This could be done by blending hydrogen with natural gas or, in later stages, possibly converting natural gas into hydrogen (if technically feasible). The potential of Norway, Russia and North Africa to deliver green fuels to Europe is immense (see Section 3). This means that even in the early stages of the establishment of a PtX market, international trade of green hydrogen can occur by utilising existing infrastructure (Figure 23).

Figure 23 Existing natural gas pipeline system in Europe



Source: Harvard Pipeline World Map.

At this stage, no unified trend towards a specific green fuel future is apparent on a global scale. Different countries currently plan for varying options, for example Japan and the UK envisage the usage of hydrogen in the transport sector in addition to electrification, whereas Iceland is opting for green methanol. In any case, the development of new energy infrastructure will require the support and facilitation from local politicians and administrations. This is particularly relevant to gain public acceptance and to be able to finance the necessary infrastructure investments. Consequently, the success of an implementation of new energy systems also relies on energy strategies developed by governments in energy-consuming countries.

In summary, the development of new energy systems such as a “hydrogen economy” requires support and facilitation from politicians and administrations. However, an energy transition can be implemented as a stepwise approach in the energy-consuming countries: The establishment of a global PtX industry can largely take advantage of existing transport and distribution infrastructure and be based on current energy systems.

Various sources can supply the CO_2 required as input for the production of synthetic fuels

During the production of hydrogen-based synthetic fuels, the second-stage conversion processes (e.g. methanisation, methanol or Fischer-Tropsch synthesis producing synthetic methane, methanol, gasoline, diesel, kerosene etc.) require CO_2 as a key input. Various sources can supply the CO_2 with varying advantages and disadvantages regarding, for example, costs and carbon neutrality. The following examples illustrate this point:

- **Direct Air Capture** (DAC): CO_2 is taken from the air by electro-dialyses or the Temperature Swing Adsorption process (TSA). DAC is by far the most expensive technology to supply CO_2 – current costs are reported at around 150-180 €/t CO_2 (and around 100 €/t CO_2 in 2030). The main advantage is that carbon-neutrality for synthetic fuels produced with CO_2 from DAC is guaranteed.
- **Capture from biomass**: CO_2 can be captured from biomass at a cost of currently around 90 €/t[96]. Costs are considerably lower than for CO_2 extracted via DAC since the CO_2 is more concentrated in the stream. The disadvantage is that the absolute potential to use biomass as a source of CO_2 is limited due to competing uses for biomass (e.g. in producing ethanol, in direct usage for heating or as a fuel in power generation). The main advantage is that carbon-neutrality for synthetic fuels produced with CO_2 from biomass is guaranteed.
- **Capture from industrial emissions:** CO_2 can be captured from emissions of industrial processes at a cost of 30-50 €/t CO_2. This option to capture CO_2 is by far the cheapest. The main disadvantage is that there are concerns about the carbon-neutrality of the CO_2, especially if the fuel input from the industry is based on fossil energy sources such as oil products or natural gas. However, given that climate change policies plan for industrial CO_2 emissions to decline (and not to be eliminated completely) in the foreseeable future, the CO_2 is emitted into the air in any case (with / without usage in PtX synthesis). Furthermore, some emissions from industrial processes can't be replaced at all or only at very high costs. In these cases, the CO_2 used in the PtX process is not additional to the baseline carbon emissions but "re-used" in the industry. As long as the CO_2 emissions from the industry are not incentivised by its utilisation during PtX conversion processes, the CO_2 can be assessed to be carbon-neutral.[97]

Due to the high cost advantages, the capturing of CO_2 from industrial processes and biomass can help to establish a global PtX industry in the short and medium term. Suitable CO_2 from industrial processes is available in many potential PtX producing countries (e.g. from the cement or chemical industry present in many countries in the world). However, CO_2 emissions from the industry will have to be

[96] See www.climeworks.com

[97] Prescribing DCA for capturing CO2 can in any case lead to an adverse situation: There will be situations in which DCA facilities generating expensive CO2 will be close to industrial sites emitting highly concentrated CO2 – from an economic point of view this situation would be highly inefficient.

cut significantly in the long term future and the availability of biomass is limited in absolute terms. Therefore, the use of DAC will be increasingly required in the long term in order to ensure carbon-neutrality of the PtX products. DAC technology needs to be further developed substantially in the next decades.

4.1.2 PtX costs are driven by electricity costs and the costs of the conversion plants

Future costs for PtX will be key to establish a global PtX industry. Trading PtX fuels around the globe will help to reduce costs for importing countries and provide economic opportunities for the exporting countries. However, costs for PtX technologies will have to come down significantly in order to compete with other carbon neutral technologies.

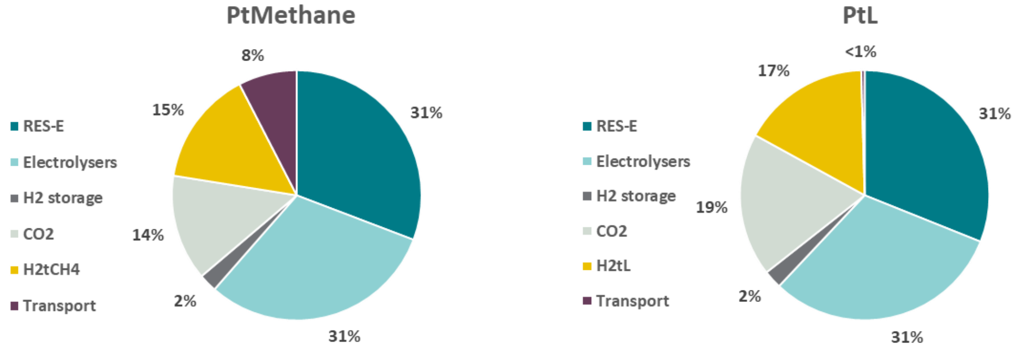
Dominant cost components of PtX production are electricity costs and investment costs for electrolysers

The cost of producing synthetic liquid fuels and gases vary substantially between fuels and for the different assumptions drawn regarding underlying cost figures. The following components are of significant importance across all PtX products (Figure 24):[98]

- **Costs for renewable electricity generation:** RES-E costs account for around one third of the total costs. Therefore, electricity costs and efficiency of the processes is a key driver of PtX costs.
- **Costs for electrolysers:** the costs for the hydrogen production (PtH2), including energy efficiency losses, amount to around one third of total costs which his equivalent to the share of RES-E costs. This includes the supply of water via saltwater desalination plants, however, the cost of water supply are negligible.
- **Costs for second-stage conversion processes (methanisation, Fischer-Tropsch-synthesis, methanol synthesis):** the costs for the synthesis of gaseous or liquid fuels (including H_2 storage and energy efficiency losses) account for around 15% to 17% of total costs – excluding the supply of CO_2.
- **Costs for the supply of CO_2:** the costs for the supply of CO_2 are around 14% to 19%, assuming that the CO_2 is captured from the air via DAC technology.
- **Costs for transportation:** the costs for the transportation of the synthetic fuels from exporting to importing countries (e.g. Germany/Europe) range from 0% for transporting synthetic liquid fuels up to 8% for transporting gaseous fuels like methane. If existing infrastructure for transporting these gases already exists, for example gas pipelines from Norway, Russia or North Africa to Europe, these costs are negligibly low.

[98] Agora Energiewende, Agora Verkehrswende and Frontier Economics (2018), Fasihi and Breyer (2017).

Figure 24 Electricity costs as main driver of synthetic fuel costs

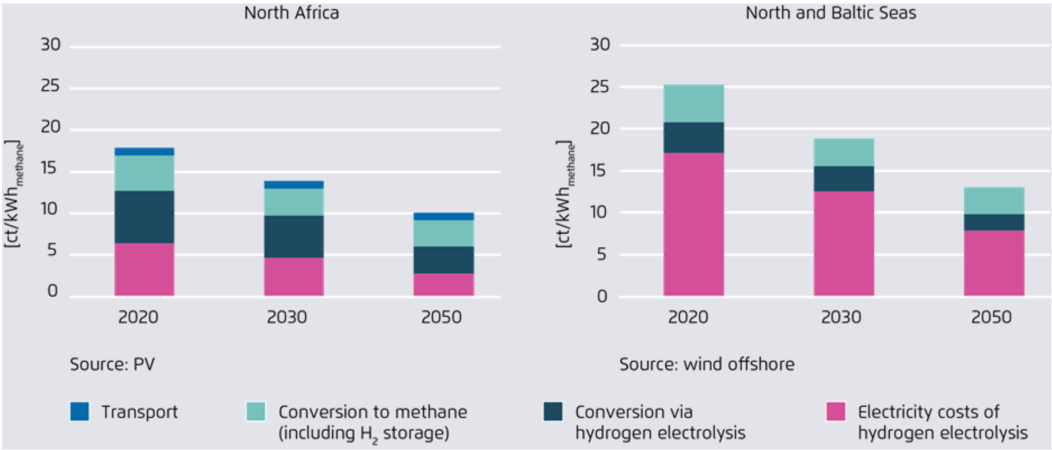


Source: Agora Energiewende, Agora Verkehrswende and Frontier Economics (2018).

Note: All cost shares (in%) and absolute figures (ct/kWh) are rounded and associated with the following scenario: North Africa, reference scenario 2030, PV-Wind-combination, CO_2 from DAC, 6% WACC.

In all studies on PtX costs, electricity generation costs are amongst the key drivers of costs (the share depends on whether energy efficiency losses are accrued to electricity generation or conversion costs).[99] Although electricity generation costs are expected to fall until 2050, they will continue to make up a significant fraction of total costs in 2050 (Figure 25).

Figure 25 Costs of generating renewable electricity as fundamental driver of synthetic fuel costs



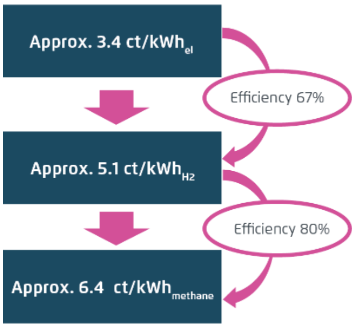
Source: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018)

Note: Reference case for methane (ct2017/kWh methane) – examples North Africa (photovoltaic) and North and Baltic Seas (offshore wind).

The large influence of the electricity generation costs on the cost of synthetic fuels is primarily linked to system inefficiencies across the PtX value chain. The illustrative example in Figure 26 demonstrates the resulting conversion losses: If electricity generation costs are 3.43 ct/kWh$_{el}$ and the system efficiency is 67% for the water electrolysis and 80% for the second-stage conversion processes (methanisation, Fischer-Tropsch or methanol synthesis), the electricity cost for the final product are 6.39 ct/kWh$_{PtX}$.

[99] i.a. Fasihi and Breyer (2017), Fasihi, Breyer and Bodganov (2016).

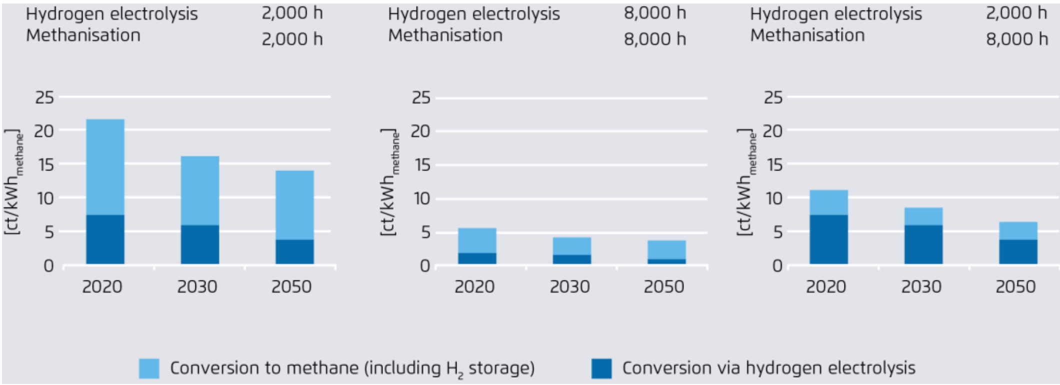
Figure 26 Illustrative example of conversion losses



Source: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018)
Note: Reference case for synthetic fuels in North Africa based on photovoltaic in 2020.

Other important cost drivers are conversion plants utilisation rates and investment costs: The larger the rate of utilisation (i.e. load factor), the smaller the share of the investment costs as part of total conversion costs (Figure 27).[100]

Figure 27 Impact of conversion plants load factors and investment costs on the cost of conversion



Source: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018)
Note: Exemplary values for hydrogen electrolysis and methanisation.

Investment costs of electrolysers and conversion plants have a significant impact on the costs of synthetic fuels. This becomes apparent in Figure 25 when comparing the costs across the years 2020 and 2050 – this assumes decreasing investment costs until 2050 as we discuss in the next section.

Essential cost savings expected for RES-E and electrolysers

The key driver of the cost decline in PtX technologies are progressive investment cost reductions over time for the construction of renewable generation plants, electrolysers and PtX conversion plants due to economies of scale and learning effects.[101] As an example, Figure 28 shows an overview of the literature on investment costs for water electrolysis plants: while there is a wide range between

[100] The case on the right-hand side illustrates a situation in which hydrogen electrolysis has fewer full-load hours because the electricity is generated using fluctuating renewable sources (and without using electricity storage) but the methanisation has upstream hydrogen storage, which increases utilisation.

[101] See Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), p. 56, Table 1.

those figures cited in the literature today[102], there is an apparent consensus regarding the development of these costs over time.

Figure 28 Decreasing investment cost for water electrolysis until 2050

Source: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018)

Technology development needs projects with increasing scale and an increasing number of installations for standardisation

The cost decline of electrolysers and other components of the value chain of the PtX production (for example direct air capture) requires considerable learning effects and efficiency improvements for the technologies to come through over time. For these predicted learning effects and efficiency improvements to pervade, economies of scale are vital. The key drivers to achieve these cost savings and technological progress are therefore:

- Scaling up of plant sizes – various studies show that investment costs fall with increasing plant size.[103]
- Scaling up of processes to standardise the processes to build the installations in standardised modular units. This requires a significant growth in the market size for the installations.

At the same time, the processes for producing liquid fuels are comparably well-established, so that smaller progressive cost reductions are expected than for hydrogen electrolysis or methanisation. The industry is planning with scaling up unit sizes of plants which will allow for substantial cost savings – as illustrated by the electrolyser example in the following box. In the study for Agora Energiewende

[102] Factors influencing the wide range of investment costs in the literature are presented in Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), p. 61 f.

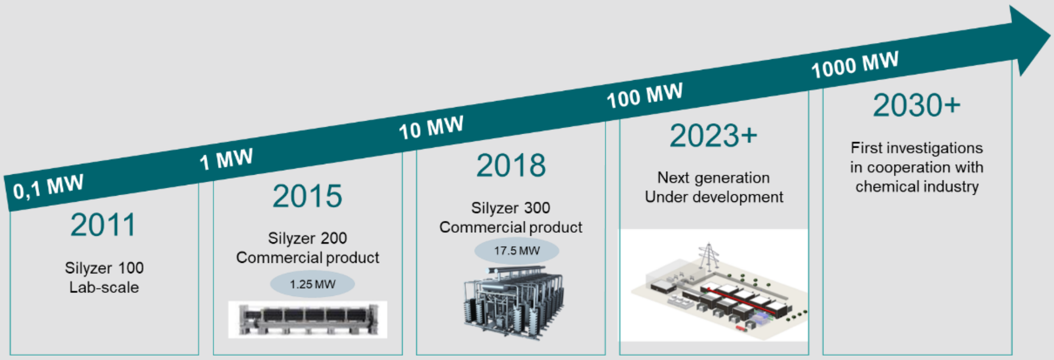
[103] For example LBST (2016) and Enea Consulting (2016).

and Agora Verkehrswende undertaken by Frontier Economics (2018), specific investment costs for electrolysers of around 660 to 770 Euro/kW for 2020 are assumed. Investment costs as low as 400 to 500 Euro/kW can be achieved in facilities with capacities of 100 MW or greater (DLR et al. 2014; IEA 2017b). In a 5-MW facility, the share of costs not related to the electrolyser stack would amount to 58%; in a 100-MW facility, the share would be 23% (DLR et al. 2014).

EXAMPLE: PEM ELECTROYSER "SILYZER" PORTFOLIO ROADMAP AND SCALE UP (SIEMENS)[104]

According to Siemens, the "Silyzer" PEM electrolyser portfolio scales up by about factor ten every four to five years, primarily driven by market demand and the co-development with Siemens customers (Figure 29). By scaling up performance, it is possible to significantly reduce specific capital and operating costs.

Figure 29 Demonstration of Silyzer scale up by Siemens



Source: Siemens

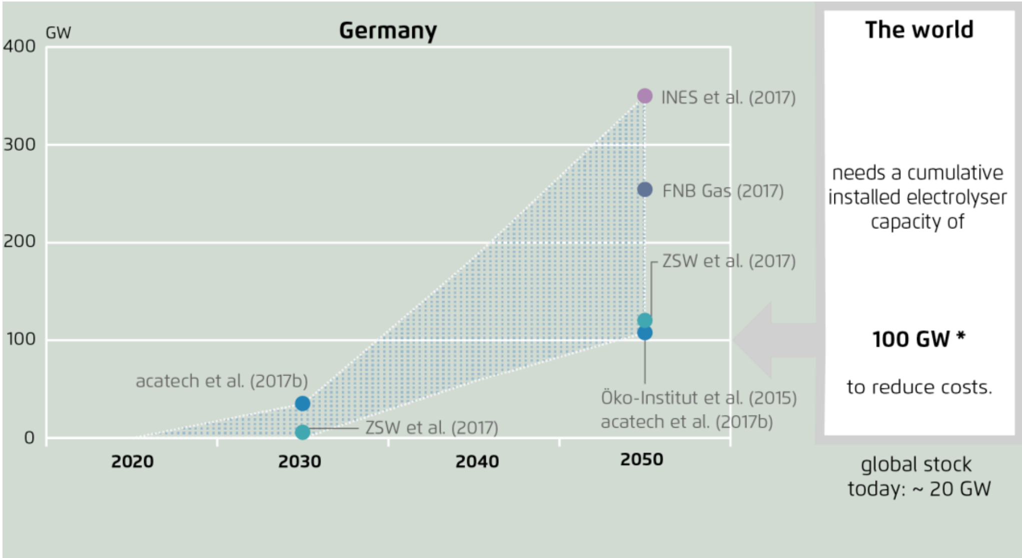
Silyzers development path over time according to Siemens:

- Around 2011, the first PEM electrolyser was demonstrated on a laboratory scale with an electrical output of several kW. The cumulative hydrogen production was thus about 150,000 Nm^3. It was thus achieved a total operating experience of over 4,500 hours. The specific costs at the time were still well over 1,500 Euro/kW.
- In 2015, the first commercial product "Silyzer 200" with an electrical input of up to 3-4 MW and a cumulative hydrogen production of 2.8 million Nm^3 was introduced. The first projects for this type of electrolyser were the Mainz Energy Park and the VoestAlpine steelworks in Linz. These projects are some of the largest in terms of capacity for power-to-gas projects worldwide.
- The next generation of PEM electrolysers is currently being developed: the "Silyzer 300". With a capacity of approximately 10 MW, it is expected to have the strongest performance of a single PEM electrolyser worldwide.
- According to experts, it is already clear that in just a few years the electrolyser capacity will develop into the 100 MW or GW range. Projects of this magnitude will preferably be realized in countries with optimal operating conditions (minimum generation costs for electricity from renewable energies). The demand for green hydrogen or green synthetic fuels comes from Europe and North America, for example, driven by a regulation such as RED-II for the gradual decarbonisation of the transport sector.

[104] The time path and explanations presented in this example are according to Siemens.

Agora Energiewende and Agora Verkehrswende estimate that to achieve the cost reductions projected in the study by Frontier Economics, global electrolysis capacity must reach an order of magnitude of 100 GW (Figure 30). A comparison with scenarios for PtX in Germany shows that the range of estimated capacity additions for Germany already meet this requirement. The 100 GW of electrolysis capacity needed for affordable synthetic fuels corresponds to a fivefold increase in the world's current installed capacity of about 20 gigawatts.

Figure 30 Installed electrolysis capacity for synthetic methane and liquid fuels in scenarios for Germany, and cumulative installed global electrolysis capacity for cost reduction in gigawatts



Source: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), S. 22.

We illustrate in Section 2.3 that the world market for PtX may reach a significant level of demand of up to 20,000 TWh per year in the very long term (e.g. 2050). Depending on the assumed load factors of the renewables generation that supplies the electrolysers, the electrolyser capacity to be installed on the world market may sum up to 3,000 GW to 6,000 GW. This means if a world market for PtX picks up it can be expected that the market size required for substantial cost savings can easily be reached.

4.1.3 What could be done?

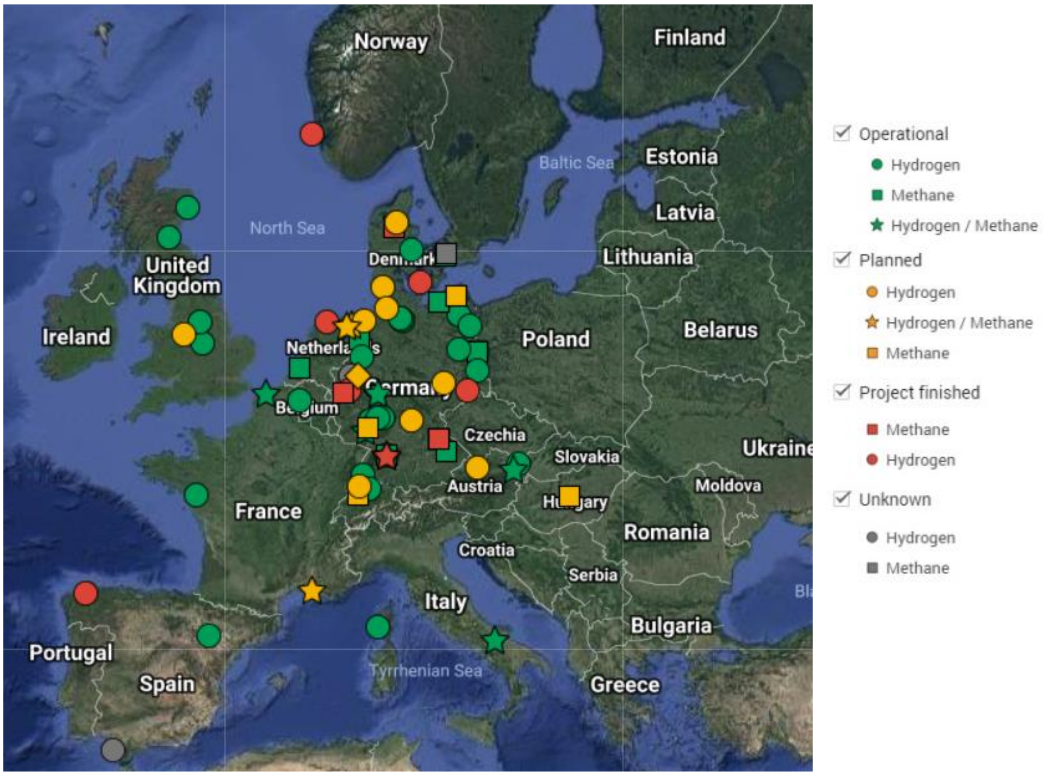
For the export of green PtX to European markets, an integrated system for the production and transportation of these fuels has to be established, including:

- Renewable power plants;
- Electrolysers;
- Hydrogen storage;
- Water supply if required (e.g. from desalination plants in dry regions);
- Facilities for capturing CO_2 (from the industry, biomass or via direct air capture);

- Potentially second-stage conversion plants to produce methane, ammonia or liquid synthetic fuels;
- Infrastructure and facilities for the transportation of the products from the producing country to Europe; and
- Distribution and marketing of the synthetic fuels to final customers in Europe.

Although there are already a number of active PtX projects around the world, only very few (and no large scale) international projects based on renewable energies currently exist demonstrating the feasibility and technical capability of PtX exports across the value chain. Currently, synthetic fuels are produced on a smaller scale, and in some cases the hydrogen is extracted from fossil fuels using carbon capture and storage for the carbon component. In other cases, the electricity is taken from the public electricity grid (see Figure 31). Furthermore, the PtX of the pilot and demonstration projects are produced for local niche markets in most cases.

Figure 31 Power-to-gas (demonstration) projects in Europe



Source: EUROPEAN POWERTOGAS, see http://europeanpowertogas.com/projects-in-europe/

Therefore, the next step could be to implement a relatively large scale integrated pilot project for PtX exports to Europe based on renewable power.

4.1.4 International roadmap for scaling up PtX technologies

Enabling the scaling up of PtX technologies and the development of larger scale pilot projects, nationally and across borders, is one of the key pillars to achieve on the path towards the establishment of a PtX market. To provide guidance on the potential next steps and milestones for facilitating these developments and to achieve the necessary economies of scale, we develop an illustrative international roadmap for scaling up PtX technologies (Figure 32).[105]

This international roadmap for PtX technologies is characterised by

- Lowering costs for PtX technologies;
- Developing transportation and distribution infrastructure; and
- Using complementing technologies to support cost recovery and market development.

The timing of the milestones is indicative.

Lowering technology costs for PtX technologies

Lowering the costs of PtX requires scaling of unit sizes as well as standardisation and commoditisation of key technologies (Section 4.1.2). A roadmap could incorporate (numbers and timing indicative) as potential milestones

- The scaling of unit sizes of electrolysers from ca. 10 MW, today, to a size of multiunit PtX plants size of over 1 GW in the years after 2030.
- The scaling of capacity additions of PtX plants from less than 200 MW pa in Europe in 2020 (electrolysers) to more than 10 GW pa before 2030 and to more than 100 GW pa after 2040.

In addition, from the mid 2020's, PtX costs can benefit from systematic development of low cost production locations.

Developing transportation and distribution infrastructure

PtX can be expected to be phased in by the use of existing transportation and distribution infrastructure in the short term. Hydrogen and synthetic fuels are blended with fossil fuels at increasing shares. This development can kick-off in the short term.

However, infrastructures may be converted to hydrogen and other synthetic fuels (such as e.g. methanol) from the mid 2020's (timing indicative). At first, pilot projects are implemented in a number of countries. In the longer term, before 2030, the establishment of new dedicated infrastructure for hydrogen and other PtX (ammonia) may commence. From 2035 onwards, hydrogen and other PtX transport infrastructure may become an integral part of the energy system.

Using complementing technologies to support cost recovery and market development

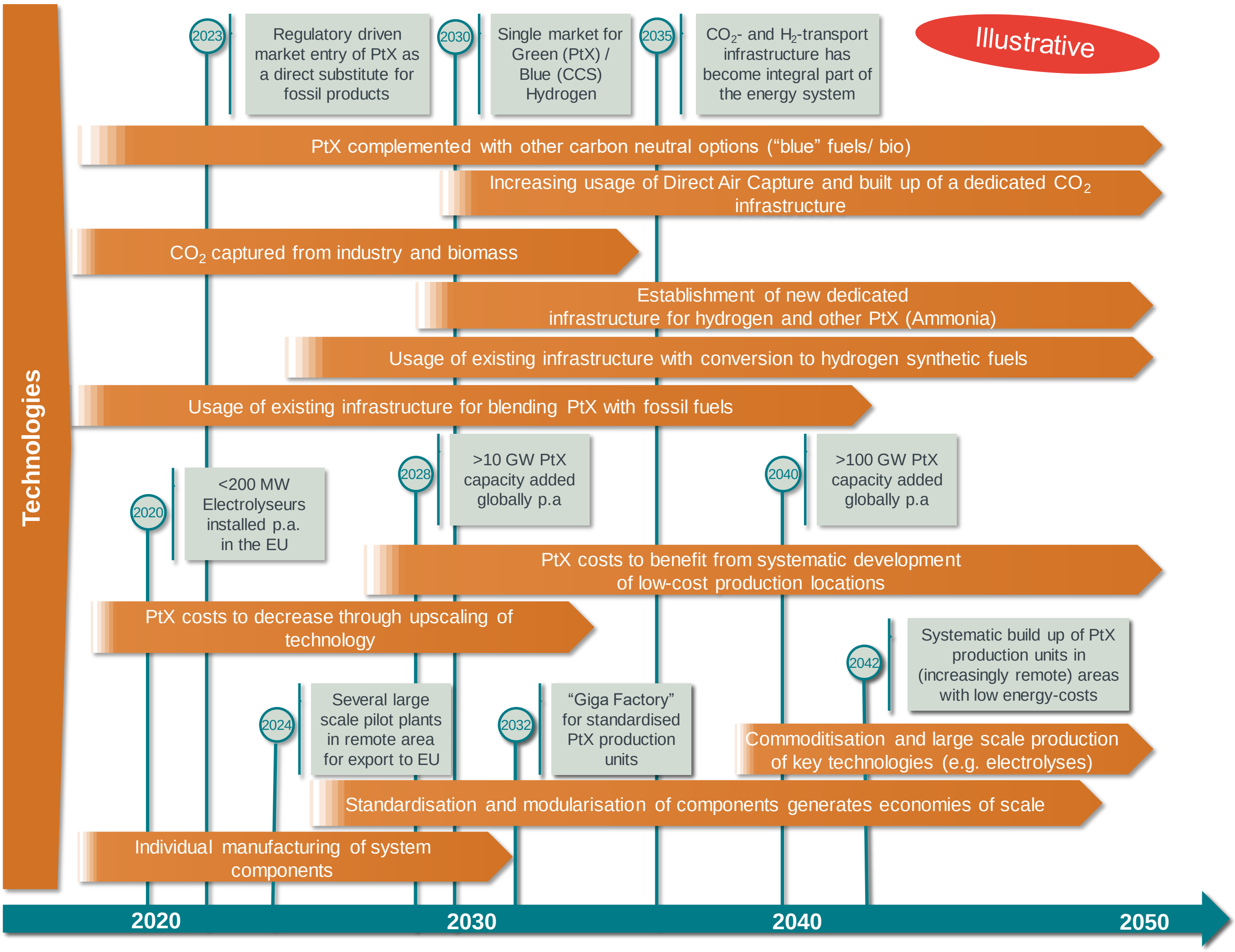
Especially in early years, the establishment of a PtX market can benefit from complementing technologies such as "blue" hydrogen/fuels which can be produced in the near term from fossil fuels with CCS. First projects are already underway in this respect. The "blue" hydrogen/fuels can help to create markets for the

[105] It is important to note that this roadmap is illustrative and provides a first indication of the potential steps and milestones to achieve, but should not be interpreted as a forecast.

respective fuels. These markets can be served in later stages by PtX from renewable electricity.

Furthermore, synthetic fuels with carbon content (synthetic diesel, heating oil, kerosene, methane) can benefit from using low cost CO_2 sources such as the capture from flue gas emissions from industries (some of them non-avoidable) or from biomass. As long as these emissions are not triggered by the use of PtX, the CO_2 can be assessed to be carbon neutral. However, in the long term (e.g. from 2030) the CO_2 has to be extracted increasingly from the air (Direct Air Capture) at higher costs. However, due to scaling up of DAC plants, manufacturing costs can be expected to decrease over time.

Figure 32 International roadmap pillar 'Technologies': Development of a PtX industry requires further scaling up of technologies



Source: Frontier Economics

4.2 Pillar 'Markets and Demand': Markets in the EU/DE have to be established to provide reliable demand perspectives

In order to build up a global market for PtX, it is key that investors can secure the financing of their projects and find the markets for their products. In the context of the international trade of green PtX from renewable energy sources, this means that synthetic fuels have to be bought by customers at a price which reflects the value of carbon-neutral energies and covers costs. Without a market and without customers, investments in PtX facilities and infrastructure will not take place – neither inside nor outside Europe.

Since the value of carbon-neutral PtX is heavily dependent on climate change policy, the demand and willingness to pay for these products is very much driven by regulation within Europe and by the Member States of the European Union. Therefore, creating a market for synthetic fuels is considered "homework" for Europe. Although we focus on the international aspects of PtX production and trade in this study, this section highlights some of the key issues and requirements regarding the establishment of PtX markets in Europe as a prerequisite of a global PtX industry.

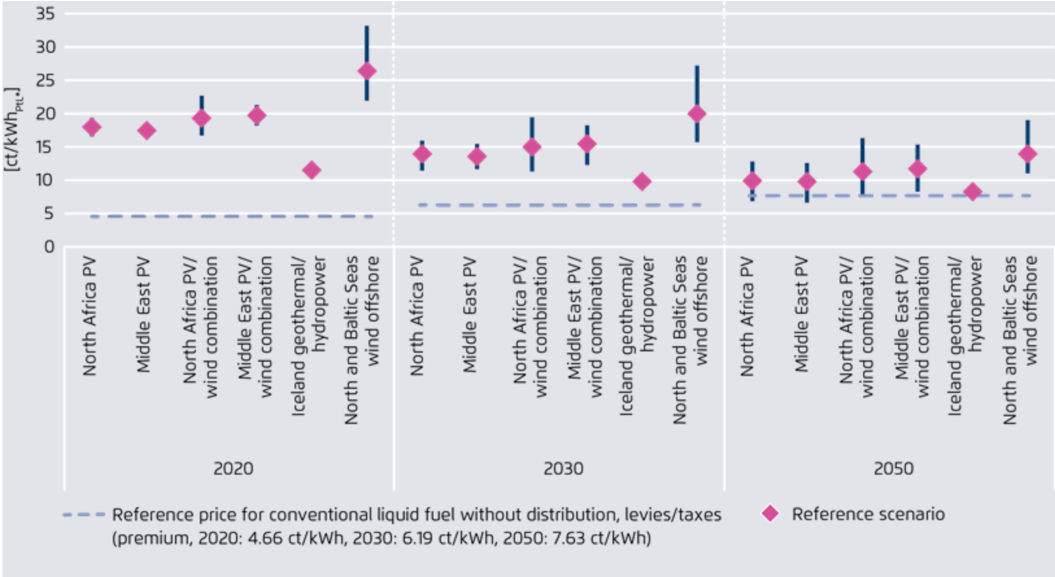
4.2.1 Regulation is needed to create PtX markets and demand

Without regulation, green PtX fuels generated from renewable energies compete with their fossil counterparts in the same market: energy customers are not able to differentiate – based on the physical characteristics of the final product – between products from fossil fuels (e.g. diesel or gasoline or hydrogen from steam reforming) on the one hand and green synthetic fuels on the other hand. Carbon-neutral PtX products are more expensive to produce than fossil fuels and this will likely continue to be true in the foreseeable future while fossil resources, such as crude oil and natural gas, are still abundantly available. Therefore, developing a regulatory framework reflecting the environmental value of green PtX is key to ensure that these products can compete in the market.

For the purpose of illustrating this point: we, Frontier Economics (2018)[106], have estimated PtX costs generated from different RES across different countries from 2020 until 2050 (Figure 33). Although PtX costs are expected to come down significantly over the next 30 years, it is unlikely that they are able to undercut the costs of fossil fuels (even if taxes on fossil fuels based on today's level are taken into account). From an economic standpoint, therefore, the expectation that PtX markets will evolve over time without additional policies incorporating the climate policy value is flawed. Instead, facilitation of regulatory frameworks is required with a focus on the economics of PtX: the value achieving climate change targets have to be reflected in the product price.

[106] Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018).

Figure 33 Costs of imported synthetic liquid fuels vs. fossil fuels until 2050



Source: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), IEA (2016)

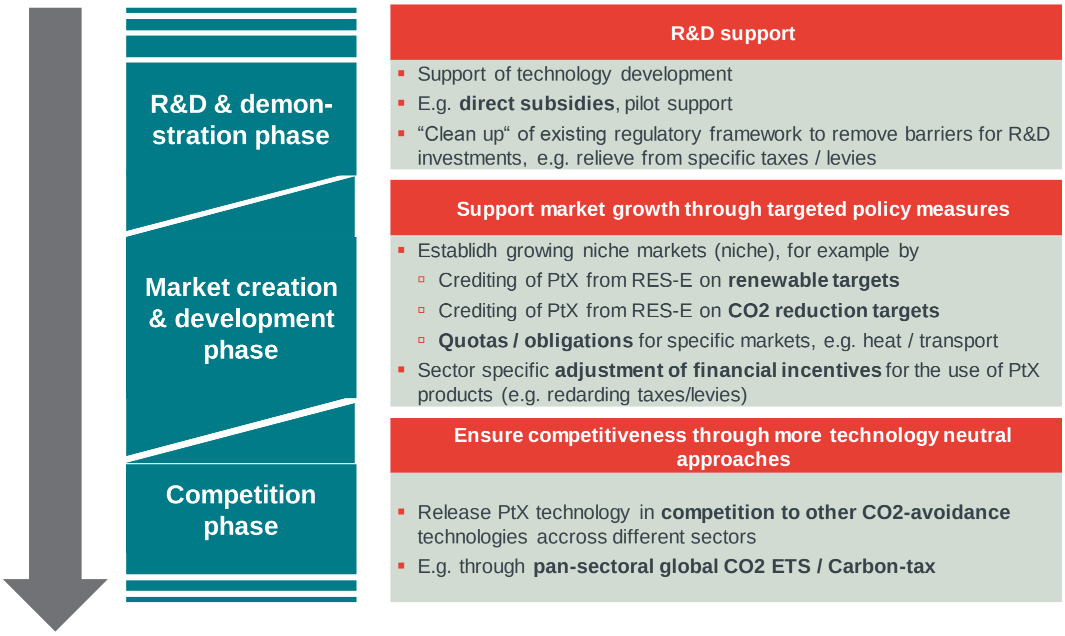
Note: Costs of generated synthetic liquid fuels (final energy, without taxes/levies)

4.2.2 Building up PtX markets requires political facilitation using a stepwise approach over time

As previously shown in Section 4.1, establishing a critical PtX market size through scaling up is crucial to achieve the cost savings and technological progresses that are required for the creation of a global PtX industry. If the size of the market remains small, the necessary PtX cost reductions will not be achieved.

In order to build up the critical market size for PtX to thrive, additional political action and facilitation is essential. The requirements for this political engagement develop over time and are directly dependant on the maturity of the industry. A potential pathway for transient policy measures might be designed as follows (Figure 34):

Figure 34 Potential path of transient policy measures



Source: Frontier Economics

Step 1 – R&D support to develop PtX technologies and demonstration

In a first step, R&D is required to develop PtX technologies (see Section 4.1.2), such as large scale electrolysers to produce hydrogen and second-stage conversion technologies to transform the hydrogen to synthetic liquid fuels or synthetic methane (if required). To demonstrate that international PtX trade can be practical and viable, larger scale integrated PtX pilot projects (including renewable energies) could be launched in countries outside of Europe with the aim to deliver synthetic fuels to Europe.

Political support during this phase is typically organised as direct subsidies for R&D and demonstration projects. Apart from developing the basic technological skills, larger pilot projects and plants are a crucial first step towards scaling up technological capacities and creating the stage for an international market.

In most countries where PtX is relevant, the PtX industry is currently undergoing this first phase: current PtX projects receive direct subsidies from public institutions and governments to cover their costs. Beyond this, some of the additional value that comes from the product being green is captured by product marketing to engage energy customers, however, the financial value derived from these marketing activities is expected to be limited to niche markets and is largely unclear.

In Germany, current pilot and demonstration projects for PtX indicate that the historically grown regulatory framework for the energy sector needs adjustment to allow for investments. In economic terms, costs for producing PtX will only be reasonable if input factors such as electricity are available at reasonable costs. However, power consumption is subject to electricity taxes as well as levies, e.g. to finance subsidies for RES-E, combined heat and power plants and other expenditures. For example, in Germany, operators of PtX plants producing hydrogen are subject to the full payment of the RES-E levy which incorporates historic costs of RES-E subsidies. Furthermore, electricity taxes were historically introduced in Germany in order to reduce electricity consumption of final customers. This reasoning does not hold for the production of PtX. Since the electricity costs are key for the economics of PtX plants (i.e. for producing the hydrogen), the current system of energy taxes and levies has to be revised to reflect the requirements of using electricity for PtX production.

Step 2 – Market creation and development phase

The scaling up of the PtX market has to be driven by creating demand and markets for the products: market driven investments need reliable demand in the short, medium and long term. For this to happen (as previously described), the additional value of green PtX has to be monetised: financial or regulatory incentives are required so customers are prepared to pay a premium on green PtX products. That means, the contribution of PtX products to lowering GHG emissions has to be expressed in monetary terms in order to finance the investments in PtX facilities.

In practice, the demand for PtX can be created and advanced in a first step by creating regulatory measures and financial incentives in specific sectors. The adjustment of the sector specific regulations with quotas and obligations can be complemented – and in later stage (see next step) replaced – by direct financial incentives to use green fuels. The aim is to develop a pathway towards a level playing field of fossil and non-fossil fuels reflecting the contribution of green fuels for achieving the climate policy targets. As an example, sector specific energy taxes/levies on the customer side could differentiate between fossil fuels and non-fossil fuels reflecting the value of green fuels for climate policy.[107]

In the following, we will focus on the first step of creating various options for integrating PtX in current climate policy regulations. In this market creation and development phase, synthetic fuels from RES-E will consistently be integrated into existing and planned climate change policy regulations in the different sectors. In this case, the value of carbon-neutral PtX products are traded on separate markets at a price premium expressing the environmental value of the product being green. The following instruments are examples to consider for implementation.

Quotas/obligations for renewable energies in the transport sector

In many countries, certain energy consumers or sectors are obliged to use a specific share of energy consumption from RES. These obligations follow the commitment of governments to fulfil targets for the usage of renewable energies.

In this context, the procurement and usage of green PtX can be integrated into the regulatory framework by crediting the fuels against the RES obligations and targets. Quotas should be as technology-neutral as possible and should also take other options into account.

[107] It has to be noted that energy taxes can have substantial negative impact on the international competitiveness of industries if implemented unilaterally. Furthermore, energy taxes can have significant impact on poor energy consumers raising social concerns. Therefore, the adjustment of energy taxes has to be embedded into other policy fields such as international agreements and social policy.

As an example, in the transport sector a quota for PtX from renewable energy sources could be introduced in analogy to the quota for biofuels, or the quota for biofuels could be extended to synthetic liquid fuels, as it is currently planned by the EU. The recent revision of the Renewable Energy Directive of the EU (RED II) points into that direction (see box below).

RECENT REVISION OF RED II CREATES FIRST MARKET FOR PTX

The Second Renewable Energy Directive (RED II) was widely discussed for years between the EC, the Parliament and the European Council. The negotiations finally ended in June 2018. The results need to be implemented in a Draft Directive which requires formal approval from the Parliament and the European Council. Most likely, this process will be finalised in Autumn 2018. Afterwards, the member states have to implement the Directive into national law within 18 months.

The trialogue of the EU resulted in new targets for renewable energies:

- The general target is set at 32% share of gross final energy consumption from renewable sources by 2030 (target is subject to revision in 2023); and
- The target for the transport sector is 14% share of final energy consumption from renewable sources by 2030, thereof max. 7% of conventional biofuels, min. 3.5% “advanced biofuels”.

Both biofuels and PtX products are accepted as options to fulfil the quota: RFNBO (renewable liquid and gaseous transport fuels of non-biological origin) are allowed to fulfil renewable targets, even as intermediate products (i.e. freeing the way of substituting fossil H_2 in refineries). However, some biofuels are limited in capacity as future restrictions apply:

- First generation biofuels (e.g. ethanol) will be frozen to 2020 level (up to a max. of 7%); and
- Palm oil will be frozen at actual import levels and will be reduced each year with a total phase out until 2030 (Note: officially there is no ban of palm oil due to international trade regulations, but palm oil will no longer be approved for renewable targets).

However, the recognition of renewables as credits in obligation systems in specific sectors should create a level-playing field for different technologies. For example, in the RED II Directive different types of renewable energies are multiplied with different factors for crediting against the obligation. While, for example, the usage of renewable power is credited with a factor of four in the road sector, 1.5 in the train sector and 1.2 in the maritime and aviation sectors, green PtX is currently only credited with a factor of 1.

This particular regulation is therefore unlikely to facilitate the development and establishment of a PtX market and further regulatory measure are called for.

Quotas/obligations for renewable energies in the heating sector:

In a number of countries, quotas/obligations to use renewable energies in the heating sector (for example for private homes) are in place. Green PtX should be integrated in these regulations on equal footing with other renewable technologies as an option to fulfil the respective quotas/obligations.

As an example, the German law for the support or renewable energies in the heating sector (EEWärmeG) could be revised in a way that PtX products are assessed as a technology option to fulfil RES obligations for heating in buildings (see box below).

RENEWABLE QUOTAS FOR ENERGY USE IN HEATING IN GERMAN LAWS

The German law for the support or renewable energies in the heating sector (EEWärmeG) obliges owners of new buildings to use in parts renewable energies for heating. The law, which is addressed to private owners as well as public builder -owners, defines minimum quotas for the usage of renewable energies. The constructors can choose from a variety of different renewable energy options. The minimum share of renewable energies for the heating depends on the renewable energy sources used. For example, the shares are the following for

- solar heating: min. 15%;
- biogas: min. 30%;
- liquid or solid biomass: min. 50%; and
- geothermal and heat from the environment (e.g. heat pumps): min. 50%.

There are also quotas in place in case of comprehensive renovations of existing public buildings. In this case the share of RES required for heating amounts to at least 15% - except for biogas (25%).

Biogas is only accepted if the gas is used in combined-heat-and-power systems (CHP).

PtX could be integrated into the quota system in order to create demand. However, due to costs, regulatory restrictions regarding appliances such as the mandatory installation of micro CHP can easily hinder PtX to enter the market even if it is part of the quota system. For example, this the case with the current quota for biogas which is not used in practice due to costs of micro CHP. The choice of end-user technologies should be left to the customers.

Crediting of green PtX against CO_2 reduction targets/obligations:

certain industries or sectors are subject to obligations to reduce absolute or specific greenhouse gas emissions (e.g. the automotive industry in Europe or in California). In this context, the procurement and usage of green PtX could be credited as fulfilling the obligations and targets regarding CO_2 reductions (under the assumption that synthetic fuels are produced on the basis of RES-E). This can hold for the obligations and targets of individual specific sectors and industries as well as for the whole of countries.

For example, in

- the automotive sector, PtX could be accepted as a measure to fulfil targets for average CO_2 emission of the new cars fleet of car manufacturers (see first box below); and
- aviation, a global quota for PtX could be integrated into the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in the medium and long term (see second box below).

PTX AS AN OPTION TO FULFIL CO_2 EMISSION TARGETS OF CAR FLEETS

Directive 2009/33/EC defines targets for the average CO_2 emissions for new fleets of the car manufacturers (OEM). Until 2020 the emission target is 130 g(CO_2)/km, from 2021 onwards the regulation becomes stricter:

- The emission target is reduced to 95 g(CO_2)/km;
- with a penalty of 95 €/g(CO_2) in excess of the target.

The targets have to be achieved by car specific technology improvements (for example more efficient combustion engines) or by modifications regarding the composition of the new car fleet (for example e-cars, smaller sized cars).

In the directive, the use of green fuels is not included as an option to reduce average emissions of the car fleet. However, the willingness to pay for green fuels of OEMs can be substantial. The penalties for OEMs can easily amount to 600€/t(CO_2) as the following example illustrates:

- A car fleet emits 28 g(CO_2)/km more than the target allows, assuming the average CO_2 emission of a VW Golf, 123 g(CO_2)/km.
- The OEM has to pay 2,660 € for each car in that fleet, namely 28 g(CO_2)/km * 95 €/g(CO_2).
- Over the lifetime of the car - assuming 150,000 km - it emits 4 t(CO_2) in excess to the target.
- Dividing the penalties for the excess emissions of the the car (2,660 €) by the emissions (the 4 t(CO_2)), the costs amount to more than 600 €/t(CO_2). (for comparison, the EU-ETS price is 22 €/t(CO_2).

Because of the high penalties, the OEMs have a high willingness to pay for CO_2 avoiding technologies. Integrating green PtX fuels into the directive and crediting PtX against the target for the average fleet emissions would create an important opportunity to scale up the market for PtX products. Furthermore, integrating PtX into the regulations for OMEs would create a level playing field with other CO_2 abatement options for cars (such as costly technological fine tuning of engines).[108]

[108] In this section, we explain various options to integrated PtX into sector specific climate policy regulations. However, if PtX is integrated into various regulations it has to be ensured that double counting of credits against targets is avoided or taken into account when defining the quotas.

MEDIUM TERM: POTENTIAL QUOTA FOR SYNTHETIC LIQUID FUELS IN AVIATION WITHIN CORSIA

In 2016, the member states of the International Civil Aviation Organisation (ICAO) agreed on a global climate protection instrument for international aviation in form of the offsetting system CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation). CORSIA is a global market-based climate change instrument for international aviation and is the world's first sector-wide carbon-offsetting program.

Together with other mitigation measures – operational improvements, aircraft technology and use of sustainable aviation – CORSIA aims to achieve the sectors' goal of carbon-neutral growth. From 2020 onwards, growth-related CO_2 emissions in air traffic will be compensated by specific climate protection projects, e.g. replacing fossil fuels with renewable energy sources. These offsetting projects are under the supervision of the UN.

CORSIA was designed to incorporate a phased-in implementation:

- States' participation in the pilot and first phase from 2021 to 2026 is voluntary.
- In the second phase from 2027, all countries with an individual share of international aviation activities above 0.5% of the total, or whose cumulative share reaches 90% of the total, are required to participate (with exemptions for least developed countries, small island states and landlocked developing countries).

To ensure that operators, states and ICAO are able to implement scheme starting 2021, ICAO is currently developing rules and procedures for monitoring, reporting and verifying a criteria system for emissions units to be purchased by aircraft operators and registries.

CORSIA already enables airlines to offset CO_2 savings by using alternative fuels against the amount of CO_2 to be compensated. Due to the much higher prices of alternative fuels, however, they will not be used to any significant extent in the foreseeable future.

In the medium term, the climate protection instrument CORSIA could be used to introduce a quota for alternative fuels and thus create a corresponding market in aviation. Additional costs would then have to be borne equally by all airlines worldwide and distortions of competition could be avoided as far as possible.

Step 3 – Competition phase

The sector specific regulations based on quotas/obligations described above allow for scaling of PtX technologies in specific (niche) markets in the short and medium term. However, these regulations are relatively focussed and require ongoing administrative adjustments and further developments. Even if administration aims at integrating new technologies and options into the regulations, the scope of technologies will remain limited. Furthermore, in practice, regulations turn out not to be technology-neutral due to the differentiation of quotas/obligations for different technologies. Finally, the regulations do not allow for cost optimisation across sectors which increases the costs of climate policies further and is inefficient in economic terms. Therefore, regulations as outlined above are short and medium term policy measures to create PtX markets based on the current approach of sector specific regulation.

However, in the long term, climate policy should focus on cost efficiency and benefits from a more general climate policy framework as outlined in the following section. In an ideal world, different CO_2-abatement technologies, including green PtX, should compete with each other across industries and sectors on a level playing field – at best on a global scale or at least between industrialised countries. One way to achieve this is to define a global common price for CO_2 emissions across all sectors, technologies and industries. Another option would be to implement a global GHG trading system for all technologies and sectors. As a result, all available technologies compete with each other to avoid the costs of CO_2 emissions.

Although a regulatory system that creates a level playing field for all technologies across all sectors on a global scale seems far-fetched from today's perspective, the concept can serve as a logical benchmark for evaluating technology or sector specific regulations in climate change policy.

4.2.3 What could be done?

Building up PtX markets through political facilitation and adjusted regulatory frameworks is crucial for the successful development of a global PtX industry. In this context, it is essential that the green environmental value of PtX is reflected in the remuneration of PtX producers and in PtX product prices.

Sufficiently large scale markets for PtX will only evolve if

- climate change policy is sufficiently stringent and green technologies are remunerated accordingly; and
- PtX products can compete in these markets on a level playing field.

In order to support the establishment of PtX markets, the following political steps should be undertaken:

- In the short term, **support for R&D and pilot projects**: The current support for R&D and pilot projects for PtX technologies should be continued. For example, the benefits of larger scale PtX projects should be demonstrated. The first plants that offer large scale generation for synthetic liquid fuels will require much greater funding than subsequent plants. Therefore a regulatory financial framework must be developed. Another short term option would be to permit synthetic liquid fuels offsetting for the emission thresholds for fleets.
- Furthermore, the **regulations of energy markets** have to be adapted in a way that R&D and investments in PtX plants can take place: For example, PtX products could be exempted from energy taxes and levies in a way that PtX technologies are not in a position of disadvantage and become economically competitive in their long term applications.
- In the medium term, **support of market growth through targeted policy measures for creating markets in specific sectors and segments,** e.g. by crediting PtX against RES-E and CO_2-abatement targets/obligations**:** green PtX should be an element of RES-E policy on an equal footing. That implies that the contribution of certified carbon-neutral PtX should be reflected when calculating the achievements regarding RES-E targets and CO_2-abatement. In

this context, the trust in PtX from renewable energy sources could be strengthened by a system of green certification.

- In the long term, **level playing field for CO_2-abatement technologies including green PtX on a global scale:** green PtX should compete with other CO_2-abatement technologies on equal terms in the long term. This could be implemented e.g. by a global uniform CO_2 pricing across sectors, technologies and energy sources, or by a global GHG emissions trading system across all sectors and technologies.

4.2.4 International roadmap for establishing PtX markets and demand

Enabling the development of market and demand structures is one of the key pillars to build a functioning and thriving PtX industry. To provide guidance on the potential next steps and milestones, we develop an international roadmap for facilitating PtX markets and demand (Figure 35).[109]

This international roadmap is characterised by

- The principle push to integrate green PtX in energy markets and demand;
- Capturing the monetary value of PtX as a green fuel; and
- Growing PtX from niche markets into a level playing field with other CO_2-abatement technologies.

The timing of the milestones is indicative.

Principle push to integrate green PtX in energy markets and demand

The principle push to integrate PtX in energy markets and demand is driven by climate change policy and the benefits of synthetic fuels from renewables (as outlined in Section 2 of the report). Increasing barriers to grow domestic renewable energies because of integration costs and lack of acceptance occur in the time before 2030. Furthermore, the storability and transportability of domestic PtX support renewable integration from the end of the 2020's. Around that time, PtX imports step in as cost efficient alternative to domestic renewable development. Large scale PtX imports to substitute fossil energy develop before 2040.

Capturing the monetary value of PtX as a green fuel

The monetary value of green PtX is captured by a stepwise approach.

- The foundation are direct and indirect subsidies for technology development and the removal of entry barriers for PtX as of today;
- Targeted policy measures support the PtX market growth from the early 2020s by integration of PtX into existing climate policy instruments in the different sectors. At that time, the automotive sector fulfils fleet targets via PtX blending

[109] It is important to note that this roadmap is illustrative and provides a first indication of the potential steps and milestones to achieve, but should not be interpreted as a forecast.

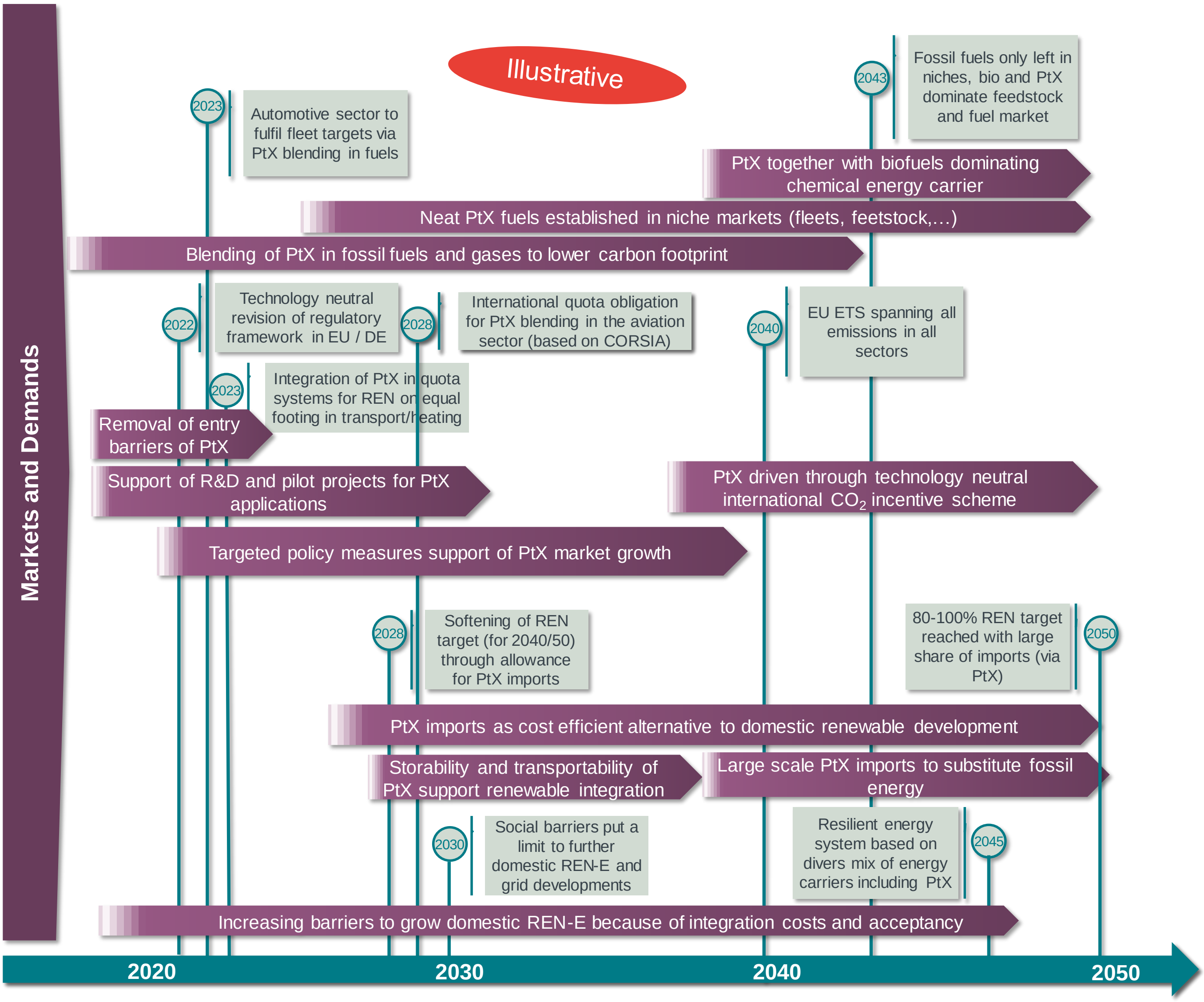
with fossil fuels, and PtX is integrated in quota systems for RES on equal footing in transport/heating.

- In the long term, e.g. from the mid 2030’s, the growth of PtX markets is driven by technology neutral international CO_2 incentive schemes and the creation of a level playing field for CO_2 abatement technologies, e.g. by introducing a (nearly) global carbon emission trading system in 2040.

Growing PtX from niche markets into a level playing field with other CO2-abatement technologies

The scaling up of demand for green PtX leads to the stepwise establishment of new infrastructures and increasing substitution of fossil fuels across a variety of sectors allowing for the required cost savings (see previous Section 4.1). PtX is established in niche markets from the early 2020’s (fleets, feedstock, etc.). From 2040, PtX could be together with biofuels the dominating chemical energy carrier, leading fossil fuels to niche markets from the mid 2040’s.

Figure 35 International roadmap pillar 'Markets and Demand': PtX markets have to be established to provide reliable demand structure



Source: Frontier Economics.

4.3 Pillar 'Investments and Supply': The establishment of a global PtX industry requires a favourable environment for investment and international cooperation

For the development of a PtX industry, huge investment in PtX plants and infrastructure in producing countries will be essential. This holds for domestic investors inside the countries, but even more for foreign investors which face additional risks compared to local investors (including currency risks and potentially weaker protection of investments). The participation of foreign investors will especially help if technology transfer from industrialised countries to potential PtX exporting countries is required. Furthermore, investments are extremely capital intense in the PtX industry. However, the availability of capital is limited in developing countries that are potential PtX exporters.

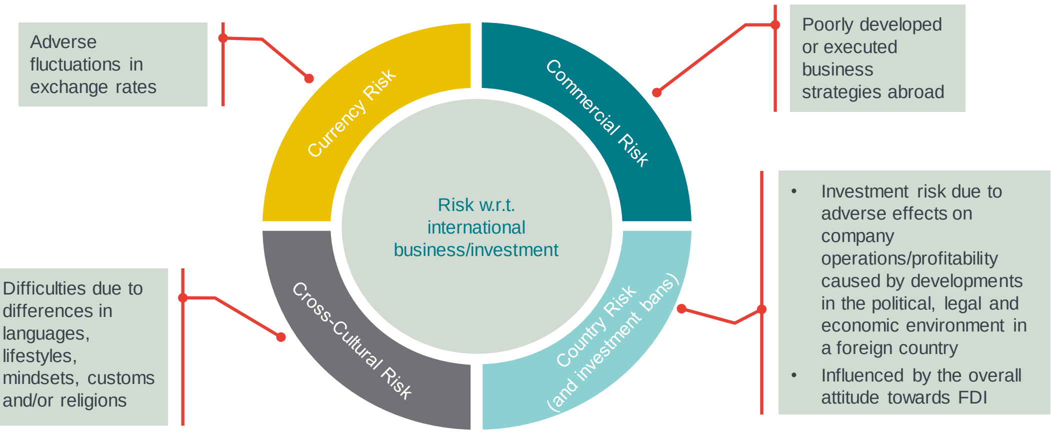
In the following, we discuss how international policy can help to mitigate risks for companies and support investments in third countries.

The key question to be discussed is how politics can help to mitigate the risks in order to make investments in PtX facilities happen. Therefore, the analyses will focus on those risks which can be mitigated by political measures. It has to be noted that international investors and companies have additional measures to reduce risks such as diversifying portfolios and hedging currency risks. These commercial risk mitigating strategies are not discussed here as they are core competencies of private companies. Furthermore, the following holds not only specific for investments in PtX facilities but all investments in the respective countries: in this respect, PtX does not differ from other industries.

4.3.1 Potential risks can be show stoppers for investments

For domestic as well as for international investors, it is crucial to define a reliable and favourable climate for investments. In this context, it is important to consider certain risks to investment that may vary greatly when investing across borders. These risks can be categorised into four main categories (Figure 36) which can be considered as potential barriers for investments, and therefore can become barriers for an adequate supply side for PtX trade.

Figure 36 General Risks for international investments



Source: *Frontier based on Cavusgil et al. (2015, p. 12 f.): International business – The new realities, Melbourne (Australia), Pearson, 2nd Edition.*

These risks include:[110]

- **Country risk**: Adverse effects on the firm's operations and profitability, which result from the legal, economic and social/political environment of the country (including e.g. investment bans).
- **Cross-cultural risk:** Adverse effects resulting from differences in languages, lifestyles, mindsets, customs and/or religions. The more similar the home country and the foreign country are, the smaller is the cross-culture risk. That means for example that for European investors doing business in countries of

[110] See for a more detailed explanation of the single risk categories e.g. Cavusgil et al. (2015, pp. 12 f.).

the “Western World” would lead to lower risk compared to doing business in countries with a different cultural background.

- **Currency risk:** Adverse fluctuations in exchange rates These fluctuations and therefore in sales are not as prevalent in developed countries.
- **Commercial risk:** A firm’s potential loss or failure due to poorly developed or executed business strategies. Commercial risk is of course also present within the home country, but the consequences can be more costly abroad, e.g. due to different regulations within a foreign country.

The focus of this section is on the first risk category **–** **country risk** **–** because

- the options to address cross-culture risks by political action is limited, and cultural risks are captured to some extent in the country risks which are discussed in the following. These include, for instance, the functioning of bureaucracy, the cultural attitude to protect contracts and potential cultural attitude towards corruption;
- currency risks are of less importance for investments in PtX plants and infrastructure since we assume that the PtX products are sold in industrialised countries/regions such as Europe with payment in US Dollar/ €/Yen; and
- commercial risks are commonly encountered in projects in the energy markets, and therefore energy companies (e.g. oil and gas companies, electricity suppliers) are used to deal with commercial risks.

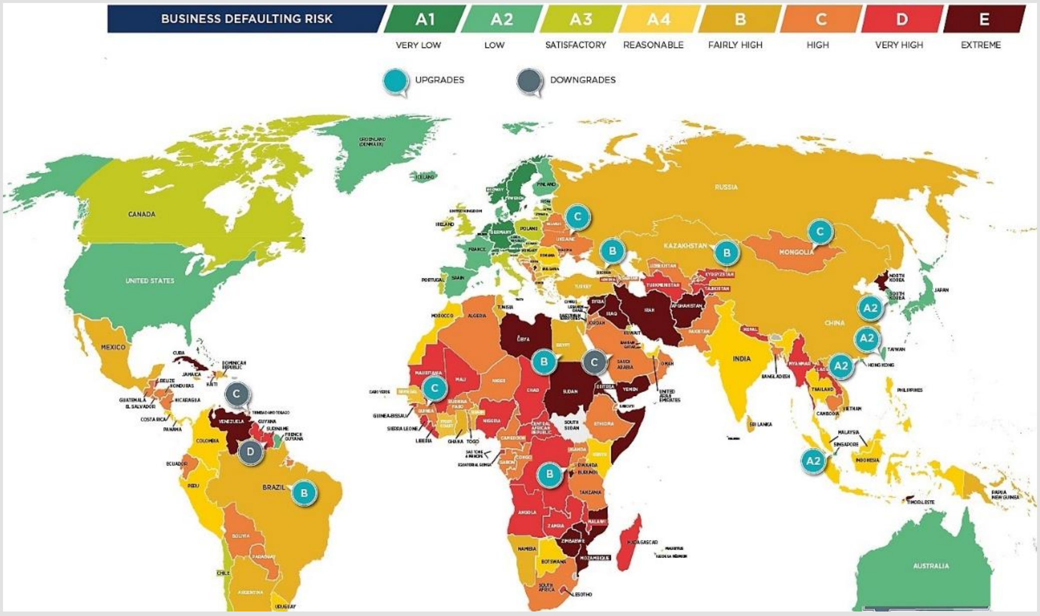
With regard to political engagement and facilitation of PtX trade, investment barriers caused by country risks are likely to have the largest impact and can be influenced by political facilitation. The most relevant categories for defining proper requirements for international investment with respect to country risks comprise

- risks regarding the legal framework;
- Industrial policies, business facilitation and corruption; and
- Social and political unrest and instability.

GENERAL ASSESSMENT OF COUNTRY RISKS - SELECTED COUNTRIES

Country risks are assessed by governments (e.g. Departments for Foreign Affairs) as well as business promotion corporations.[111] Furthermore, country credit ratings offered by different credit rating agencies provide an overall risk assessment of different countries.[112]

For the countries selected in Section 3, the country risk assessment undertaken, for example, by Coface rates the risks of Norway and Australia as very low/low. Chile's country risk is assessed to be satisfactory whereas China's and Saudi Arabia's country risks are rated as high. This reflects the assessment especially of the general business environment for foreign investments and the legal regimes.



Source: https://www.coface.com/News-Publications/Publications/Country-risk-assessment-map-January-2018.

Legal framework

For low risk for (European) investors, the legal regime need judicial independence and transparency of the legal environment, and grounding in the principles of procedural fairness. It also needs to use equal treatment before the law, which refers also to an equal treatment of national and foreign investors.

In addition, for foreign investors who own a certain technology, it is important that private property rights – including intellectual property rights – are respected and enforced.

[111] In this report, information was mainly collected from the Country Commercial Guides provided by the U.S. Department of Commerce's International Trade Administration, which are available at https://www.export.gov, last downloaded 22/08/2018, and the business promotion corporation of Germany Germany Trade and Invest.

[112] Furthermore, Coface – a French credit insurance company – provides a country risk assessment map, available at http://www.coface.com/News-Publications/Publications/Country-risk-assessment-map-January-2018, last downloaded 22/08/2018.

Finally, the application of independent arbitral courts' decisions is vital for foreign investors in countries with a legal regime, which does not fulfil the standards listed above.

Industrial policies and business facilitation

With regard to the industrial policies in place for facilitating business, aspects like bureaucracy (e.g. for opening a business), protectionism and the attitude towards foreign direct investments (FDI) play a role. A positive attitude towards FDI can for example be manifested through the existence of an agency supporting FDI or financial promotion of FDI.

Protectionism encompasses, inter alia

- prohibitions for foreign investors to invest in certain sectors,
- requirements to involve local partner, or
- limits for the amount of investment.

Specific regulations like hiring quotas for local employees and training requirements can hinder – at least in the beginning – the investment in countries with a low number of skilled employees.

A further main obstacle for foreign investments can be corruption in the respective countries. Corruption reduces the efficiency of administration and bureaucracy and endangers the reliability of the legal regime. Corruption can be one of the main obstacles of economic prosperity of development countries and emerging markets.

Social and political unrest and instability

Social and political unrest and instability refers to local wars and revolutions, which increase investment risk. There is a number of potential PtX exporting countries which face sever social and political unrest and instability such as Somalia, Nigeria and Libya.

Risks of social and political unrest and instability are very difficult to manage for companies / foreign investors. Furthermore, the options for foreign governments to help diminishing the economic and social effects of political instability are very limited. Therefore, severe political unrest and instability are insurmountable barriers for foreign investments, which forms a major hurdle for economic development and welfare of the respective countries.

4.3.2 International collaboration and cooperation as a measure to reduce political risks

As stated in the previous section, country risks can have a substantial negative impact on investments in PtX facilities and infrastructure in a number of countries with very favourable conditions and prospects for PtX production and exports.

International politics can aim at improving the investment climate for FDIs by policy initiatives, framework contracts and international agreements. The aim is that states participating in the agreements commit to a specific behaviour in relation to trade and/or the movement of capital and labour exchange which, among other things, reduces country risks for international trade and investments. The initiatives and agreements can be organised

- multilaterally, e.g. in the framework of the WTO, UN or IMF that means between groups of countries; or
- bilateral between countries.

Furthermore, the international cooperations can have very different binding characters from very informal declarations up to international legally binding treaties.

Multilateral cooperation in energy treaties

There are many general (non-energy specific) international declarations, agreements and treaties in place and under negotiation which have an impact on international trade and investments. Obviously general treaties such as the rulings of the World Trade Organisation (WTO) or multilateral treaties such as the Comprehensive Economic and Trade Agreement (CETA) between Canada and Europe (concluded in 2014) also have an impact on mitigating risks of investments in PtX facilities and infrastructure.

For the energy sector, there is a limited number of specific multilateral international treaties in force. Examples are:

- The **Energy Charter Treaty (see also info box below)**: **The Energy Charter Treaty was signed in December 1994 and entered into legal force in April 1998. Currently there are fifty-three signatories and contracting parties to the treaty including the European Union. The treaty is legally binding for its signatories.**
- The **International Energy Charter**: The International Energy Charter is a declaration of political intention aiming at strengthening energy cooperation between the signatory states. The International Energy Charter covers selected energy related topics **promoting energy cooperation among nations for the sake of energy security and sustainability. However, it is not legally binding.**
- The **Africa-EU Energy Partnership**: Established in 2007, the Africa-EU Energy Partnership (AEEP) is a long term framework for strategic dialogue between Africa and the EU aimed at sharing knowledge, setting political priorities and developing joint programmes on the key energy issues and challenges in the 21st century. The overall objective of the AEEP is to improve access to secure, affordable and sustainable energy for both continents, with a special focus on increasing investment in energy infrastructure in Africa. The AEEP is perceived as a long term framework for structured green between the two continents on energy issues of mutual strategic importance, allowing Africa and Europe to develop a shared vision, common policy approaches and actions.

THE ENERGY CHARTER TREATY FROM 1994

The Energy Charter Treaty provides a multilateral framework for energy cooperation which is designed to promote energy security through the operation of more open and competitive energy markets, while respecting the principles of sustainable development and sovereignty over energy resources.

The Energy Charter Treaty was signed in December 1994 and entered into legal force in April 1998. Currently there are fifty-three Signatories and Contracting Parties to the Treaty.

The Treaty's provisions focus on four broad areas:

- the protection of foreign investments, based on the extension of national treatment, or most-favoured nation treatment (whichever is more favourable) and protection against key non-commercial risks;
- non-discriminatory conditions for trade in energy materials, products and energy-related equipment based on WTO rules, and provisions to ensure reliable cross-border energy transit flows through pipelines, grids and other means of transportation;
- the resolution of disputes between participating states, and – in the case of investments – between investors and host states;
- the promotion of energy efficiency and attempts to minimise the environmental impact of energy production and use.

The signatory countries include the European Union, Australia and Norway. However, neither Norway nor Australia ratified the treaty. China, Morocco, Chile and Saudi Arabia did not sign the treaty.

Multilateral cooperation in climate change agreements and renewable policies

In order to secure a reliable long term investment framework, PtX should be part of the international climate change policy agenda, e.g. within the UNFCCC and the future agreements. Following the Paris Agreement, a "rule book" for concrete implementation measures for GHG emission reductions are envisaged[113] – in case of consideration of single technologies, PtX could be included. Imports of carbon-neutral PtX should be regarded as flexibility mechanisms to achieve national and regional CO_2 emission reduction targets as it is currently the case for imported biofuels and biomass or for projects under the Clean Development Mechanism[114].

Furthermore, international initiatives for innovations as well as renewable energy organisation could examine PtX in more detail in their reports. For example, the IRENA report on "Accelerating the Energy Transition through Innovation" is focussed on the direct use of renewable energies and electrification of end-uses in a number of sectors. In other sectors the focus is on hydrogen and low carbon ammonium from hydrogen – assuming that the hydrogen is generated from natural gas with CO_2 capturing and storage. The expected innovations from PtX are not

[113] Bundeszentrale für politische Bildung (2018), available at http://www.bpb.de/apuz/269300/internationale-klimapolitik-2018-von-paris-ueber-bonn-nach-katowice?p=all.

[114] The Clean Development Mechanism was introduced by the Kyoto Protocol. Parties of the UNFCCC can finance sustainable development projects which reduce GHG emissions in developing countries, but emission reductions are credited to the country.

assessed in greater detail in the report. This example confirms that the perception of PtX as a renewable energy option can be improved on a global scale. As a consequence, international organisations such as IRENA and initiatives for innovation should examine and support PtX projects more widely. The UN and national governments may politically push these organisations to take PtX into account as an alternative option.

Bilateral cooperations in the energy sector

Besides these multilateral international energy agreements, the European Union and EU member states (e.g. Germany) aim to form bilateral cooperations with specific countries with regard to energy topics.

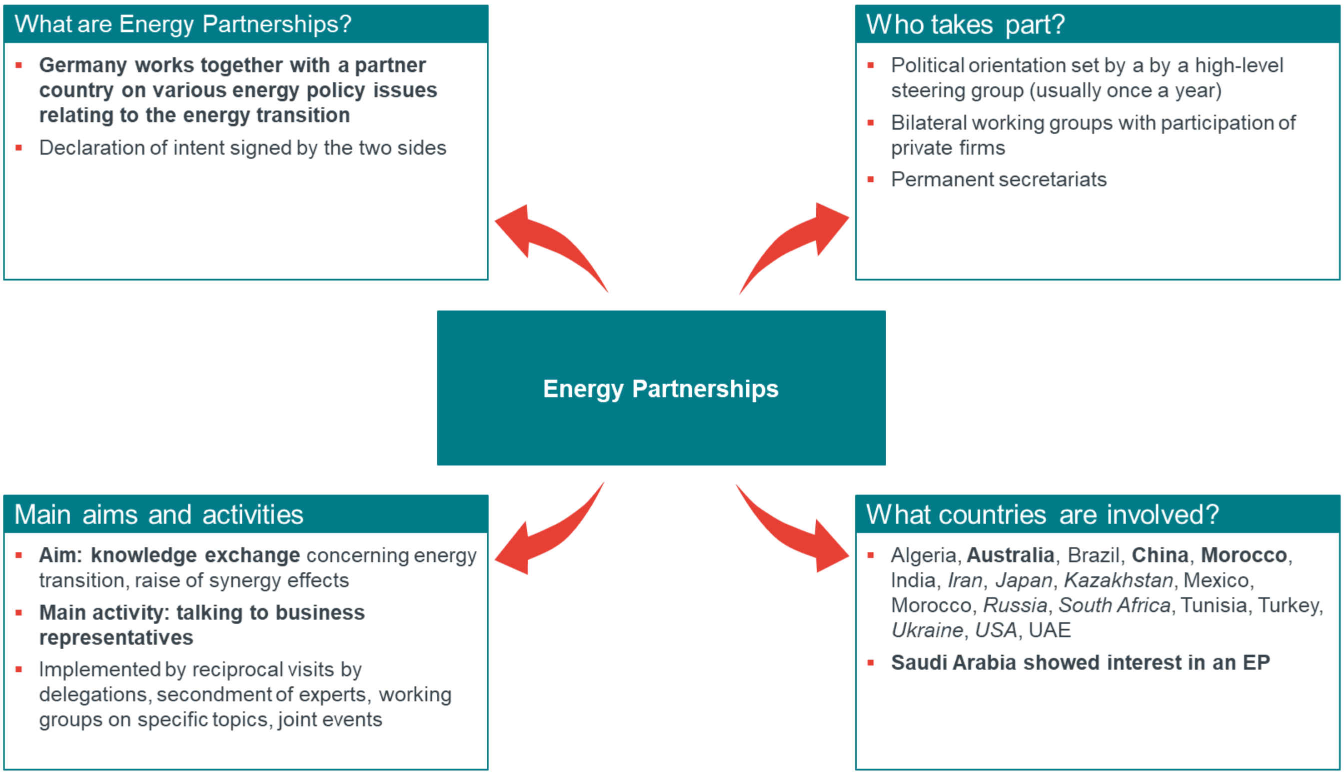
For example, energy partnerships between the German government and individual countries demonstrate this type of cooperation (Figure 37).[115] In an energy partnership, Germany and a partner country are working together on various energy related policy issues. The main aim of an energy partnership is to support the expansion of renewable energy and the wider use of efficient energy technologies. This is not only important for mitigating climate change, but also for securing the long term energy security. This aim shall be achieved by a constant exchange between the countries, whereby the main topics of exchange are set by a high-level steering-group. The exchange takes various forms, such as reciprocal visits by delegations, secondments of exports, working groups on specific topics or joint events.

German Energy partnerships (and dialogues)[116] currently exist with Algeria, **Australia,** Brazil, **China**, India, Iran, Japan, Kazakhstan, Mexico, **Morocco**, Norway, Russia, South Africa, South Korea, Tunisia, Turkey, Ukraine, USA and the UAE.

[115] In addition to the energy partnerships, energy dialogues exist, which pursue the same goals, but are less formal. See for further information on energy partnerships and energy dialogues the homepage of the Federal Ministry for Economic Affairs and Energy, available at https://www.bmwi.de/Redaktion/EN/Textsammlungen/Energy/internationale-energiepolitik.html, last downloaded 23/08/2018, and Federal Ministry for Economic Affairs and Energy (2017).

[116] Energy dialogues are less formal collaborations compared to energy partnerships.

Figure 37 Energy partnerships can help to overcome investment barriers



Source: *Frontier Economics*

Note: *Countries written in italic are countries with energy dialogues.*

STRENGTHENING OF INTERNATIONAL GREEN VIA ENERGY PARTNERSHIPS: THE EXAMPLE OF MOROCCO

Morocco has ambitious targets for the expansion of renewable energies. Topics such as the integration of renewable energies in the electricity grid, the expansion/exchange of electricity grids with neighbouring countries and the opening of the renewable energy market to the private investor are being examined.

The German energy partnership supports Morocco, for instance by providing advice on the development of long term energy scenarios and the establishment of a think tank. In addition, various topics were discussed at the German-Moroccan Energy Day in Rabat in 2017 with more than 400 Moroccan and German experts from politics, business and science.

Energy partnerships were typically relatively informal and dealt with specific topics and initiatives, such as renewable energies. They can be useful to kick-off specific political projects and improve the information exchange on energy related topics between the countries involved. However, they don't include legally binding provisions to enforce a stable legal framework for international investments in the energy sector – they do not replace legally binding treaties for trade and investments.

4.3.3 Financial instruments to mitigate the impact of country risks for investors

As long as country risks are persistent for international investors, these risks can have a substantial negative impact on the economics on investments in PtX facilities and infrastructure: Investors will reflect the economic costs of the risks in the business plan for PtX installations, e.g. by increasing the hurdle rate for the expected rate-of-return to be achieved by the investment. Therefore, these risks can block even relatively prospective investments in countries facing substantial specific country risks.

In order to reduce the economic impact of the country risks described above and to promote international investment, states can implement supporting instruments for financing international projects. In Germany, for example, the following measures are in place to mitigate country risks for German investors.

- **Investment guarantees**[117] provide an insurance against (long term) political risks and a support for damage prevention. Requirements to be fulfilled for receiving an investment guarantee are amongst others that the requesting firm is based in Germany and the investment is new or at least capital widening. Furthermore, the investment must have a positive effect on Germany and the country of investment, e.g. the use of environmentally-friendly technologies, and legal protection needs to be provided (see third bullet point).
- **Guarantees for untied financial loans (UFL)**[118] are part of the raw material strategy of the German government and aim at increasing the security of supply of Germany. The UFL guarantee protects creditors, who finance raw material projects abroad, against default risk. Requirements for receiving an UFL guarantee are the conclusion of a long term contract for raw materials with a German customer/purchaser, an acceptable project risk and a technically and commercially matured project.
- Further instruments, which could potentially be relevant for PtX investments are **export credit guarantees**[119] (also called "Hermes insurances"), which provide an insurance for the claims of German exporters to their payments abroad. This insurance against economic and political risk should especially be used for the case of absence of a private insurance market. "Hermes insurances" might

[117] For more information see https://www.investitionsgarantien.de, last downloaded 26/06/2018.

[118] For more information see https://agaportal.de/ufk-garantien/, last downloaded 26/06/2018.

[119] For more information see https://www.bmwi.de/Redaktion/DE/Textsammlungen/Aussenwirtschaft/finanzierung-und-absicherung-von-auslandsgeschaeften.html, last downloaded 22/08/2018.

come into effect e.g. for the export of electrolysers from Germany to third countries.

- Finally, **financial support of special banks** like AKA-Bank, KfW-IPEX, DEG and EIB as well as **bilateral investment promotion and protection contracts** exist. The latter provide usually the required legal protection for investment guarantees.

Direct financial support from the German government is difficult to achieve for investors since a number of conditions have to be met in order to receive the support. Currently, there is no large scale financial support from public institutions to build-up a PtX industry in third countries to export of green synthetic fuels to Europe.

4.3.4 Policy can support global PtX markets by establishing a sustainability assessment and green certificate system

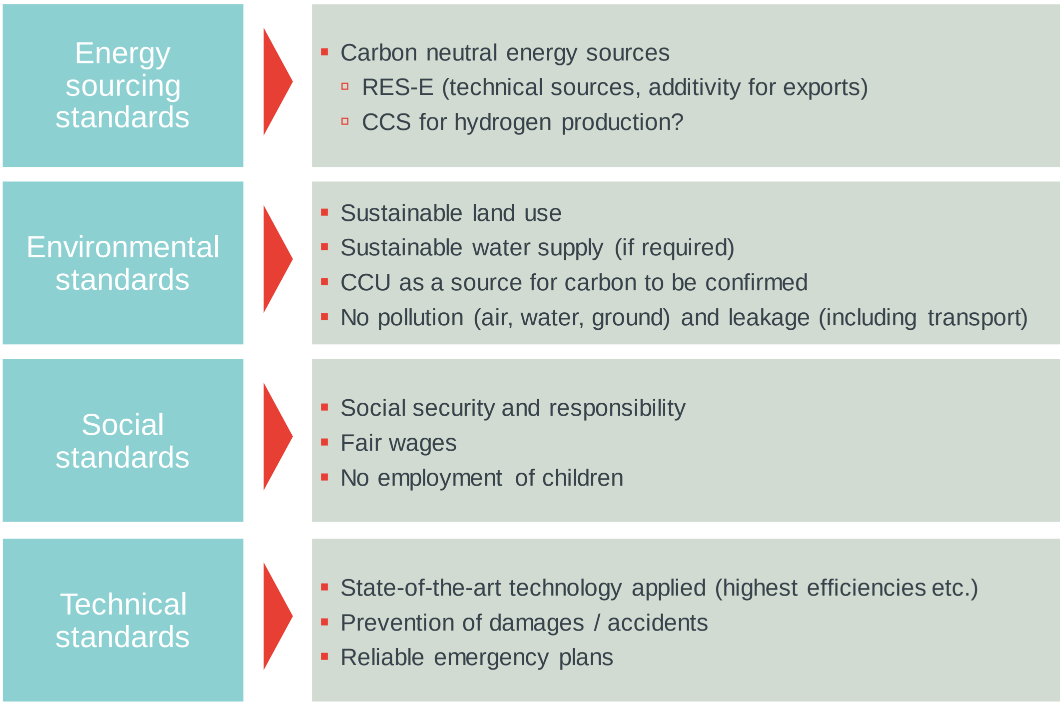
In order to ensure the acceptance of PtX products in an international market, producers and suppliers must ensure that certain standards for producing and distributing synthetic fuels and gases are previously agreed upon and consequently complied by. These pre-defined standards aim to ensure the acceptance of PtX imports in the consumer countries – a crucial element to ensure that international trades may evolve and blossom.

Binding sustainability regulation would ensure that PtX benefits the climate and encourages long term planning. Market incentives for synthetic fuels only make sense for climate policy if they are tied to mandatory sustainability regulations. This is a lesson learned from experience with biofuels from food crops in the EU. At first, quotas increased demand and made massive increases in production capacity possible. A critical analysis of indirect land use changes on greenhouse gas levels of biodiesel and bioethanol found that the benefit of these fuels on the environment was much less than initially supposed.[120]

The following sustainability criteria are of considerable importance in this regard (but are not limited to this snapshot): energy sourcing, environmental concerns, social aspects and technical standards (Figure 38).

[120] [●Quelle ergänzen]

Figure 38 Snapshot of sustainability criteria and standards to facilitate



Source: Frontier Economics

Standards for carbon neutral energy sourcing and RES additionality prerequisite to producing PtX

To make a valuable contribution to Germany/EU and its ambitious climate protection goals, electricity based synthetic fuels must meet crucial sustainability criteria:

- **Electricity input from RES:** The main input to producing PtX is electricity which need to be generated from renewable sources, such as wind power or PV. The production of PtX therefore may require the facilitation of further installation of renewable energy sources in the supplier countries.
- **RES additionality**: RES additionality should be considered to prevent the displacement of local renewable electricity generation. The concept of additionality considers whether renewable power generation in the countries of origin occurs in addition to or displaces other renewable power generation. One challenge in analysing the additionality of electricity generated from renewable sources lies in defining the reference base relative to which the generation is supplemental. In this regard, one could adopt the criterion that renewable electricity generated for the purpose of producing synthetic fuels for export must occur on a supplemental basis to renewable electricity generation,
  - that would in any case be generated on the basis of purely economic criteria in the production country;
  - that is required to satisfy the renewable energy targets in the production countries; and/or
  - that is required to cover the entire electricity (or even energy) demand of the production country.

- **Closed CO_2 cycle**: To produce green synthetic fuels using a carbon component (second-stage conversion to synthetic methane or liquid fuels), a closed CO_2 cycle has to be ensured.[121] The final use of synthetic methane or liquid fuels produces CO_2 emissions. However, CO_2 as a key input to the second-stage conversion processes should be carbon-neutral (e.g. via air capture, from biomass or biogas, or from unavoidable industry emissions). Furthermore, as long as industrial processes do not have to be fully de-fossilised, CO_2 from industry's emissions can be accepted as carbon source for synthetises as long as there is no impact on the amount of fossil fuels used in combustion. Evidence of a closed carbon dioxide cycle is comparably simple to provide - for example by comparing the CO_2 quantity captured from the air with the CO_2 quantity used in the conversion processes.

Finally, it has to be decided whether PtX production from fossil fuels with steam reforming with Carbon Capture and Storage (CCS) (blue hydrogen produced from fossil fuels with CCS) can be considered as a green fuel.[122] For example, the UK is currently investigating a hydrogen economy which is based on producing the hydrogen via steam reforming. Whereas steam reforming and CCS seem not to be acceptable across countries like Germany, this may not hold for other countries following different pathways towards a carbon-neutral economy.

Facilitating environmental standards enhance the acceptance of PtX production and trade – for supplier countries but also for consumers

Similar to the preceding discussion around RES additionality, facilitating certain environmental standards for producing PtX enhances acceptance of the product and thus fosters the development of international markets. When PtX is sourced sustainably, the perception of PtX as a means for a greener future may be positively shaped – for the local population in production countries, but also for consumers worldwide, and especially in Germany and the EU.

- **Sustainable use of space**: Another sustainability criterion relates to competition between various land uses. Competition with the use of land for food production and with forested areas are of particular importance in this regard. Renewable power facilities, synthetic fuel production plants and, if necessary, plants for obtaining water and CO_2 – all require space. Each local and regional situation has to be examined individually to determine how the required space for synthetic fuel production has been used to date, and which uses could potentially be displaced. Desert areas may be of particular interest.
- **Existing water supply must not be used in dry climate zones**: In dry climate zones such as North Africa and the Middle East, it must be ensured that the water required for the electrolysis is sourced from seawater desalination plants and not from the existing water supply.

121 Hydrogen generates no CO2 emissions upon combustion.

122 Technically, natural gas can also be split into hydrogen and black carbon by methane cracking. The process is still under development, however, if methane cracking turns out to be economical viable, the black carbon can be stored at a large scale or used in industrial processes.

Sustainable economic development in production countries and compliance with ethical standards may be minimal requirements

Some cases may require that CO_2 reduction measures in foreign countries are implemented in a manner that encourages sustainable economic development. Criteria for sustainable development could include the requirement to make additional investment, reduce poverty levels, and/or transfer new technologies. A study conducted as part of the Desert Power 2050 project, which aims to cover a considerable share of energy demand in Europe, North Africa and the Middle East with renewables by 2050, determined that successful economic development depends heavily on political and regulatory factors. Model-based calculations indicate positive growth in real incomes when international climate policy is implemented that internalises the negative consequences of CO_2 emissions.

Export countries could therefore benefit economically in the long term from investment in renewable energy and the infrastructure needed for exporting synthetic fuels. The extent to which export countries can create the political and economic conditions necessary for this long term domestic value creation still needs to be investigated.

Technical standards

To ensure public acceptance of PtX products produced in foreign countries, certain technical standards need to be met.

These technical standards include

- The deployment of state-of-the-art technology (highest efficiencies) – since PtX technologies are by themselves innovations on large scale, this criterion should be met in any case;
- The prevention of damages, accidents, leakages – this includes for example the minimisation of losses when transporting PtX; and
- The classification of reliable emergency plans in case of accidents.

A green certificate trading system could raise trust and market efficiency

It is essential that suppliers can provide proof that the energy supplied was sustainably sourced – that the synthetic fuels are in fact green. This is a crucial element of a functioning green energy market, as once in the infrastructure, renewable energy is physically difficult to separate from the conventionally generated energy.

In reality, these systems may will undergo quite a lengthy development process – from direct stakeholder involvement and industry attempts on a rather minimal scale to a full-fledged regulated system, possibly across border.

A system of green certificates can develop in a number of steps (Figure 39):

- In a first step, green PtX products can be traded on a bilateral basis with ensuring the characteristics of the product by bilateral agreements between producers and distributors. Those bilateral arrangements emerge e.g. when green PtX from R&D and pilot plants is sold to third parties such as refineries or automotive companies which use the labelling for marketing purposes.

- In subsequent steps, the certification system can be extended privately to a group of actors – this can be done in private initiatives with some independent institutions for certification or can be backed in later stages by governmental authorities.
- In the long term, certification systems may be defined by national and international governmental bodies, finally set up as a global system in an ideal world. The degree of formalisation is the highest in this stage, and therefore also the credibility of the system. The challenge here is to define common standards for the products and the requirements for the certification. If no common solution is found, a number of parallel certification systems may evolve.

Figure 39 A system of green certificates can develop across various stages

Source: Frontier Economics

It is important to note, that green certificates can be traded completely independent from the physical energy products. This means that the energy is physically traded together with all other energy sources, including the remaining fossil fuel products. The additional value of the “greening” of the product is captured by the revenues of selling the green certificate which is used to proof CO_2-neutrality of the energy source.

The separation of the energy part of the product from the environmental value is efficient from an economic perspective: For example, energy consumers in Europe can proof the reduction of CO_2 emissions by buying green certificates whereas the energy is physically consumed in the producing countries. Cost savings for transporting the energy from the producing countries to the consuming countries can be realised. However, it has to be accepted in this system that consumers can’t claim to use CO_2 neutral energy in a physical sense – this might be an obstacle to purchase green certificates for some of the energy consumers and reduce the acceptance of green PtX in energy consuming countries. Furthermore, double counting of achievements in CO_2-abatement has to be avoided (e.g. double counting of CO_2-abatament in the exporting/selling country as well as in the importing/buying country)

THE GREEN CERTIFICATE TRADING SYSTEM IN EUROPE

The Renewable Energy Certificate System (RECS) is a voluntary system for international trade in renewable energy certificates that was created by RECS International to stimulate international development of renewable energy. It advocated the use of a standard energy certificate to provide evidence of the production of a quantity of renewable energy, and provided a methodology which enables renewable energy trade, enabling the creation of a market for renewable energy and so promoting the development of new renewable energy capacity in Europe. The principal is that green energy is fed into the electrical grid (by mandate), and then the accompanying certificate can be sold on the open market. Certifying agencies guarantee the quality and credibility of the certificate by means of various checks and controls. Typically, these certificates retire when they are "used" - normally when the associated energy is consumed.

In Europe, “Guarantees of Origin” (GO or GoO), issued via The European directive 2009/28/EC[123], known in the electricity industry as *‘The Renewables Directive’*, provides proof in form of an electronic record that the owner of the certificate has purchased renewable energy. The Directive defines the Guarantee of Origin in article 15 as being *the* mechanism for, “proving to final customers the share or quantity of energy from renewable sources in an energy suppliers energy mix” (Renewables Directive, Article 15). In simpler terms, the GO is the tool in Europe used by the electricity tracking system to deliver electricity attributes to the consumer.[124]

These Guarantees of Origins are further standardised within the framework of the European Energy Certification System (EECS). The EECS Rules will be interpreted by each country or region according to its "Domain Protocol". The adequacy of this interpretation is assured by the Association of Issuing Bodies to provide a properly regulated platform for Renewable Energy Guarantees of Origin – around 24 European countries mostly represented by their transmission system operator, electricity regulator or energy market operator.[125]

EECS builds upon the concept proposed by the Basic Commitment of the Renewable Energy Certificate System (RECS) and now supports all types of electricity, regardless of source or production technology.

Until these green certificates are issued and controlled under a mature regulatory system, such as the EECS in Europe, there are often many attempts from industry and stakeholders to develop certification methods and to convince regulatory authorities to facilitate their trade.

[123] See https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028

[124] See http://www.recs.org/voluntary-market/what-is-the-voluntary-renewable-energy-market

[125] See https://www.aib-net.org/eecs

4.3.5 What could be done?

Country risk can be a substantial challenge to invest in a green PtX industry outside Europe. Our analyses indicates that there is a number of countries which have a huge potential for green PtX production and export, but come along with specific country risks for investors. (Foreign) Investments in PtX facilities and infrastructure in these countries on a large scale may turn out to be difficult – as it is for any other large scale investment.

In order to improve the investment conditions for green PtX, European/German energy policy should aim at further improvements regarding green with (potential energy) exporting countries such. Potential improvements include:

- Intensifying **(non-binding) cooperation** with energy exporting countries e.g. by increasing the number of states/regions with an Energy Partnership. Furthermore, energy partnerships (on German as well as on EU level) can be used to promote the concept of producing and exporting green electricity and PtX both for the domestic as well as the international energy markets. This approach can help to improve the accessibility to Energy as well as the economic development in the respective countries.

- **Pushing for legally binding Energy Agreements/Treaties:** Declarations for cooperation in the energy sector (such as the (multilateral) Energy Charter, the Africa-EU Energy Partnership and the (German) Energy Partnerships with specific third countries) improve the energy dialogue between states. However these declarations don't contain legally binding provisions which can help to reduce the financial impact of country risks on potential PtX investments. Pushing for more legally binding treaties based on experience in cooperations can be a stepwise approach for an improved climate.

  In this context, the Energy Charter Treaty could be promoted with an increasing number of states. So far, only around 50 countries have signed and ratified the Energy Charter Treaty. Important countries such as Saudi Arabia, Australia and China haven't signed the treaty so far. It would be an important step forward regarding the investment framework if further countries signed the treaty.

- **Evaluating financial support for building up a global PtX industry:** As long as significant country risks exist, evaluating whether governments and state authorities may support investments in green PtX in foreign countries in order to mitigate the financial risks is required. A specific measure could be to grant stronger state guarantees or specific loans as they are already in place nowadays. For example, green PtX could be included as a fundable technology within the UFL guarantees, or the EU could further progress on investment promotion and protection contracts, who guarantee investors a certain legal protection. For this, states / state agencies should formulate a programme for building up a PtX industry, transparent rules for getting access to the support mechanisms and clear criteria for the termination of the programme, e.g. when country risks are reduced or global PtX markets become more mature.

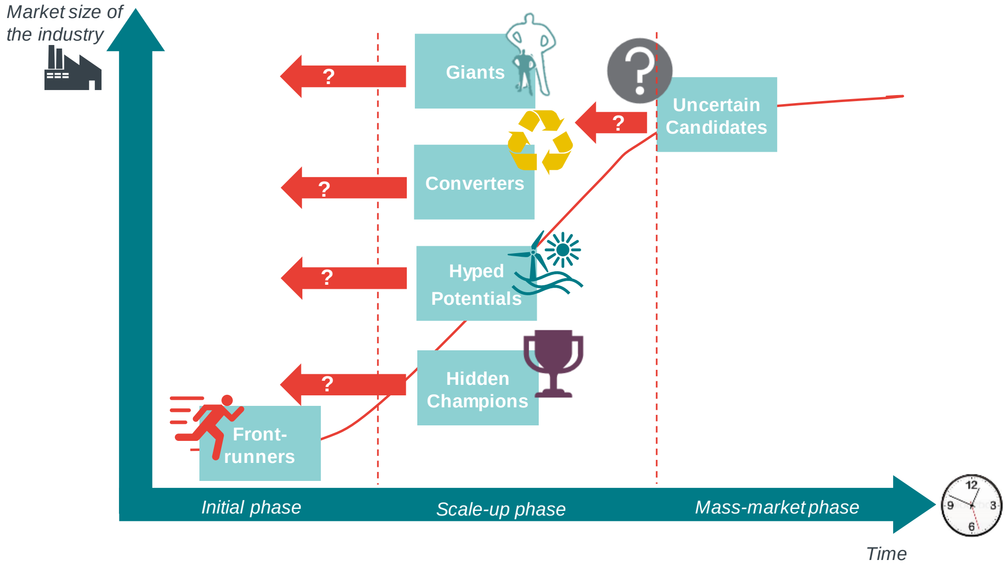
- **Multilateral cooperation in climate change agreements and renewable policies:** In order to secure a reliable long term investment framework, PtX should be part of the international climate change policy agenda. Furthermore, international initiatives for innovations as well as renewable energy organisation such as IRENA and initiatives for innovation should investigate and support PtX projects more widely. The UN as well as national governments could politically push these organisations more widely to take PtX into account as an alternative technology option.

- **In addition, additional diplomatic support** may be helpful in some countries, e.g. in MENA-countries. For example, the French government is supporting companies investing abroad via engagement of ambassadors or ministers. It may be evaluated if e.g. Germany should get more involved in more pro-active diplomatic negotiations in order to overcome e.g. cross-cultural barriers for investments.

In order to kick-off projects for an international PtX industry in a timely manner, the process of seeking cooperations and coordination should start as of today, however, with different perspective for different countries/regions of the world (Figure 40):

- **Early projects:** Systematic PtX imports can start of from frontrunners in early stages, even though these countries may only have limited PtX export potential in some cases.
- **Early dialogue:** In order to realise the PtX volumes required globally in the long term, it will be crucial that large scale PtX exporting countries step into the market (giants, hidden champions, converters). The development of respective cooperations and PtX projects will require time. Therefore, the dialogue with these countries should be intensified as of today. Starting of these initiatives on an early stage is of importance, since countries currently not in the lead for PtX can turn into frontrunners quite fast if political conditions and perceptions change.
- **Long term markets**: In the long term, the aim is to establish a global PtX commodity market that facilitates market entry of various countries independent from foreign investments.

Figure 40 Illustrative timing of market dynamics



Source: Frontier

4.3.6 International roadmap for facilitating PtX investments and supply

Creating a healthy investment environment and mitigating investment risks is key to ensure that PtX will be supplied in an international market. To provide guidance on the potential next steps and milestones, we develop an international roadmap for facilitating PtX investments and supply (Figure 41).[126]

This international roadmap is characterised by (timing of milestones indicative)

- A differentiated approach to explore cooperations with potential partner countries;
- International coordination and cooperation on the investment climate and PtX trade; and
- Establishing monitoring and certification systems for PtX.

Differentiated approach to explore cooperations with potential partner countries

Systematic PtX imports could start with frontrunner countries as of today, although these countries may only have limited PtX export potential in some cases in the long term. Several large pilot plants driven by international corporate joint ventures could start operation in the early 2020's.

However, for scaling up PtX imports and trade, cooperations with countries with currently more challenging investment frameworks should be prepared as of today.

[126] It is important to note that this roadmap is illustrative and provides a first indication of the potential steps and milestones to achieve, but should not be interpreted as a forecast.

Scaling up imports require large scale investments in countries with huge PtX potential though often higher country risk. These projects could kick-off well before 2030.

In the long term (e.g. from the mid 2030's), the objective is to establish a global PtX commodity market that facilitates market entry of various countries independent from foreign investments. In this stage, the market is developing by itself.

International coordination and cooperation on the investment climate and PtX trade

As of today, a systematic cooperations with potential PtX suppliers to decrease country risks for later investments can be established. Various bi/multilateral energy partnerships with focus on PtX are signed from 2020. Furthermore, in the short term financial instruments lowering investments risks can support investments (temporarily).

In the medium and long term, international binding energy treaties can be extended to secure the investment framework and multilateral agreements could support the formation of a global PtX market. Large multilateral agreements to support the formation of a global PtX market. For example, in the later stages (e.g. 2028) PtX is established in international climate agreements as a renewable energy option and GHG abatement technology. In the early 2030's, the global PtX market may be shaped through similar set of treaties as currently fossil fuel markets.

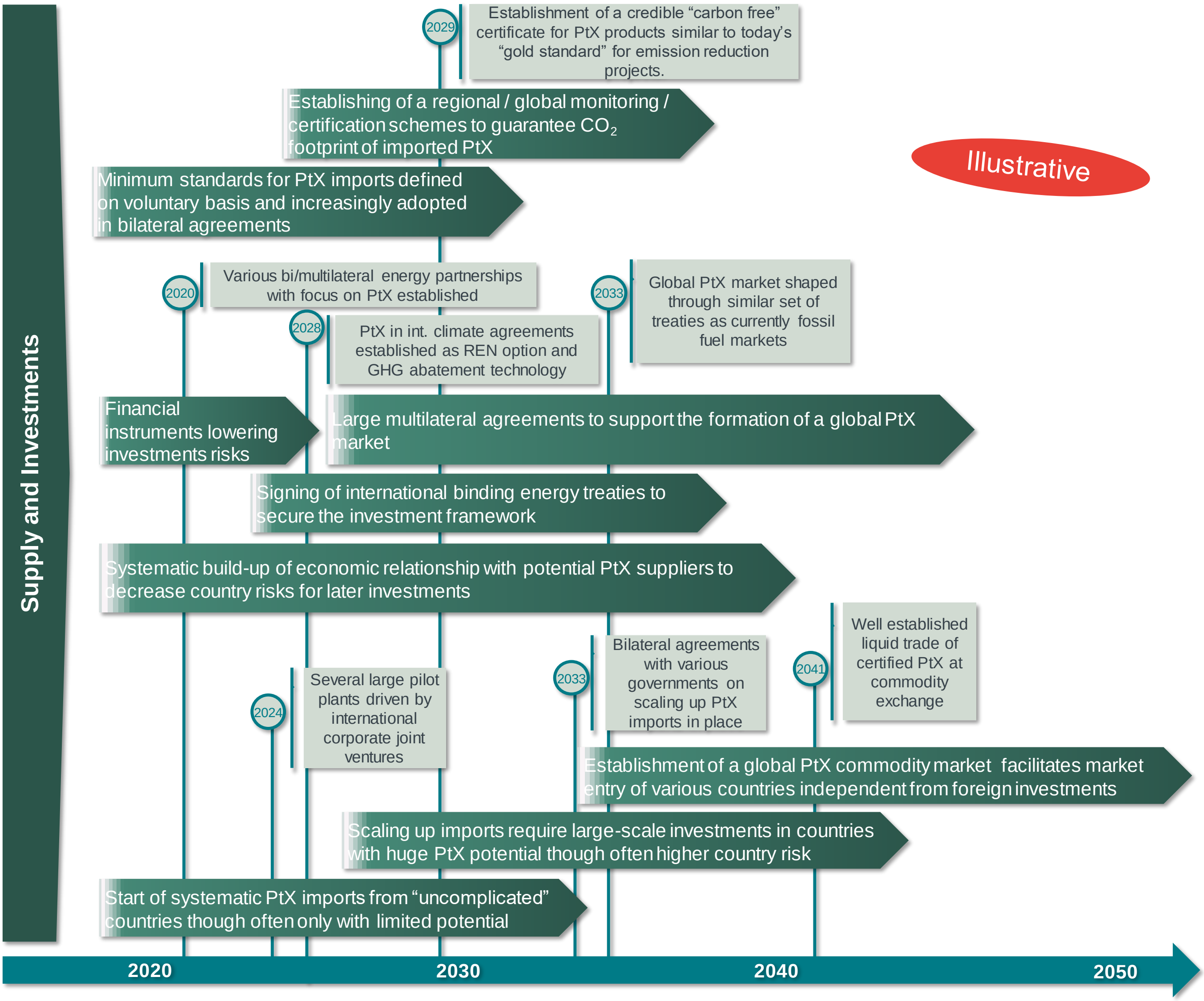
Establishing monitoring and certification systems for PtX

Social, technological and environmental minimum standards for PtX products raise the trust in global PtX markets from the customer perspective and allow for trading of the green value of PtX.

Minimum standards for PtX imports can be defined on voluntarily basis as of today. These standards can increasingly be adopted in bilateral agreements between states, organisations and institutions.

In a second phase, the establishing of a regional/global monitoring or certification schemes can follow in order to guarantee the CO_2 footprint of imported PtX. For example, a credible "carbon free" certificate for PtX products similar to today's "gold standard" for emission reduction projects may be established around 2030.

Figure 41 International roadmap pillar 'Investments and Supply': Development of a PtX industry further requires the adequate framework for investments and cooperation



Source: Frontier Economics.

5 THE ROAD TO PTX IS COMPLEX AND REQUIRES COORDINATED ACTION

While we have identified the various steps towards an international PtX market in the preceding sections based on three key pillars, for a successful realisation, these pillars cannot be developed in isolation but require an aligned and coordinated approach:

- Upstream investments in PtX supply will only be attractive if a long term demand for the products can be expected; and
- Vice versa applications for PtX will only be developed if there is going to be sufficient and cost efficient supply;
- Finally, both the demand and supply side will heavily depend on the availability of large scale technology as a prerequisite.

The full roadmap towards an international PtX market is therefore complex and relies on the conjunction of the three pillars identified. There are many parallel development paths across the pillars (as shown in condensed form in Figure 42).

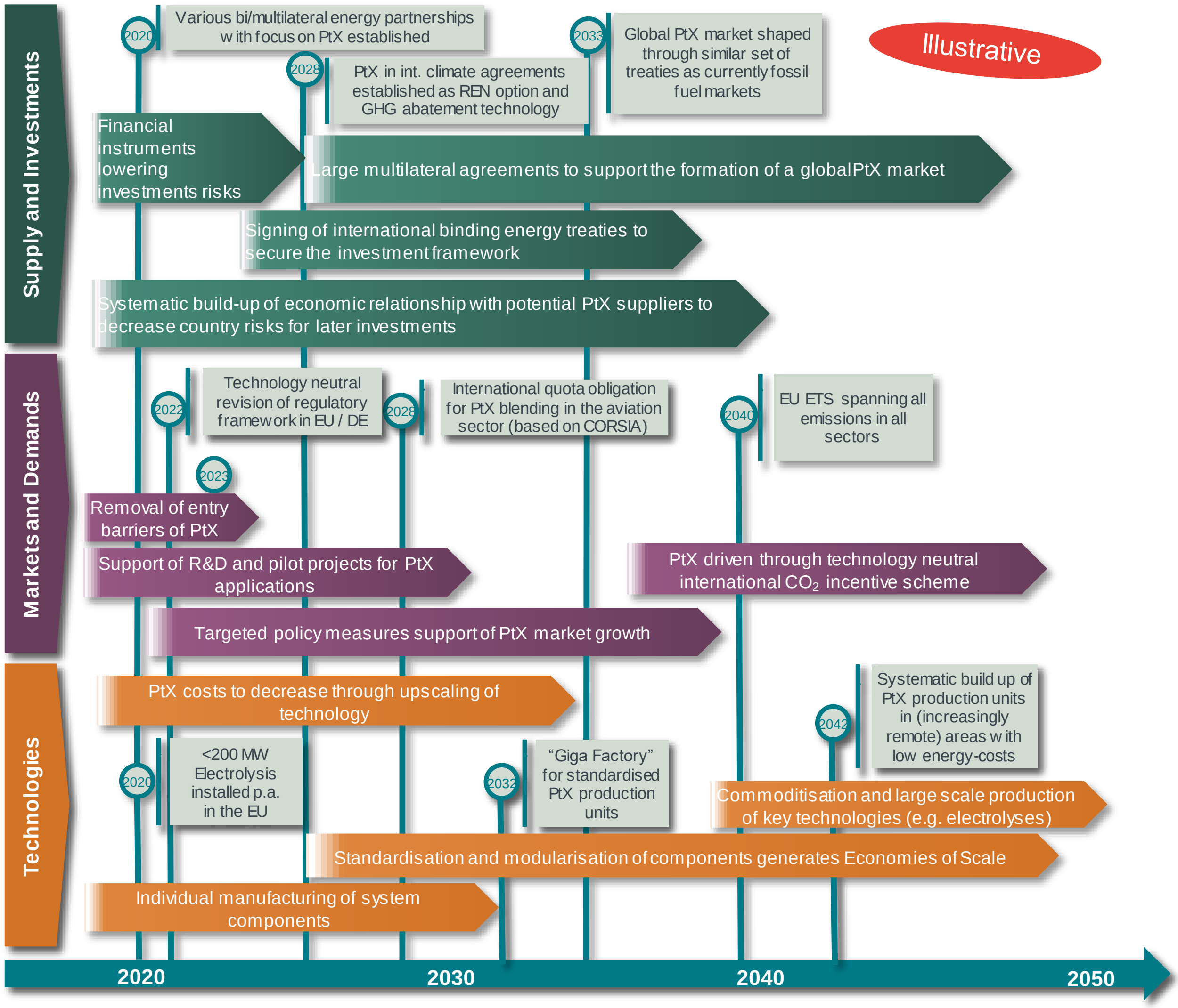
Timing and complex interdependencies require a coordinated approach to developing an international PtX market

In addition to the necessary steps outlined within each pillar, there is a need for coordinated action across the development stages of each pillar. Policy makers therefore need to facilitate and support the development in all areas in parallel.

- The development and scaling up of the required technologies could be facilitated through direct and indirect R&D support. More importantly, creating early opportunities and business cases can help to develop, apply and test the required applications in pilot project and niche markets.
- Effective climate change policies and/or suitable incentives (e.g. crediting of PtX on renewable energy and/or CO_2-targets) will ensure the validation and certification of PtX products and support the market development.
- Investments in production capacities should be fostered through a general favourable investment environment and a prospect for future business models.

With increasing maturity and growth of the PtX market, policy should aim towards international integration and move from more technology-focused policies towards a more generic approach to provide a level playing field for all carbon-neutral technologies, including PtX.

Figure 42 The three pillars of an international PtX roadmap



Source: Frontier Economics

A broad range of stakeholders have to engage in order to achieve the path outlined in the roadmap

The roadmap towards a global PtX industry requires the engagement and contribution of a broad range of different stakeholders:

- **National politics** in PtX exporting and consuming countries have to pave the way for investments in PtX facilities and define the framework for reliable medium and long term demand for synthetic fuels and hydrogen. Furthermore, since the establishment and maintenance of large scale energy infrastructure (e.g. pipes, grids) for transporting and distributing the fuels is part of the story, regulation of energy companies should allow for the investments required.
- **International politics** has to provide the framework for international coordination and cooperation in order to establish global markets and trade. PtX should be part of the agenda of international treaties and climate policy agreements. International trade of PtX products is beneficial for both, the

importing countries, e.g. due to cost savings, and the exporting countries, especially due to investments and remarkable opportunities for economic development.

- **The industry** has to take the risk to enter the market at a stage with significant uncertainties about volumes, costs and margins. Companies have to consequently develop PtX technologies further and invest in facilities. While PtX technology might challenge existing market structures, e.g. in the current fossil fuel markets, it will provide ample opportunities for new coalitions to be formed – across industries, sectors and geographies.
- **Consumers** have to demand green energy and feedstock, including PtX products. Synthetic fuels, ammonia and hydrogen have to be accepted and appreciated by consumers as carbon neutral alternatives to fossil fuels. However, access to energy, especially in poor countries, should not be restricted by the costs of energy. International politics has to make sure that the "greening" of fuels and the access to energy can both be achieved. International cooperation in financing of PtX projects may be necessary for a number of countries as it is the case for a wide range of development projects in renewable energies and carbon abatement technologies.
- **Science** has to further develop PtX technologies and develop ideas for an adequate framework for energy transition including an efficient and reasonable use of PtX alongside other green energy options and CO_2 abatement technologies. The research on implementing a PtX industry in political and economic terms is still at the beginning.
- **The public and non-governmental stakeholders** has to perceive the use and the global trade of PtX as an element of the energy transition contributing to climate change policy. International trade of energy should not be regarded as a risk but rather as an opportunity. There should be a common understanding that local initiatives for low carbon technologies should be complemented by large scale international technologies such as PtX.

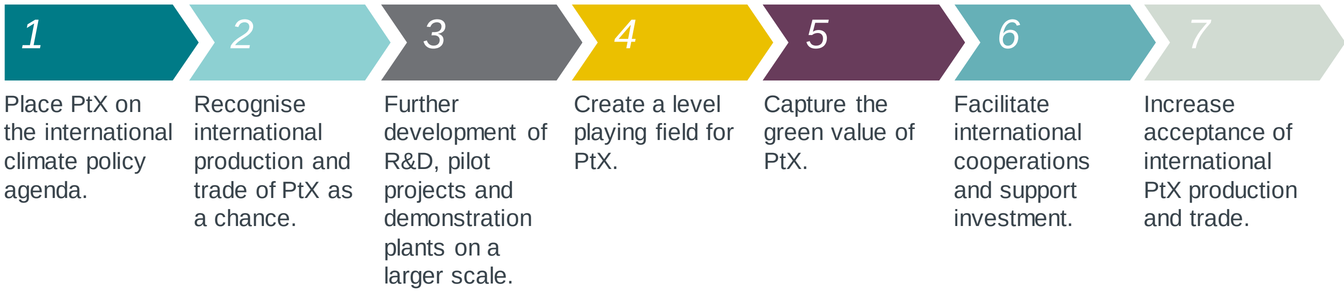
The pillars and elements of the roadmap need the facilitation from all of these stakeholders. Missing out on specific elements of the stakeholder process means a fragmentation of the PtX market and missed opportunities for benefiting from scaling up the industry.

The way to go is long, therefore a quick start is needed!

The roadmap towards establishing an international PtX market is complex and requires parallel developments and coordination. However, time is pressing if the global community wants to meet the agreed Paris climate targets. Key is to act soon, whereby a mix of immediate actions and first measures towards a long term oriented development will support the establishment of an international PtX market.

The following seven next steps support this development (Figure 43):

Figure 43 The seven next steps towards establishing an international PtX market



Source: Frontier Economics.

1. **Place PtX on the international climate policy agenda.** PtX should be treated as an innovative option to reduce CO_2 emissions and to foster the use of renewable energies. PtX should therefore be on the international climate policy agenda.
2. **Recognise international production and trade of PtX as a chance.** PtX importing and exporting countries benefit from a global market and international trade. These benefits should be recognised by the public and policy makers alike.
3. **Further development of R&D, pilot projects and demonstration plants on a larger scale**. Large scale PtX pilot projects, including renewable power production, conversion plants and transport of green synthetic fuels to Europe, could demonstrate the feasibility of international PtX trade and its benefits over the course of the next decade(s).
4. **Create a level playing field for PtX**. Regulations such as energy taxes and levies should be adjusted in order to support the realisation of early-stage PtX projects and to eliminate barriers for market entry for PtX.
5. **Capture the green value of PtX**. The green value of PtX should be reflected in current climate policy regulations at least in industrialised countries. PtX should be recognised as an option to fulfil CO_2-abatement and renewable obligations of sectors, market participants as well as states.
6. **Enable support of an international PtX production and trade / facilitated international cooperations and backing of investments in third countries.** Energy partnerships (on a German as well as on an EU level) and energy treaties can be used to promote the concept of producing and exporting green electricity and PtX – both for the domestic as well as for international energy markets. This approach can help to improve the accessibility to energy as well as the economic development in the respective countries.
7. **Increase acceptance of international PtX production and trade by minimum standards and certification.** Environmental and social standards for international PtX production and trade (including additionality of renewable installations and carbon neutrality) can increase the acceptance of imported synthetic fuels in energy consuming countries. Transparency can be achieved by a system of certification.

6 ABBREVIATIONS

AC	Alternating current
AEC	Alkaline Electrolysis
AEEP	Africa-EU Energy Partnership
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CETA	Comprehensive Economic and Trade Agreement
CGN	Chinese General Nuclear Power Group
CHP	Combined-heat-and-power systems
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSP	Concentrated solar power
Ct	Cent
DAC	Direct air capture
DAP	Diammonium phosphate
DC	Direct current
DE	Germany
DEG	Deutsche Investitions- und Entwicklungsgesellschaft
DME	Dimethyl ether
EnLAG	Gesetz zum Ausbau von Energieleitungen (Energy Line Extension Act)
EC	European Commission
EECS	European Energy Certification System
EEWärmeG	Gesetz zur Förderung Erneuerbarer Energien im Wärmebereich (German law for the support or renewable energies in the heating sector)
EIB	European Investment Bank
EU	European Union
FC	Fuel cell
FDI	Foreign direct investments
FCV	Fuel cell vehicle
FOCAC	Forum on China-Africa Cooperation
GDP	Gross domestic product
GHG	Greenhouse gas

GIZ	Deutsche Gesellschaft für internationale Zusammenarbeit
GO/GoO	Guarantees of Origin
GW	Gigawatt
GWh	Gigawatt hours
H_2	Hydrogen
ICAO	International Civil Aviation Organisation
IMF	International Monetary Fund
KfW	Kreditanstalt für Wiederaufbau ("Reconstruction Credit Institute")
kW	Kilowatt
kWh	Kilowatt hours
LCOE	Levelized cost of energy
LNG	Liquefied natural gas
MENA	Middle East and North Africa
METI	Japanese ministry of Economy, Trade and Industry,
MTBE	Methyl tert-butyl ether
MW	Megawatt
MWh	Megawatt hours
NABEG	Netzausbaubeschleunigungsgesetz Übertragungsnetz (Network Expansion Acceleration Act)
O_2	Oxygen
OECD	Organisation for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
OME	Oxymethylenether
PAREMA	German-Moroccan Energy Partnership
PEMEC	Proton Exchange Membrane Electrolysis
PtG	Power-to-gas
PtL	Power-to-liquids
PtX	Power-to-X
PV	Photovoltaic
R&D	Research and development
RECS	Renewable Energy Certificate System
RED II	Second Renewable Energy Directive

RES	Renewable energy source
RES-E	Renewable energy sources for electricity
RFNBO	Renewable liquid and gaseous transport fuels of non-biological origin
SOEC	Solid Oxide Electrolysis
TSA	Temperature Swing Adsorption process
TSO	Transmission system operator
TWh	Terawatt hours
UFL	Guarantees for untied financial loans
UN	United Nations
US	United States
WTO	World Trade Organization
CH_4	Methane
HVDC	High-voltage direct current
HH	Households
EHV	Extra-high voltage
HV	High voltage
MV	Medium voltage
LV	Low voltage
$PtCH_4$	Power-to-methane
PtGtP	Power-to-gas-to-power
PtH_2	Power-to-hydrogen
UBA	Umweltbundesamt (Federal Environment Agency)

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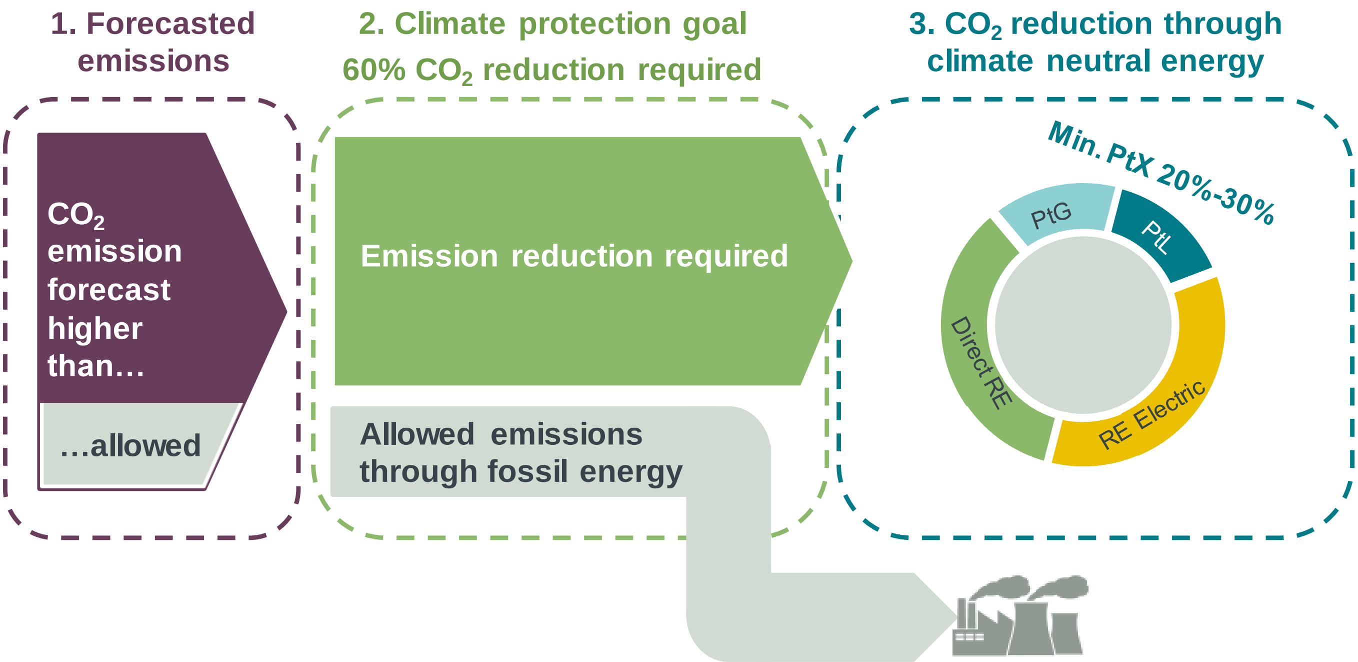
ANNEX A COMPLEMENTARY PTX DEMAND ESTIMATION

A.1 Complementary approach substantiates the results from Section 2.3

In order to substantiate the estimation of global PtX demand based on PtX shares in energy demand by 2050 (Section 2.3), we illustrate the potential order of magnitude of the long term future PtX market from a different angle. The complementary approach estimates how large the role of PtX as a green energy carrier might be until 2050 – in a world where climate protection goals for 2050 are achieved. We derive the potential volumes of PtX required to contribute to fulfilling the 2°-target of the Paris agreement in a 3-step approach (Figure 44).

Figure 44 Conceptual illustration of the complementary approach



Source: Frontier Economics.

- **Step 1 – Reference to established forecasts for predicted CO_2 emissions level from global energy demand forecasts by IEA and WEC.**[127] Even when taking current climate policies into account, global energy demand forecasts still predict constant CO_2 emissions and increasing energy demand relative to current levels. While the baseline scenarios assume a declining share of fossil fuels in the energy mix (e.g. natural gas substituting mineral oil), they disregard PtX as an option. Climate policy goals are not achieved in these scenarios: the forecasts expect CO_2 emissions at around 30bn t CO_2 in 2050, with a stagnation at this level due to increasing energy demand and insufficient fossil

[127] IEA, World Energy Outlook 2016, New Policy Scenario: forecast until 2040; World Energy Council 2016, Modern Jazz Scenario: forecast until 2050.

energy substitution. Thus, the predicted scenarios fail to decrease emissions to the levels required to meet the Paris agreement.

- **Step 2 – Estimation of additional CO_2 reduction requirements:** fulfilling the global 2°-target requires a global emission reduction by 60% until 2050 compared to 1990.[128] This limits allowed emissions to less than 10 bn. tons CO_2, i.e. 20 bn. tons CO_2 (thereof 63% caused by natural gas and mineral oil) need be additionally reduced on a global scale to meet the target.[129]
  - All countries which signed the Paris Agreement committed to prevent a climate warming of more than 2° by 2100. Therefore, countries have to define and pursue specific CO_2 reduction targets. In Germany, the climate protection debate is relatively advanced, and the government has committed itself to the challenging goal of reducing emissions by 80% to 95% until 2050 relative to 1990s level. In the rest of the world, the potential for contributions to CO_2 abatement across regions will vary. Highly developed and economically strong regions as the EU are obliged to contribute more than economically weaker regions. It would therefore be intuitive to assume a lower climate protection target for the world than for Germany or the EU.
  - We therefore consider a 60% reduction of emissions until 2050 rel. to 1990 levels, both achievable and sufficient to reach the 2° target. We thereby base our estimate on
    - the IPCC report, which limited the possible range to 23% - 63% CO_2 reduction, as this would make the achievement of the target "likely".
    - IEA, which claim that with a 40% global CO_2 reduction there is only a 50% likelihood to meet the target.

    Hence we consider an emission reduction target at the upper end of the range, namely at 60%, as plausible. This corresponds to limiting allowed emissions to less than 10bn t CO_2, i.e. compared to the predicted 30bn t CO_2 in 2050, there is an additional need to reduce 20bn t CO_2 to ensure meeting the 2°-target.
- **Step 3 – Estimation of a PtX share in achieving this target:** the additional 20 bn. tons required CO_2 reductions correspond to substituting at least 80,000 TWh of fossil energy (thereof ca 50,400 TWh mineral oil and natural gas). We assume a PtX share of at least 10% to 30% of these targeted emission reductions due to certain limitations regarding alternative forms of green energy (see Section 2):
  - the direct use of renewables (biomass, biogas, geothermal etc.) is limited,
  - electricity from renewables cannot be used in all end-user applications; and

[128] There is no clear data and consensus on the worldwide reduction percentage to reach the 2°-target. We consider a 60 % emissions reduction target against 1990 a sensible assumption based on: IPCC report with a possible range from 23 % to 63 % and IEA stating that a 40% global CO_2 reduction there is only a 50% likelihood to meet the target.

[129] Predicted emissions in 2050 are 30 bn. tons CO_2.

- carbon capture and storage for the production of "blue" hydrogen/fuels is limited due to the limited availability of CO_2 storage sites in a number of world regions in the long term.

Assuming a conservative PtX share of 10% (low case), 20% (reference case) and 30% (high case) in replacing fossil fuels with PtX to achieve the CO2 abatement targets leads to a global PtX demand of 8,000 TWh to 24,000 TWh in the long term (Figure 45).

Figure 45 Complementary estimation: range of potential global PtX demand by 2050

Source: Frontier Economics

ANNEX B DETAILED COUNTRY STUDIES

B.1 Norway – the frontrunner

Great and largely unexplored potential for renewable wind electricity generation

Wind speed levels are among the highest in Europe in almost all parts of Norway (**Figure 46**) with the potential to install onshore as well as numerous offshore wind farms.[130] For example, Wind Europe (2017) envisages up to 11 GW of installed wind generation capacity in 2030 in Norway. However, Norway's current electricity generation is primarily based on hydro (96.3%, 2016) with only minor shares of gas (2.3%) and wind (1.4%).[131] Installed wind generation capacity totalled only 838 MW (1,162 MW in 2017)[132] at the end of 2016, and production of wind-generated electricity was only 2.1 TWh[133]. Considering a land area size equivalent to Germany's[134] – however far less populated[135] – the wind generation potential remains evidently largely unused.

130 OCED, IEA (2016), p. 135.

131 Statistics Norway, available at https://www.ssb.no/en/energi-og-industri/statistikker/elektrisitet/aar, last downloaded 03/09/2018.

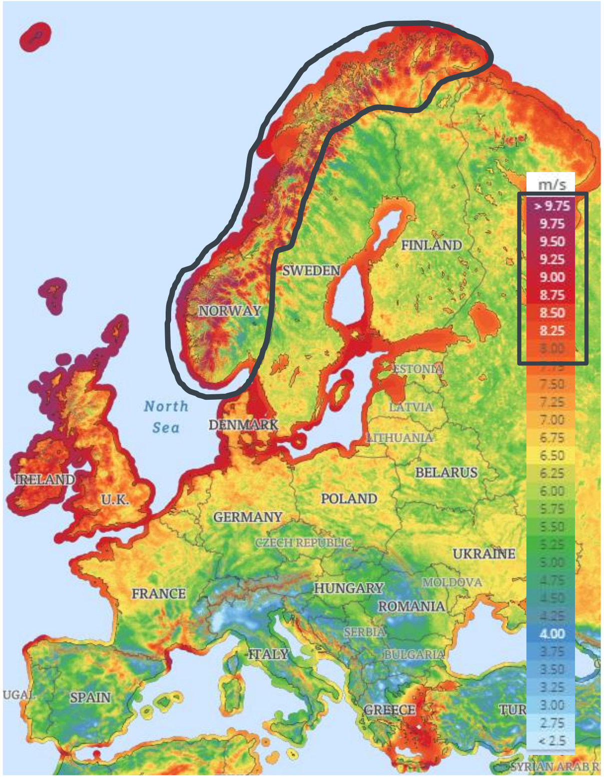
132 Wind Europe (2018).

133 Statistics Norway, available at https://www.ssb.no/en/energi-og-industri/statistikker/elektrisitet/aar, last downloaded 03/09/2018.

134 Norway has a land area of 365,245 km², Germany of 348,900 km². World Bank Indicator: Land area, available at https://data.worldbank.org/indicator/AG.LND.TOTL.K2?year_high_desc=true, last downloaded 03/09/2018.

135 Norway has only 14 people/km² while Germany has 236 people/km². World Bank Indicator: Population density, available at https://data.worldbank.org/indicator/EN.POP.DNST?year_high_desc=true, last downloaded 03/09/2018.

Figure 46. Heat map of wind speed, Norway



Source: World Bank Group, https://www.globalwindatlas.info/.
Note: Wind Speed @ 100 m – [m/s].

Inputs for PtX production are available and infrastructure for export to Europe is already existent

Key additional inputs into the PtX production process are water for the electrolysis and CO_2 as an input for the second-stage conversion processes. Water availability is not an issue in Norway[136] and CO_2 can either be directly captured from the air or indirectly from industrial processes to ensure a closed CO_2 cycle. CO_2-emitting industries, such as iron and steel, are located mainly in the south of Norway, but single factories are also scattered throughout the rest of the country.[137] For example, two cement plants are located in the north (close to the Lofoten) and one in the south close to Porsgrun.[138] However, even if half of Norway's CO_2 emissions are from employable (unavoidable) industrial combustion/non-combustion, the absolute amount of these CO_2 emissions is relatively low: Norway's industry emitted only 20 million tons of CO_2 in 2016 compared to 200 million tons emitted by Germany's industry.[139]

In addition, Norway already has comprehensive infrastructure in place to produce and export PtX, particularly hydrogen, methane or synthetic liquid fuels. Due to the strong gas and oil industry and the fact that most of the produced gas and oil is

136 World Energy Council (2016), p. 107.

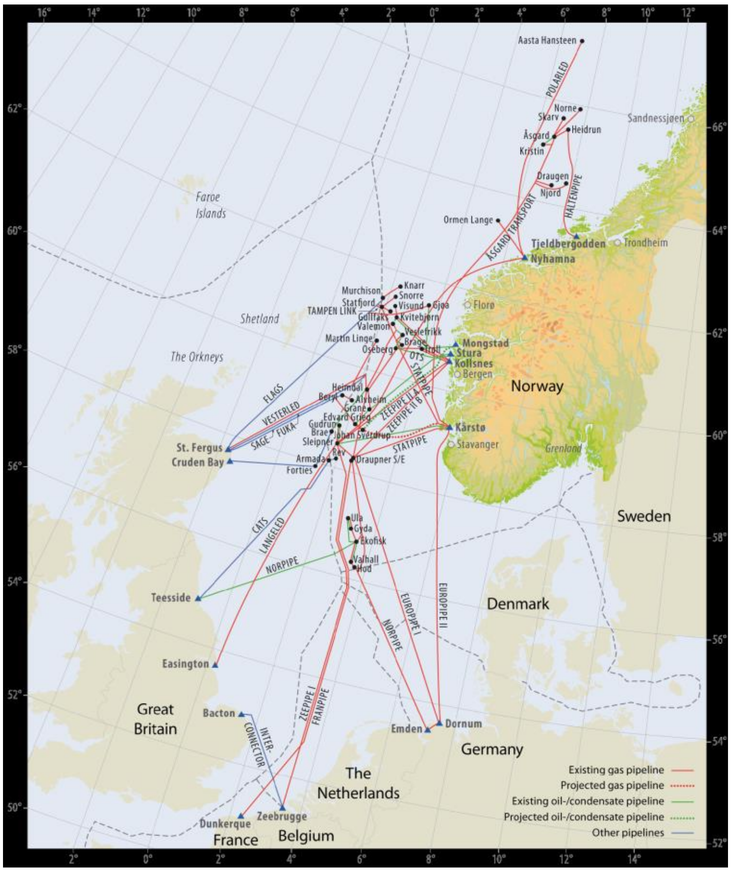
137 See https://www.stepmap.de/karte/norwegens-industrie-6MwU66PKQL, last downloaded 03/09/2018.

138 See https://www.cemnet.com/global-cement-report/country/norway.

139 Janssens-Maenhout et al. (2017), pp. 92 and 156.

exported to Europe (see next subheading),[140] several gas and oil pipelines are already available (**Figure 47**). These pipelines lead to offshore production fields, to the UK or to mainland Europe. In addition, one liquefaction terminal for LNG in the north of Norway (Melkøya facility) and two harbours for liquid products (Trondheim and Bergen) exist, which could be the base for additional PtX exports.[141]

Figure 47. Existing oil and gas pipelines, Norway



Source: Norwegian Petroleum Directorate, available at https://www.norskpetroleum.no/en/production-and-exports/the-oil-and-gas-pipeline-system/, last downloaded 03/09/2018.

Norway is in a strong position not just to produce, but to become a PtX exporter

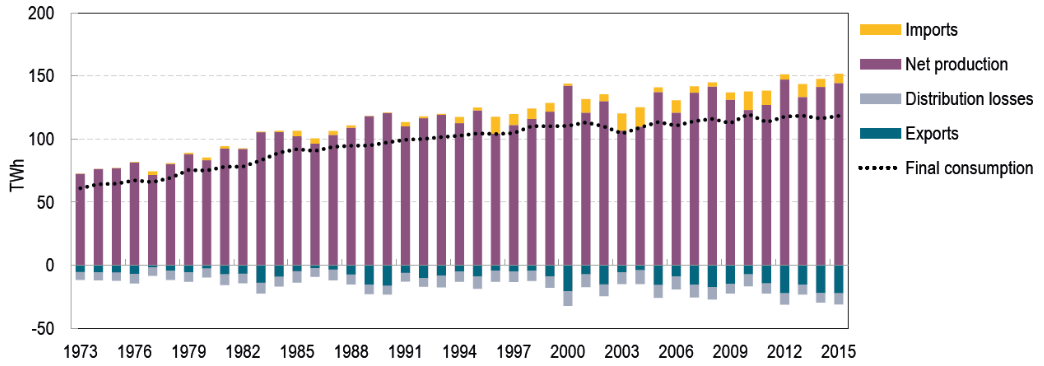
Over the course of the last years, Norway has usually been able to meet its increasing domestic energy demand autonomously (in large parts by generating sufficient energy from renewables) and is effectively a net energy exporter (**Figure 48**).[142] With an expected increase of wind generation capacity in the future, Norway is expected to generate sufficient excess electricity from RES to produce and export PtX.

[140] Homepage run by the Ministry of Petroleum and Energy and the Norwegian Petroleum Directorate, available at the https://www.norskpetroleum.no/en/production-and-exports/exports-of-oil-and-gas/, last downloaded 03/09/2018.

[141] For more information on the oil and gas pipeline system see Ministry of Petroleum and Energy and the Norwegian Petroleum Directorate, available at https://www.norskpetroleum.no/en/production-and-exports/the-oil-and-gas-pipeline-system/, last downloaded 27/08/2019.

[142] OECD, IEA (2017), p. 100.

Figure 48. Electricity production, imports and exports, Norway, 1973-2015



Source: OECD, IEA (2017), p. 100.

Note: Data based on IEA, Electricity Information 2016, www.iea.org/statistics/.
No data for distribution losses and final consumption in 2015.

The installation of further wind generation capacity and the construction of PtX plants are expected to be highly practicable in developed country such as Norway. Norway's legal system is transparent and consistent with international standards and there is no extraordinary extensive bureaucracy and the social and political environment is very stable.[143] Accordingly, Norway received the top score from various rating agencies in terms of its investment climate.[144] Furthermore, Norway is part of the European Economic Area agreement and very close to the EU – geographically, culturally and in terms of its trade relationships. This makes the country an uncomplicated PtX trade partner with ideal investment conditions. However, concerns over local environmental impacts and limited public acceptance might need to be addressed[145] (see also Section 2.2 for a discussion of potential challenges in Germany).

PtX could replace the current oil and gas exports and fits well with Norway's energy-political agenda

Norway is an important oil and gas producer and exports almost all its produced oil and gas. Norway's oil exports valued at 22.7 billion US dollar in 2016[146] – supplying about 2% of global oil consumption. Gas exports added up to 21.6 billion US dollar in value in 2016[147] and Norway is thus the 3rd largest gas exporter worldwide. Most of the oil and gas exports are going to European countries. The oil and gas sector is also very important for Norway's economy in terms of value-added, government revenues and investment.[148]

143 See for more information the Norway Country Commercial Guide provided by the U.S. Department of Commerce's International Trade Administration and is available at https://www.export.gov/article?id=Norway-market-overview, last downloaded 03/09/2018.

144 Norway is rated AAA by Moody's, S&P and Fitch.

145 See https://community.ieawind.org/about/member-activities/norway.

146 See https://atlas.media.mit.edu/en/profile/country/nor/, last downloaded 03/09/2018.

147 See https://atlas.media.mit.edu/en/profile/country/nor/, last downloaded 03/09/2018.

148 The petroleum sector's share of GDP is 14%, the share of the State's revenues 17% and the share of total investment 19%. The service and supply is not yet included in this figures. Ministry of Petroleum and Energy and the Norwegian Petroleum Directorate, available at https://www.norskpetroleum.no/en/economy/governments-revenues/, last downloaded 03/09/2018.

Even though there are still large oil and gas resources available[149], Norway might be incentivised to follow a transition towards alternative export strategies to diversify the portfolio, especially with regards a path towards a global carbon-neutral future. One of these alternative growth export strategies could be the production and export of PtX.

PtX would also fit well with Norway's own renewable energy and climate targets. For example, the national renewable energy action plan from 2010 envisaged that 114% of electricity demand should be met by electricity generated from RES, i.e. there will be excess capacity of electricity generated by RES already in the near future. Furthermore, Norway pledged under the Paris Agreement to be carbon neutral in 2030 if other developed nations also undertake ambitious commitments.[150]

PtX is already on Norway's energy-political agenda

Considerations to produce PtX are quite advanced in Norway with pilot projects currently in testing. Nordic Blue Crude for instance plans a production site for synthetic liquid fuels for use in cars (or potentially also airplanes) in the south of the country (Porsgrunn) – producing 10 million litres per year from 2020 onwards, later increasing the production to 100 million litres per year. The CO_2 as a key input will be captured from air. If the plant is successful, nine further PtL plants are envisaged.[151]

Furthermore, the Norwegian government appointed a "National Hydrogen Committee", already back in 2003. The committee was responsible for proposing a broad research, development and demonstration programme covering production, storage, distribution and the use of hydrogen.[152] The activities of this committee resulted in a national hydrogen strategy formulated in 2005 and finally to the creation of the Norwegian Hydrogen Council, which acts as a liaison and advisor to the Ministry of Petroleum and Energy and the Ministry of Transport and Communication. The council publishes action plans (two to date: 2007-2010 and 2012-2015) which aim to enable Norway to profit from a global hydrogen economy.[153] In this context, different measures for facilitating the use of hydrogen were established, and the main outcomes of the action plans were

- the introduction of incentives schemes to enable equal treatment of fuel cell electric vehicles and other electric vehicles on a level playing field;
- several national lighthouse projects (e.g. a project to demonstrate fuel cells in ship propulsion or the demonstration of green harbours[154]); and

[149] The oil and gas resources would allow continuously high production activities over the next 50 years. Ministry of Petroleum and Energy and the Norwegian Petroleum Directorate, available at https://www.norskpetroleum.no/en/production-and-exports/oil-and-gas-production/, last downloaded 03/09/2018.

[150] Climate Action Tracker, available at https://climateactiontracker.org/countries/norway/pledges-and-targets/, last downloaded 27/08/2018.

[151] See for more information of the project http://nordicbluecrude.no/, last downloaded 05/07/2018.

[152] IEA Climate policies and measures databases, available at https://www.iea.org/policiesandmeasures/climatechange/, last downloaded 04/09/2018.

[153] Fuel Cell Today (2013), pp. 17-20.

[154] Green harbours mean that docked ships do not switch any longer to diesel generators, but to a hydrogen-based solution. Fuel Cell Today (2013), p 19.

- the establishment of Transnova, now called Enova.[155] Enova is a state enterprise, which provides mainly investment support for projects aiming at the reduction of greenhouse gas emissions. In 2017, three projects related to hydrogen infrastructure in Akershus and Oslo were supported.[156]

Norway has the potential to be a front-runner

Overall, Norway has the potential to be in the lead in the early phases of market penetration, fostering scaling up of PtX technologies and leading PtX trade, based on the strong combination of its developed hydrogen strategy, on-going (pilot) projects, ambitious climate change targets, favourable investment conditions and existent infrastructure.

With regards to a long term sustainable supply of increasing worldwide PtX demand once the market has matured, it may depend on Norway's PtX capacity potential and its competitiveness whether the country will remain a key player. Considering its relatively small size compared to countries such as Australia, China or Saudi Arabia, Norway may not be one of top producers, but may still be an important exporter to Europe due to its geographical and cultural closeness.

B.2 Chile – the hidden champion

Strong and largely unused RES potential in different parts of the country

Chile shows very strong wind power in the south and along the coast as well as very strong solar power potential in the north and currently installed RES plants (and those under construction) overlap with the identified potentials in terms of location (**Figure 49** and **Figure 50**). Combinations of wind and PV are also possible, and especially along parts of the coastline.

Since the Chilean government does not subsidise the development of RES and since they are in direct competition to conventional energy sources, electricity from wind or solar plants was virtually non-existent before 2014.[157] Capacities have steadily increased since due to decreasing RE generation costs and the increasingly competitive prices for RES-E – however, absolute figures remain low: Total installed PV and wind-onshore capacities add up to only 3.5 GW in 2017[158], while total RES potential is estimated at around 1,800 GW in the north/centre of the country.[159]

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[155] See for more information Fuel Cell Today (2013), pp. 17-20.

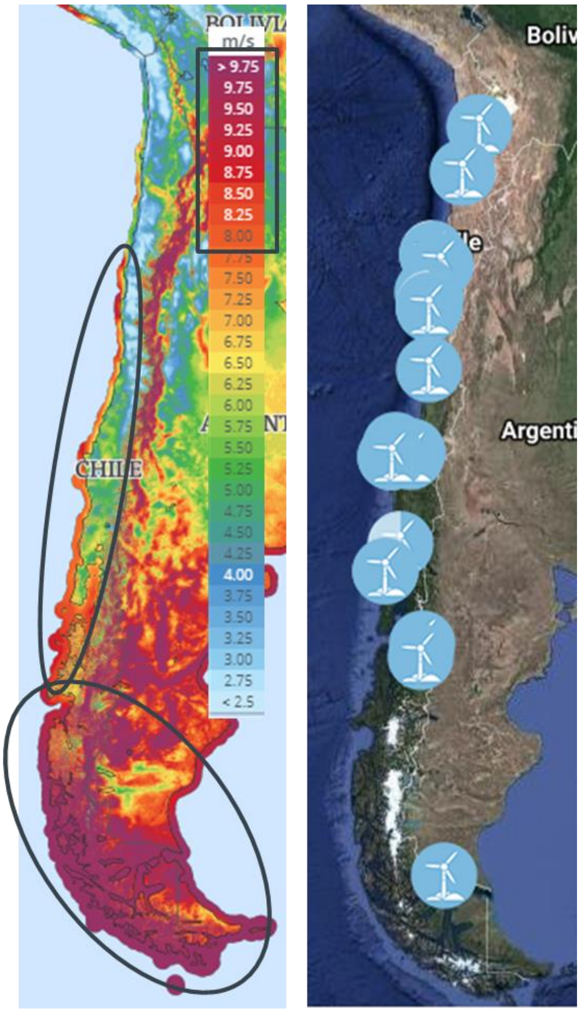
[156] Enova (2017), p. 27.

[157] Only electricity generation by hydro was already available (5-6 GW between 2007 and 2017) and increased slowly. IRENA (2018), available at http://resourceirena.irena.org/gateway/dashboard/, last downloaded 07/09/2018.

[158] IRENA (2018), available at http://resourceirena.irena.org/gateway/dashboard/, last downloaded 07/09/2018.

[159] Ministry of Energy Chile, GIZ (2014), p. 7.

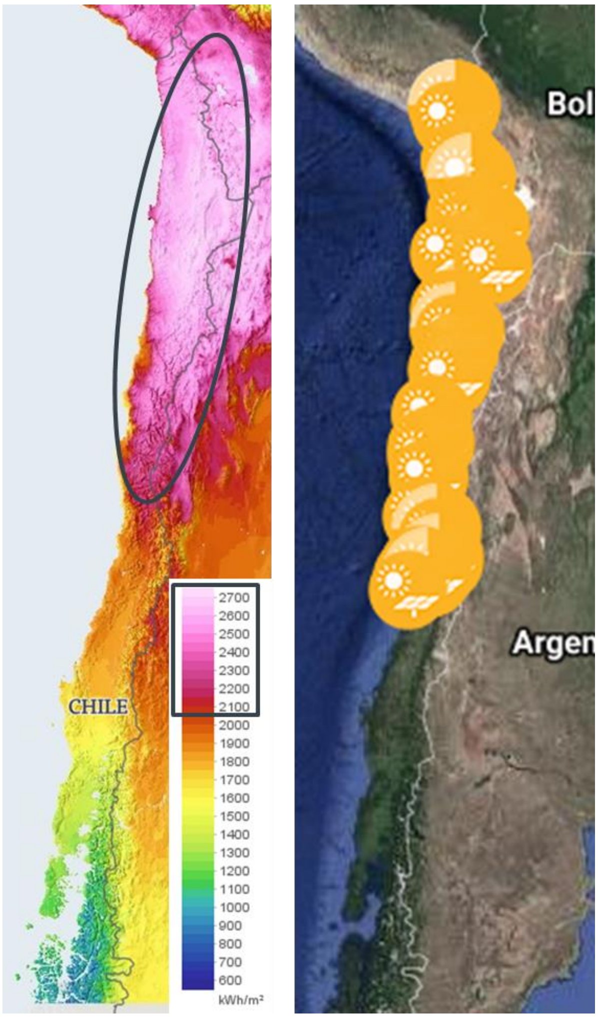
Figure 49. Heat map of wind speed and installed wind plants (2018), Chile



Source: World Bank Group, [https://www.globalwindatlas.info/;](https://www.globalwindatlas.info/) ACERA, http://www.acera.cl/centro-de-informacion/?solar=true&construccion=true&operacion=true&region=&keyword=&submit=Filtrar.

Note: Left side: Wind Speed @ 100 m – [m/s]; right side: Installed wind plants and those under construction.

Figure 50. Heat map of solar power and installed PV plants (2018), Chile



Source: World Bank Group, [http://globalsolaratlas.info/;](http://globalsolaratlas.info/) ACERA, http://www.acera.cl/centro-de-informacion/?solar=true&construccion=true&operacion=true&region=&keyword=&submit=Filtrar.

Note: Left side: Global Horizontal Irradiation (GHI) – [kWh/m²]; right side: Installed PV plants and those under construction.

Inputs available for the PtX production process

The electrolysis requires water which is quite scarce in Chile, especially in the northern part of the country.[160] However, due to the long coastline that stretches all the way from the south to the north, saltwater desalination plants could be built and given how narrow Chile is, this should not affect the location of PtX plants dramatically. For the second-stage conversion processes, CO_2 needs to be sustainably sourced, i.e. extracted either from the air or from industrial processes. The cement industry is one of the biggest emitter of CO_2 and cement plants are scattered across the country (**Figure 51**). However, concerning the total emissions of 20 million tons CO_2 from industrial combustion/non-combustion in 2016

[160] World Energy Council (2016), p. 107.

compared to Germany, for example, with around 200 million tons of CO_2, the potential of extracting CO_2 from industrial processes might only be sufficient at the beginning of a developing PtX industry.[161]

Figure 51 Location of cement plants in Chile

Source: CemNet, available at https://www.cemnet.com/global-cement-report/country/chile

Ambitious climate change targets and a path toward RES in the mining industry could accelerate RES expansion

Chile has ambitious climate and strong RES targets. Chile ratified the Paris Agreement (January 2017) and aims to reduce (unconditionally) the economy's GHG-emissions intensity by 30% until 2030 compared to 2007 levels. In 2015, the Ministry of Energy published the "National Energy Policy 2050", which aims to support meeting Chile's nationally determined contributions. The largest measures are the improvement of energy efficiency and quota obligations that support renewable energy in electricity generation. Specifically, the share of electricity generation from RES is targeted at an increase from currently 40% to 60% until 2035 and to 70% by 2050.[162] In addition, the "Mitigation Plan for the Energy Sector" was adopted in December 2017. It foresees (amongst other things) that low-cost renewable electricity will replace imported fuels and therefore lead to cost savings in the medium to long term.[163] Finally, Chile is the first country in Latin America which introduced a carbon tax. However, the tax has been very low at 5 USD per ton of CO_2 since its recent application in 2017/18.[164]

[161] Janssens-Maenhout et al. (2017), pp. 57 and 92.

[162] More details on the National Energy Plan are given in IEA (2018), pp. 116 f.

[163] IEA (2018), pp. 14 and 117 f.

[164] IEA (2018), pp. 14 and

Chile has a large mining industry, i.e. Chile is the world's top copper producer[165] and the mining industry accounts for almost 40% of total electricity consumption[166]. The mining companies usually have bilateral long term energy supply contracts with energy generators and usually conventional power sources, especially coal, are associated with these contracts. However, these long term contracts are about to expire and the energy companies are keen to transform towards a RES-based long term strategy.

Chile has sufficiently strong institutions to facilitate the creation of a PtX industry

Chile generally has a very good investment environment, especially compared to most other countries in Latin America, but this is equally true when compared to many Western economies.[167] Chile has a very liberal economy and the legal regime is transparent and well-developed. There are only minor gaps concerning the protection of intellectual property rights or concerning the length of legal disputes.[168] Chile provides a very good setting for doing business[169] and has a positive attitude towards FDI, which manifests itself in the activities of an agency promoting FDI (APIE/InvestChile) and the many international companies doing business in Chile. Chile is economically and politically strong compared to most other Latin American countries and corruption is restricted[170].

Finally, strong trade relationship exist between Chile and Europe as well as a Free Trade Agreement since 2003.[171] On the energy political level, foreign co-operations and support, e.g. by the GIZ, are present.

Increasing energy demand and strong dependency on energy imports may slow down PtX development in the short term

Chile's strong economic growth has led to a rise in demanded electricity over the last years and electricity consumption is predicted to increase even further in the future.[172] Due to the increased electricity demand, overall generation capacity (coal, gas, hydropower, wind, PV etc.) already more than tripled over the past 20 years (from 6.5 GW in 1997 to 23 GW in 2017) and will need to increase further. [173] The same applies to Chile's energy demand in general, which has been growing

[165] IEA (2018), p. 19.

[166] IEA (2018), p. 89.

[167] This corresponds to the evaluation of different rating agencies. Chile usually gets a high or very good upper medium grade rating (this is only a bit lower than countries like Australia or Norway).

[168] Chile's Country Commercial Guide provided by the U.S. Department of Commerce's International Trade Administration, available at https://www.export.gov/article?id=Chile-Protection-of-Property-Rights, last downloaded 03/09/2018.

[169] Chile ranks 55th out of 190 in the Ease-of-Doing-Business-Index. The World Bank, Doing Business, available at http://www.doingbusiness.org/rankings, last downloaded 25/09/2018.

[170] The score of the Corruption Perception Index is for Chile at 67 (whereby 0 is highly corrupt and 100 very clean) and Chile is on rank 26 out of 180 countries. Transparency International, available at https://www.transparency.org/news/feature/corruption_perceptions_index_2017#table, last downloaded 25/09/2018.

[171] European Commission, countries and regions, available at http://ec.europa.eu/trade/policy/countries-and-regions, last downloaded 06/08/2018.

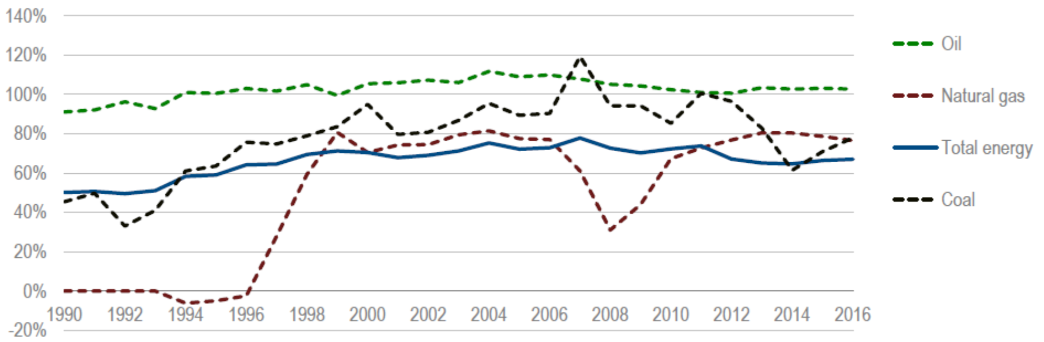
[172] IEA (2018), pp. 12 and 86.

[173] IEA (2018), p. 12.

over the last decade. Especially oil consumption has shown strong growth due to the demand in the transport and industry sectors.[174]

Most of the energy consumed (up to almost 80% over the past decade) needs to be imported.[175] Chile's import dependency is highest for oil, and slightly lower for coal and natural gas (**Figure 52**).

Figure 52. Energy imports by fuel, Chile



Source: *IEA (2018), p. 23.*

Note: *Net import as share of the TPES. Data are estimated for 2016. Original source of data: IEA, World Energy Balances 2017, www.iea.org/bookshop/753-World_Energy_Balances_2017.*

Overall, Chile may therefore be incentivised to focus on covering its own energy demand. However, if market participants abroad are willing to pay for the green property of synthetically produced fuels, then Chile may export PtX even in the short term and could continue to import fossil oil and gas. At least in the medium to long term, Chile has definite potential to become an important PtX exporter due to several beneficial factors: Chile's supply potential exceeds the electricity demand growth expected for the next decades,[176] PtX production is expected to be relatively cheap and Chile follows a liberal market approach.

An additional argument for Chile to become a future PtX exporter is that it creates the opportunity to diversify its export portfolio, as 10% to 20% of GDP from 2006 to 2016 came from natural resources.[177]

PtX is already a hot topic in Chile and hydrogen pilot projects are possibly already underway

PtX is already on the country's agenda and especially hydrogen is a hot topic amongst the key players in Chile's energy markets. This is also due to international cooperation, e.g. the German Climate Technology Initiative (supported by the German Federal Environment Ministry) organised Chile's first hydrogen conference in 2017.[178] Also a conference in September 2018[179] provided room for discussion between Chile's authorities and the private sector.

[174] IEA (2018), p. 23.

[175] IEA (2018), p. 22 f.

[176] Ministry of Energy Chile, GIZ (2014), p. 9.

[177] The World Bank Databank, Indicator: Total natural resources rents (% of GDP).

[178] See https://www.international-climate-initiative.com/en/news/article/%E2%80%98green%E2%80%99_hydrogen_from_chile/.

[179] Conference: Green Hydrogen for the Chilean Energy Transition, in Santiage de Chile, 04/09/2018.

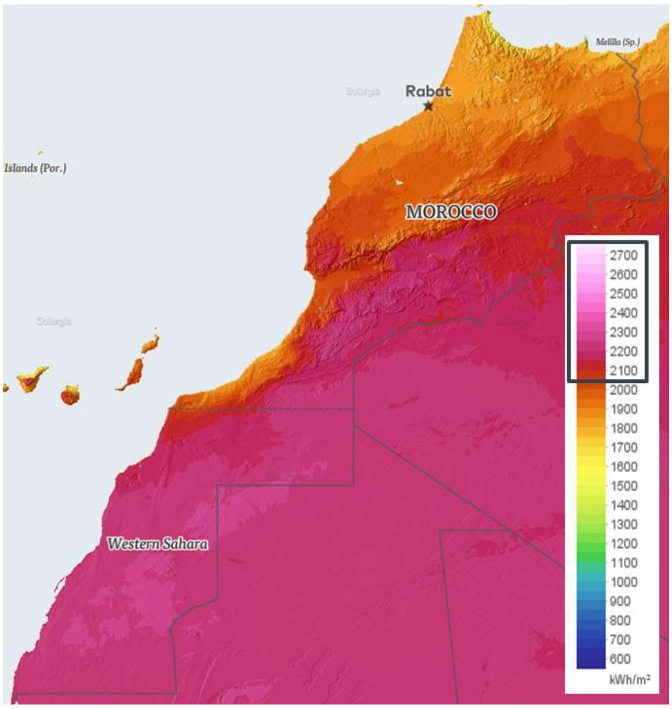
Hydrogen was finally explicitly mentioned in the "Energy Route 2018/22" of the Ministry of Energy and projects in four lines of business are envisaged: mining transport (i.e. replacing diesel or using dual engines), the storage of hydrogen, ammonia-based fertilizer and the export of green hydrogen.[180] According to regional PtX experts, there are already two hydrogen projects underway in Chile, paving the way for PtX production and export. Overall, this seems to be a promising start for a future hydrogen and/or PtX industry.

B.3 Morocco – the hyped potential

Morocco shows strong RES potential with renewable development targets

Morocco demonstrates very high solar potential across the entire country (**Figure 53**) with an average level of solar irradiation of around 5 kWh/m²/day[181]. In addition, wind power also shows huge potential across large parts of the country, especially in the southern part and along most parts of the coast line (**Figure 54**). This also enables the use of PV-wind-hydro plants as a RES-E basis for the production of PtX.

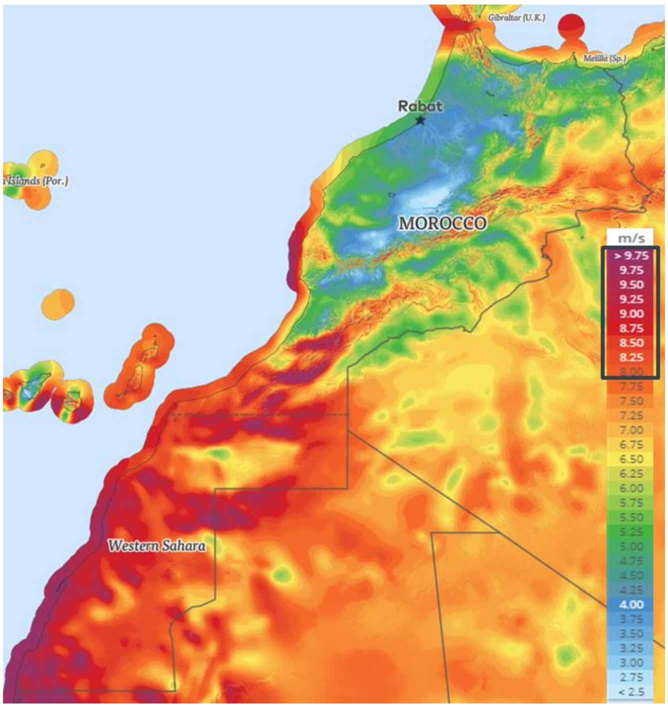
Figure 53. Heat map of solar power, Morocco



Source: World Bank Group, http://globalsolaratlas.info/.

Note: Global Horizontal Irradiation (GHI) – [kWh/m²].

Figure 54. Heat map of wind speed, Morocco



Source: World Bank Group, https://www.globalwindatlas.info/

Note: Wind Speed @ 100 m – [m/s].

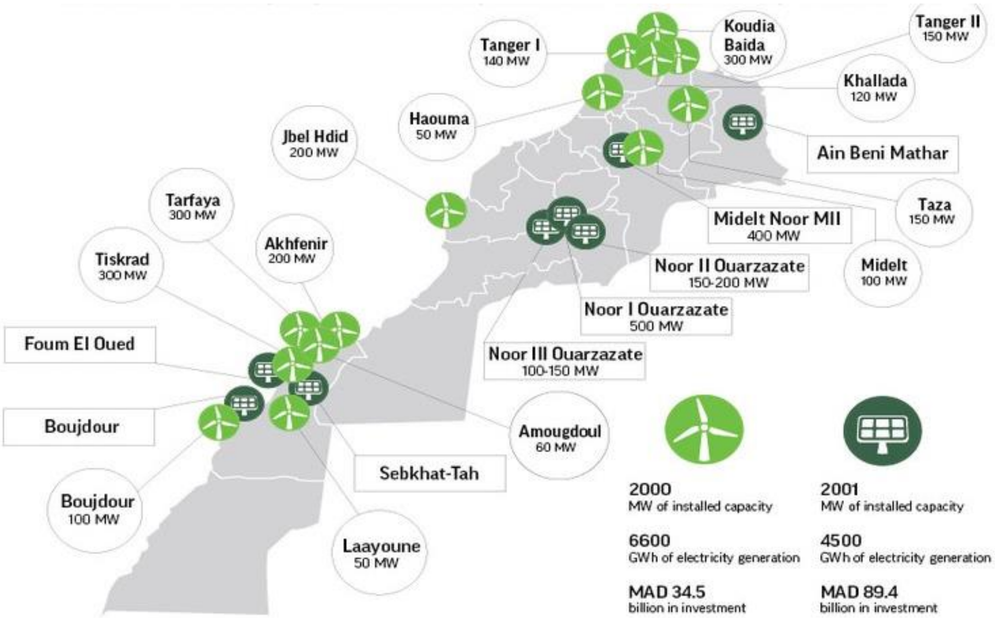
The locations with strong RES potential also overlap with those where wind and solar projects are already installed, or are currently in the planning (**Figure 55**). By

[180] See http://blog.investchile.gob.cl/chiles-first-steps-to-producing-green-hydrogen, last downloaded 25/09/2018.

[181] U.S. Department of State, available at https://www.export.gov/article?id=Morocco-Energy, last downloaded 27/08/2018.

early 2016, an estimated wind generation capacity of around 750 MW has been installed and the first 160 MW of solar generation (CSP) were launched in Ouarzazate.[182] Albeit these still small absolute installed capacities, Morocco still performs relatively well compared to other countries in the MENA region and was one of the first countries investing in RES and Morocco strives for a fast rise.[183]

Figure 55 Wind and solar projects in Morocco by 2020



Source: Renewables Now (2017), https://renewablesnow.com/news/overview-morocco-to-add-4-gw-of-wind-solar-capacity-by-2020-555087/.

Concerning Morocco's RES development targets, the envisaged installed RES production capacity (solar and wind) for 2020 is around 4 GW[184] and the target figure for the year 2030 is 52% RES of total electricity generation capacity[185]. Overall, Morocco has a great potential for electricity generation by RES – according to the GIZ, Morocco's entire electricity consumption times 1,500 could be supplied by its renewable sources.[186]

Necessary infrastructure for PtX already exists in parts, and further resource inputs for production are also available

The synthetic fuels are produced on the basis of water electrolysis (using renewable energy and water) and, if relevant, synthesis via methanisation, Fischer-Tropsch process, or methanol synthesis etc. by using hydrogen, carbon and/or nitrogen as inputs (see Section 1.2 and Section 4.1).

[182] Steinbacher (2019), p. 188.

[183] Chentouf and Allouch (2018), pp. 5 f. for an overview of the legal and institutional reforms in the energy sector.

[184] U.S. Department of State, available at https://www.export.gov/article?id=Morocco-Energy, last downloaded 27/08/2018.

[185] Climate Action Tracker, available at https://climateactiontracker.org/countries/morocco/pledges-and-targets/, last downloaded 28/08/2018.

[186] Altmann (2012), p. 33.

Water as a key input to the water electrolysis is not abundantly available in Morocco and could be a constraint to PtX production with plants located inland.[187] However, saltwater desalination plants along the coast can be built to provide water, so any locations in close proximity to the coastline are particularly interesting – where RES potentials are also abundantly available, so this is not a very concerning resource constraint in Morocco.

For the second-stage conversion processes, CO_2 is a key input which can either be captured from air or from industrial processes. CO_2 emissions from industrial combustion/non-combustion in Morocco amounted to around 13 million tons in 2016.[188] In order to use this CO_2, the emitting industry needs to be located in close proximity to the PtX production and conversion plants. For instance, the cement industry, as an important CO_2 emitter in Morocco,[189] is scattered throughout the country(**Figure 56**), and some iron and steel plants are located at Casablanca and El Jadida,[190] too. Therefore, at least some of the CO_2 required as production input could be provided by the industry.

Figure 56 Location of cement plants in Morocco

Source: CemNet, available at https://www.cemnet.com/global-cement-report/country/morocco

Next to the key resource inputs, an appropriate infrastructure is also required to produce and export PtX. A gas pipeline from the northern part of Morocco to Europe and several harbours qualified for liquid products are already in place (**Figure 57**). However, a PtX industry may require large infrastructure investments to connect to the existent grid as there are no pipelines currently installed, but some gas pipeline extensions to a planned LNG import terminal in Jorf Lasfar are already envisaged[191].

[187] World Energy Council (2016), p. 107.

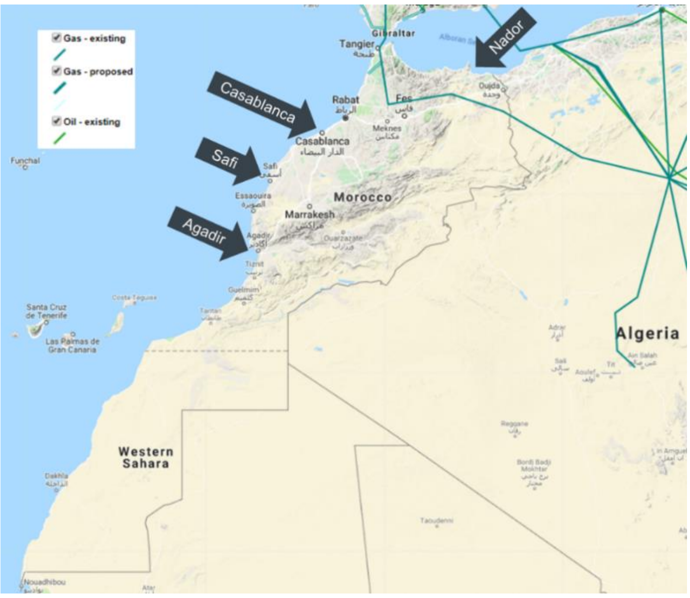
[188] Janssens-Maenhout et al. (2017), p. 144.

[189] In 2009, CO_2 emissions from the production of cement added up to 6 million metric tons in Morocco. Trading Economics, available at https://tradingeconomics.com/morocco/co2-emissions-from-cement-production-thousand-metric-tons-wb-data.html, last downloaded 05/09/2018.

[190] See https://www.industryabout.com/morocco-industrial-map, last downloaded 01/10/2018.

[191] See https://www.reuters.com/article/morocco-lng/update-1-morocco-preparing-tender-for-45-bln-lng-project-minister-idUSL8N1WH485, last downloaded 01/10/2018.

Figure 57 Currently available infrastructure in Morocco



Sources: Harvard Pipeline World Map (available at https://worldmap.harvard.edu/maps/pipelines1), Transport-Informations-Service der Deutschen Transportversicherer

Note: One gas pipeline installed connecting to Spain and one connecting to Algeria. One further national gas pipeline in the north is proposed. The arrows point at the harbours for liquid fuels.

Morocco and Europe already have a strong energy partnerships, even if investment climates may be diverse

Despite apparent cultural differences between the regions, the relationship between the EU and Morocco is well-established and strong. The free trade area between Morocco and the EU was introduced almost two decades ago and bilateral partnerships also foster the development of renewable energy and accompanying technology, such as the German-Moroccan Energy Partnership (PAREMA) since 2012[192] that focuses on the integration of RE energies into the power grids, energy efficiency and the funding of climate protection projects. German financial cooperation commitments in the energy sector in Morocco add up to over one billion Euro, with the main partners KfW for financial cooperation and GIZ in the domain of technical assistance.[193] For instance, the KfW – as well as other European actors – is also involved in the prominent large scale solar project in Ouarzazate.[194]

Finally, the OCP Group[195] of Morocco and the Fraunhofer **Institute for Microstructure of Materials and Systems IMWS in** Germany have signed a cooperation for developing solutions for a sustainable fertiliser industry. This includes the production of green hydrogen and green ammonia, consisting of green hydrogen and nitrogen – this is very relevant for Morocco due to its high dependency on ammonia imports. As part of this cooperation, one pilot plant in Leuna (Germany)

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192 Commissioned by BMWi. Federal Ministry for Economic Affairs and Energy (2017), pp. 26 f. and https://www.giz.de/en/worldwide/57157.html

193 Steinbacher (2019), p. 195.

194 BMZ, BMU (2014), available at http://www.bmz.de/20141222-1, last downloaded 05/09/2018.

195 OCP is a leading exporter of phosphate and its derivatives in Morocco.

and a similar plant for the production of ammonia will be built in the Green Energy Park in Ben Guerir, which is the largest test field and research platform for photovoltaic modules and systems in Africa.[196] This project and Morocco's general interest in hydrogen and ammonia could also be seen as a first step towards a future production of PtX.

For the transformation towards a PtX producer/exporter, Morocco will probably also need foreign investments. With regard to its relatively poor credit ratings from different rating agencies[197] this might pose a challenge. A better protection of intellectual property rights, a reduction of bureaucracy and corruption could improve investment conditions for foreign direct investment.

Morocco is a net energy importer and may focus on covering its significant national energy requirements – depending on market prices

Morocco is currently highly dependent on energy imports, e.g. Morocco imports gas from Algeria, electricity from Spain and coal from the world market. At the same time national electricity demand is rising and has almost tripled between 1985 and 2015.[198] This burdens the country's economic budget and leads to high uncertainties concerning security of supply, which were important drivers for the establishment of the national energy strategy in 2009.[199]

In order to balance national supply and demand in the midterm, Morocco aims to install additional electricity generation capacity. In 2009, the National Energy Strategy (NES) was adopted which aims to "diversify the electricity mix, accelerate the deployment of renewable energies, enhance measures of energy efficiency, support foreign investments in the sector and improve regional integration of the energy sector and allow energy access for different social segments" (Chentouf and Allouch (2018), p. 5). The NES was implemented via various measures, e.g. the creation of the Moroccan Agency for Solar Energy responsible for the Solar Plan, the creation of the National Agency for the Promotion of Renewable Energy and Energy Effieciency (AMEE) in 2010 as well as IRESEN, a research agency for solar energy and renewable energies in 2011.

In order to be able to produce PtX sustainably, i.e. without importing large quantities of fossil fuels at the same time to meet national demand, large investments in RES capacity are required. It may therefore be possible that Morocco is incentivised to focus on meeting its national demand rather than to export it (if both are sold at competitive prices). If, however, market participants abroad are willing to pay for the green property of synthetically produced fuels from renewable energy, then Morocco may export PtX regardless, even in the short term, and could continue to import fossil oil and gas.

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196 Fraunhofer CSP (2018), available at https://www.csp.fraunhofer.de/en/kontakt/presse/pressemitteilungen/OCP-group-cooperation-fertilizers-ammonia-hydrogen.html,last downloaded 06/09/2018.

197 Moody's, S&P and Fitch rate Morocco as Ba1 or BBB-, which means that investments are speculative. This rating is lower than the rating of e.g. Saudi Arabia.

198 Chentouf and Allouch (2018), p. 2.

199 Chentouf and Allouch (2018), p. 5.

Morocco may be incentivised to lead initial market phases with (energy) political facilitation from EU/DE, potentially supporting future PtX export

Combining domestic energy demand with excellent meteorological site conditions, Morocco could be highly motivated to quickly start building large scale PtX plants in its own country. PtX technology transfer into the country can accelerate and due to the existing technology know-how and energy partnerships, Germany could play a key role today as a technology partner for these projects in Morocco. Morocco's general interest in hydrogen and ammonia could be regarded a first step towards a strong PtX future. Depending on the speed of the progress with regard to the scale up of RES and PtX production structures, Morocco's medium to long term energy political agenda could focus on PtX exports on a larger scale (especially if prices become more competitive during the market saturation phase). In the long term, PtX could be regarded a very interesting and sustainable value creation perspective for Morocco.

B.4 Saudi Arabia – the converter

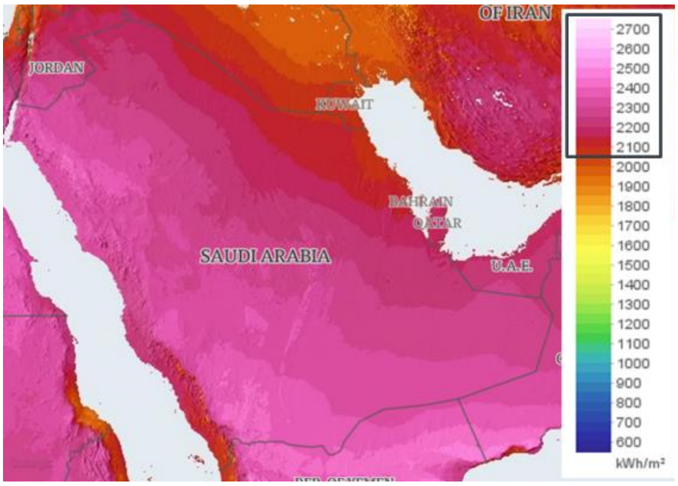
Large potential of generating RE with numerous potential plant locations for PtX and existing infrastructure for PtX

Saudi Arabia is blessed with abundant resources of solar power and in parts of the country also of wind power (**Figure 58** and **Figure 59**). Wind speed is stronger towards the centre parts of the country, however, this potential remains largely unused, since only 3 MW of onshore wind power plants were installed in 2017.[200] Naturally, solar power is Saudi Arabia's primary renewable energy potential. Saudi Arabia is located in the earth's sun belt – the area within ±35° latitude around the equator which gets worldwide the most sun per day, month and year. Therefore, almost the entire land area is depicted from dark red to pink, demonstrating some of the world's strongest horizontal irradiation values for solar power (**Figure 58**). Total installed wind and solar capacity is only around 90 MW in 2017, carried almost exclusively by Photovoltaic.[201]

[200] IRENA available at http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=19, last downloaded 06/08/2018.

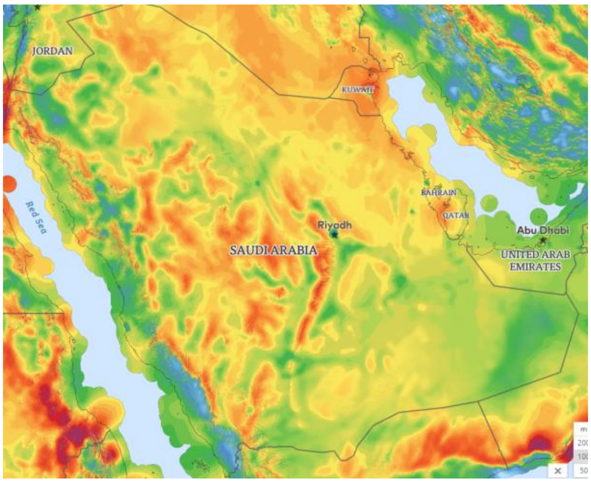
[201] See http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=19

Figure 58. Heat map of solar power, Saudi Arabia



Source: World Bank Group, [http://globalsolaratlas.info/.](http://globalsolaratlas.info/)
Note: Global Horizontal Irradiation (GHI) – [kWh/m²].

Figure 59. Heat map of wind speed, Saudi Arabia



Source: World Bank Group, https://www.globalwindatlas.info/
Note: Wind Speed @ 100 m – [m/s].

In addition, Saudi Arabia is ranked the world's 13th largest country with almost 2.2 million km^2 land area and the entire country is relatively flat and not very densely populated – only 15 people/km^2 as compared to 237 people/km^2 in Germany.[202] Vast areas of land are available for installing RE and PtX plants and in combination with year-round clear skies[203], Saudi Arabia has a huge and largely unused[204] potential to produce renewable electricity via solar plants.

However, some of the surface areas in Saudi Arabia are composed of sand dunes and shifting sand (**Figure 60**). Sand cones do not form a strong compound and shifting sand can lead to dust on the surface of PV modules, which reduces the PV module's efficiency. Locations of shifting sand in Saudi Arabia are mostly concentrated in Al-Dahna desert, Al-Nafud desert, and the Empty Quarter.[205] Even considering these potential limitations, there are still very large areas that may be exploited to install RES and PtX plants. [206]

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[202] World Bank Indicators 'Land area' and 'Population Density'.

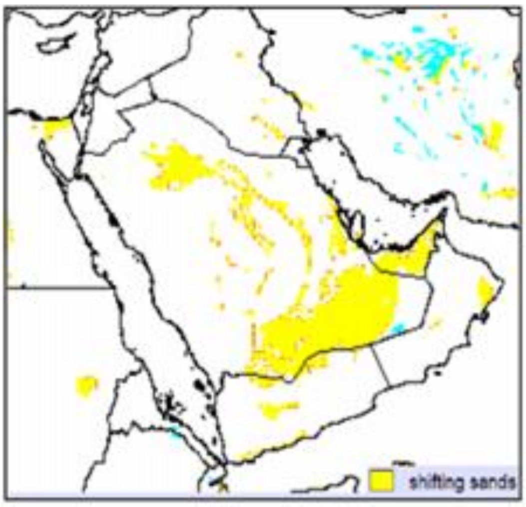
[203] Almasoud, Gandayh (2015), p. 153.

[204] The installed capacity of solar photovoltaic adds up to 89 MW in 2017. IRENA homepage available at http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=19, last downloaded 06/08/2018.

[205] Almasoud, Gandayh (2015), p. 156.

[206] The Empty Quarter is the largest continuous body of sand and has a size of over 500,000 km², the two other deserts are a lot smaller and a land area over 1 million km² remain due to Saudi Arabia's huge land area of almost 2.2 million km². The remaining land area is more than three times larger than the land area of Germany (350,000 km²). See WWF, available at https://www.worldwildlife.org/ecoregions/pa1303, last downloaded 01/10/2018, and World Bank Indicator 'Land area'.

Figure 60. Locations of shifting sands, Saudi Arabia



Source: Rehman (1998) based on Almasoud/Gandayh (2015), p. 156.

While there are many locations where RES and PtX plants could be installed, there may be further sustainability criteria to consider in Saudi Arabia as necessary inputs into the supply chain for producing PtX should be sustainably sourced (see sustainability discussion in Section 4.3.4):

- Water processing as a key input to producing PtX (water electrolysis) may not negatively impact water supply, and since Saudi Arabia has limited water availability[207], desalination plants could serve as a solution close to the Red Sea or the Persian Gulf.
- To ensure a closed CO_2 cycle, CO_2 can either be directly captured from the air or (in parts) indirectly from industrial processes. Around 120 million tons of CO_2 was emitted from industrial combustion/non-combustion processes in Saudi Arabia in 2016.[208] As a comparison, Germany emitted around 200 million tons of CO_2 in 2016 from these industrial processes. For this CO_2 to serve as an input for producing PtX (other than Hydrogen), however, the industrial plants would need to be located in close proximity to the PtX plants. Examining exemplarily the cement industry as an important industrial emitter in Saudi Arabia, these cement plants are scattered throughout the country (**Figure 61**) and could possibly serve (at least in parts) as CO_2 input to the PtX production.

[207] World Energy Council (2016), p. 107.

[208] Janssens-Maenhout et al. (2017), p. 92 and 180.

Figure 61 Location of cement plants in Saudi-Arabia

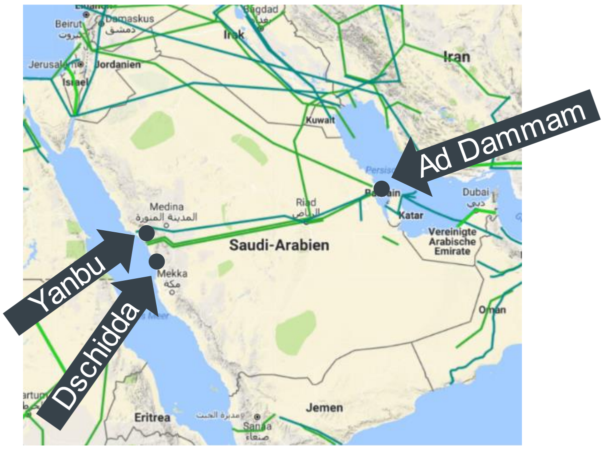
Source: CemNet, available at https://www.cemnet.com/global-cement-report/country/saudi-arabia

Existing infrastructure also accommodates for PtX, especially for synthetic liquid fuels (PtL)

Due to the strong oil industry, there are already six oil pipelines currently installed[209] as well as two harbours for exporting liquid products at the Red See (Yanbu and Dschidda) and one harbour at the Persian Gulf (Ad Dammam) (**Figure 62**)[210]. This infrastructure could serve as a basis for a PtL industry.

Furthermore, there are four gas pipelines, but no LNG terminals for exporting liquified gas. This corresponds to the fact that Saudi-Arabia is a strong natural gas producer, but the whole domestic production is currently being consumed within Saudi Arabia and national gas demand is expected to grow even further.[211]

Figure 62 Existing oil and gas pipelines and harbours, Saudi Arabia



Source: Harvard Pipeline World Map (available at https://worldmap.harvard.edu/maps/pipelines1), Transport-Informations-Service der Deutschen Transportversicherer.

Note: Oil pipelines are in light green, gas pipelines in dark green. The harbours in Yanbu, Dschidda and Ad Dammam are able to export liquid products.

[209] Harvard Pipeline World Map, available at https://worldmap.harvard.edu/maps/pipelines1, last downloaded 06/08/2018.

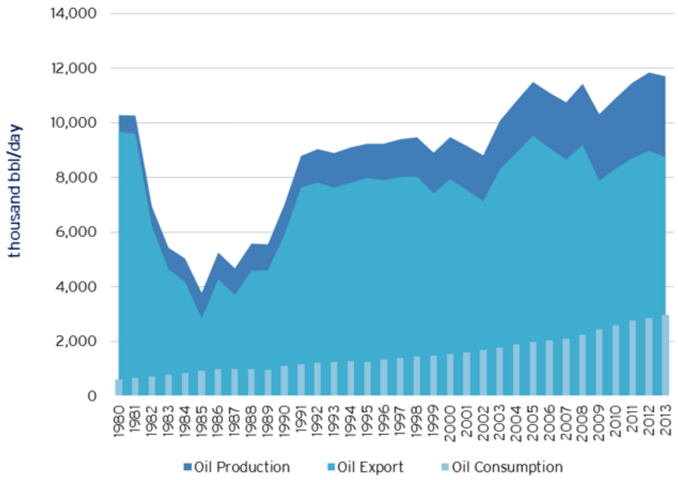
[210] Transport-Informations-Service der Deutschen Transportversicherer, available at www.tis-gdv.de, last downloaded 06/08/2018.

[211] World Energy Council (2016), p. 54.

Strong position in energy and high dependence on oil exports as strong incentives to export PtX – also as potential long term growth strategy

In addition to the country's large PtX potential, Saudi Arabia is effectively one of the world's strongest net exporter of energy in terms of crude and refined petroleum. The country exports roughly three times as much oil as it consumes (**Figure 63**).[212] The potential for synthetic liquid fuels (PtL) is not limited by local demand and Saudi Arabia is therefore well positioned to become an exporter and a supplier on the world stage.

Figure 63 Oil in Saudi Arabia – production, export, and domestic consumption



Source: Brookings based on data from BP Statistical Review of World Energy 2014 and IEA

In terms of resource export dependence, Saudi Arabia's economy relies heavily on the oil sector: Saudi Arabia is the 2nd biggest oil producer worldwide (2017) and between 25-50% of national GDP over the last ten years were associated with oil rents. In the medium to long term, Saudi Arabia might fear that the basis of its prosperity could be withdrawn in the face of a tightened climate policy – in 2016 King Salman presented a Renewable Energies "Vision 2030" with the aim to diversify the economy to be less dependent on the revenues of its oil production. Synthetic fuels could provide Saudi Arabia with an alternative long term growth prospect, and Saudi Arabia might develop serious interest in becoming a "converter".

Concerning the gas sector, as previously described, Saudi Arabia is a strong natural gas producer, but the whole domestic production is currently being consumed within Saudi Arabia and national gas demand is expected to grow even further.[213] Therefore, Saudi Arabia may be incentivised to produce PtG to supplement supply within the country to cover national demand, rather than exporting these synthetic gases – at least in the short and medium term.

[212] See https://www.theglobaleconomy.com/rankings/Energy_imports/#Saudi-Arabia

[213] World Energy Council (2016), p. 54.

Interest in renewable energies and international policy co-operation evident, however investment/business environment requires political facilitation

Saudi Arabia ratified the Paris Agreement and shows generally a very positive attitude towards climate change. In 2016, King Salman presented the plan "Vision 2030". The target of the plan is to diversify the Saudi's economy to be less dependent on the revenues of its oil production. The plan addresses multiple sectors and projects – amongst other things the establishment of a functioning renewable energy market and 9.5 GW of renewable energy in 2023. This target is much lower than the announced 23.9 GW by 2020 by King Abdullah in 2010.[214]

The slow progress raises uncertainty around actual implementation: Experiences from historic announcements show that pure (industry-) political ambitions do not necessarily secure the actual implementation. Political facilitation from international partners and energy project co-operations with the EU/DE may therefore be key for a successful emergence of PtX in Saudi Arabia.

International policy co-operation in general could further be based on the existing trade relationships between the EU and Saudi Arabia[215] and on the ongoing cooperation between the EU and the Gulf Cooperation Council on trade and investment issues, climate change, energy and environment as well as research[216].

According to the regional experts, there are currently no established energy partnerships with other countries, particularly not within Europe. However, Saudi Arabia has shown interest in an Energy Partnership with the BMWi in Germany.[217] It might be important for Saudi Arabia to involve companies from abroad to support them in developing PtX projects, to thrive from partnerships based on an exchange of technological expertise. In terms of international policy cooperation regarding RE and the production of hydrogen, Saudi Arabia is currently in discussion with Japan to form a partnership for the production of hydrogen.

On the one hand, some elements of the legislative and business environment may hinder foreign investment and the development of international co-operations, such as:

- Institutions suffer from bureaucracy, hiring quotas and training requirements for Saudi citizens as well as from a new tax-system (e.g. fees for visa).
- Legislation aimed at constraining corruption is limited, e.g. there is no prohibition against bribery in the private sector.

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[214] Climate Policy Observer, available at http://climateobserver.org/country-profiles/saudi-arabia/#_ftn1, last downloaded 06/08/2018.

[215] The EU is Saudi Arabia's first trading partner in goods (16.3% of Saudi Arabia's global trade) and Saudi Arabia is the EU's 15th trading partner in goods (1.5% EU market share). See http://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_ATA(2017)608780, last downloaded 06/08/2018.

[216] European Commission, countries and regions, available at http://ec.europa.eu/trade/policy/countries-and-regions, last downloaded 06/08/2018.

[217] Federal Ministry for Economic Affairs and Energy, available at https://www.bmwi.de/Redaktion/DE/Artikel/Energie/internationale-energiepolitik-2.html, last downloaded 13/08/2018.

- Transparency is not sophisticated and many disputes are handled through intra-ministerial administrative bodies.[218]
- The country's increasingly unstable political situation being at war in Yemen and hostile with Qatar.

In terms of its official investment risk classification, Saudi Arabia's country risk is therefore ranked as "upper medium grade"[219].

On the other hand, the current crown prince aims to modernize the country, thus potentially becoming closer to international investors expectations. In any case, international investment and therefore barriers for international investors are less relevant for Saudi Arabia as compared to other countries – at least in terms of financial investments. If visions, e.g. certain infrastructure projects, are signed off by the King, these tend to be funded directly from the countries large own national funds without much (if any) foreign investment.

Bottom-line: Is Saudi Arabi ready to consider PtX?

Due to the excellent resource availability, the well-developed existing oil and gas infrastructure and strong potential incentives for exporting PtX, a speedy transformation to PtX production and export logistics is plausible – if facilitated adequately. For such a transformation to be successful, Saudi Arabia's economic power and the existing technological know-how could serve as an important starting point, also for forming energy partnerships with EU/DE.

B.5 Australia – the giant

Vast potential of generating electricity from RES paired with enormous land areas

Australia has a land area of almost 8 million km² and is thus the 6th largest country in the world. Almost the entire country shows strong solar irradiation values of around 2,000 kWh/m² per year (**Figure 64**) and some parts of the country, especially coastal areas, allow also for a combination of solar and wind (**Figure 65**). In combination with low population density[220] and a suitable orography, the potential of producing electricity from RES is huge.[221] However, only 450 MW of large scale solar systems (> 5 MW) and 4.8 GW of wind power were installed at

[218] At least for dispute settlement a big improvement was made in 2016 with the establishment of the Saudi Centre for Commercial Arbitration.

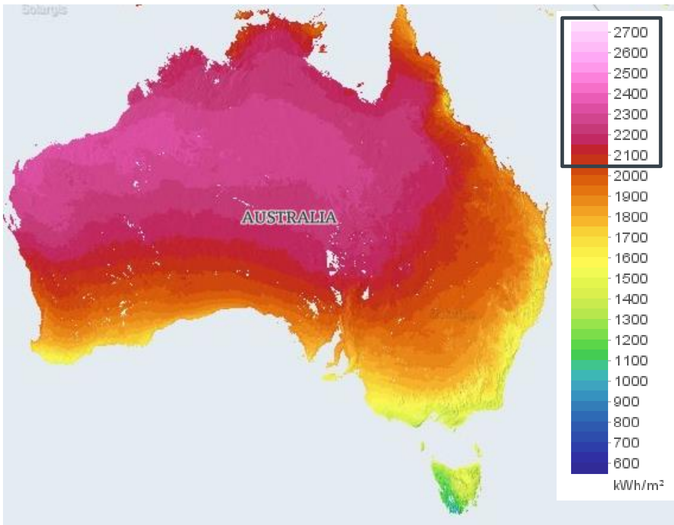
[219] The rating agencies Moody's, Standard & Poor's and Fitch rank Saudi Arabia as upper medium grade (2018). The OECD classifies Saudi Arabia's risk for export credits as relatively low (2 out of 7); OECD Country risk classification for export credits, available at http://www.oecd.org/trade/xcred/crc.htm, last downloaded 06/08/2018.

[220] Australia is with only 3.2 people per km² one of the least populated countries in the world. The World Bank Databank, Indicator: Population density (people per sq. km of land area).

[221] For example IRENA projects in the REmap Country Roadmap 34-89 TWh of electricity generation from PV and wind in 2030. These numbers are available at http://resourceirena.irena.org/gateway/dashboard/?topic=15&subTopic=39, last downloaded 14/08/2018.

the end of 2017.[222] In total, renewables accounted for 17% of electricity generation in 2017.[223]

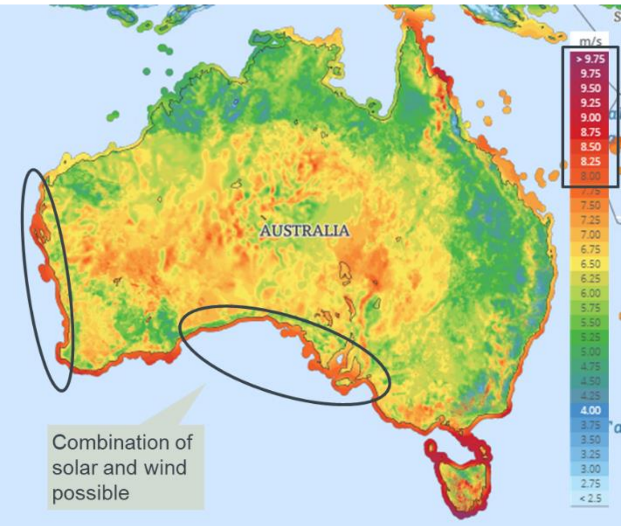
Figure 64. Heat map of solar power, Australia



Source: World Bank Group, http://globalsolaratlas.info/;.

Note: Global Horizontal Irradiation (GHI) – [kWh/m²].

Figure 65. Heat map of wind speed, Australia



Source: World Bank Group, https://www.globalwindatlas.info/.

Note: Wind Speed @ 100 m – [m/s]; the ellipsis show possible locations with strong potential for PV-wind-hybrid, but other areas also show moderate potentials

Additional resource inputs for PtX production as well as necessary infrastructure already available

The water requirement as a key input for the electrolysis may negatively impact water supply, and Australia has limited water availability in at least some parts of the country.[224] Water scarcity could therefore be an issue if, for instance, PtX plants are located in close proximity to RES potentials towards the centre parts of the country because seawater desalination plants are not an option here. However, many locations with strong RES potential are along (or close to) the coastline where seawater desalination plants can be build.

For the second-stage conversion processes, CO_2 is needed as a key input which can be extracted either from the air or from industrial processes. Australia's CO_2 emissions from industrial processes accounted for about 100 million tons of CO_2 emissions in 2016.[225] Important emitters, such as the cement and paper industries, are primarily located at the coast in the south east of Australia (**Figure 66**) and the locations overlap with those of high wind speeds. Furthermore, iron and steel plants can be found in Perth (west) and Adelaide (south) (**Figure 66**), where solar irradiation levels are not the highest, but noteworthy. Therefore, CO_2 emissions from industrial processes can be at least in some cases a relevant input to the PtX process.

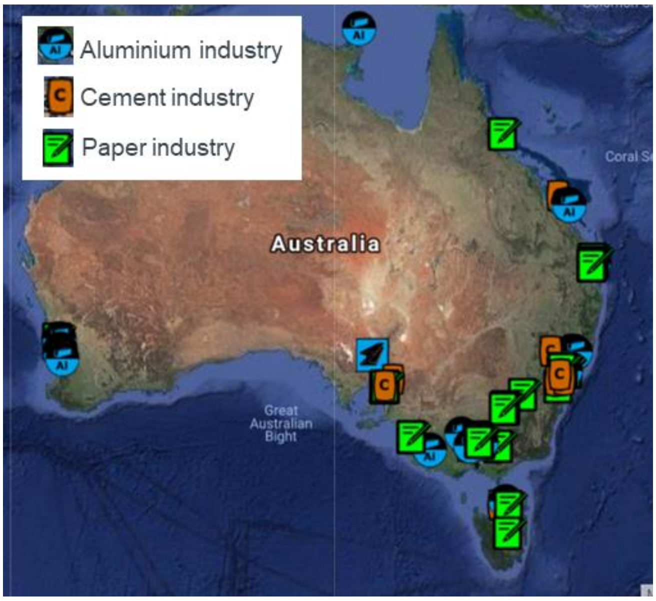
[222] Clean Energy Council (2018), p. 53 and 56. Currently installed PV and wind plants fit well with the identified location of solar and wind potential – a map of PV/wind plants in operation and under construction can be found at http://www.cleanenergycouncil.org.au//technologies/renewable-energy-map.html.

[223] Clean Energy Council (2018), p. 9.

[224] The World Energy Council (2016, p. 107) assumes high water stress in Australia, i.e. the ratio of withdrawals to supply is 40 to 80%.

[225] Janssens-Maenhout et al. (2017), p. 28.

Figure 66 Location of CO_2-emitting industries in Australia



Source: https://www.industryabout.com/australia-industrial-map.

Australia offers favourable investment conditions and has a strong relationship with the EU

Australia generally offers a very good investment environment with low levels of corruption[226] and a social and politically very stable environment. Furthermore, Australia's legal regime is transparently applied and consistent with international standards such as equal treatment before the law or judicial independence. (Intellectual) property rights are well enforced and business registration is relatively straightforward[227]. Prominent rating agencies awarded Australia the best grade possible (i.e. AAA) and close ties between Australia and the EU further reduce investment risk for foreign investors. [228]

The only aspect which may negatively affect international investment in PtX is the "national interest test", which was implemented following a number of recent investments made by foreign companies in key sectors of Australia's economy. The test was introduced to review the risks associated with FDI and is particularly relevant for investment in infrastructure and agriculture land. However, there is no precedent case, so this aspect requires further observation in the future.

In addition, PtX production and exports could benefit from existent extensive trade between the EU and Australia and from energy-related partnerships. For example, the energy partnership between Australia and Germany (since 2017) aims to

[226] Australia has a score of 77 (whereby 0 is highly corrupt and 100 very clean) and is ranked 13th out of 180 countries in the Corruption Perception Index. Transparency International, available at https://www.transparency.org/news/feature/corruption_perceptions_index_2017#table, last downloaded 13/08/2018.

[227] In the Ease-of-Doing-Business-Index, Australia is ranked 14th. The World Bank, Doing Business, available at http://www.doingbusiness.org/rankings, last downloaded 13/08/2018.

[228] For general information on investment barriers, see the U.S. Department of State, available at https://www.state.gov/e/eb/rls/othr/ics/investmentclimatestatements/index.htm#wrapper, last downloaded 13/08/2018.

incentivise investment in technologies to allow both countries to attain their energy and climate change targets.[229]

Pilot projects for green hydrogen and ammonia are driven by economic considerations, however climate targets are only moderate

Australia has only moderate renewable energy[230] and climate change targets[231] and the current government repeatedly questioned the efficacy and reliability of RES and advocates the funding of new coal-fired power plants[232]. There is currently no clear strategy for reducing CO_2 emissions, but a "Low Emissions Technology Roadmap" was at least commissioned by the Australian Government in 2017 in order to meet its emissions abatement commitments under the Paris Agreement.[233]

In general, hydrogen is intensely discussed in Australia and several hydrogen projects (e.g. one with Japan aiming at testing the logistics for exporting hydrogen, currently still produced from coal) are envisaged. This focus on hydrogen is probably driven by an increasing demand for (green) hydrogen, inter alia from Japan and South Korea. If the government starts facilitating these initiatives, the export of hydrogen (or ammonia primarily interesting in this context as a carrier for hydrogen) may well be a prospect in the short term. Likewise, if demand for PtX continues to grow from abroad too, market forces will likely drive PtX production as export would proof profitable.

Reliance on export of fossil fuels could provide incentives for PtX export as a long term diversification strategy

Australia is a country rich in natural energy resources:

- Australia has significant coal reserves and is one of the leading coal producers and exporters worldwide.[234]
- Australia is one of the top ten producers of natural gas and the world's second biggest LNG exporter.[235]

229 Federal Ministry for Economic Affairs and Energy (2017) p. 14.

230 The Renewable Energy (Amendment) Act envisages 33,000 GWh generated from large scale renewable energy plants until 2020, i.e. 23.5% of electricity generated should come from RES. For comparison, the electricity generated from RES in Germany accounts for 38% in 2017. Frauenhofer ISE, available at https://www.energy-charts.de/energy_pie.htm?year=2017, last downloaded 14/08/2018.

231 Unconditional climate change targets in the Paris agreement include a reduction of CO_2 emissions of 26-28% by 2030 compared to 2005 levels.

232 Climate Policy Observer, available at http://climateobserver.org/country-profiles/australia/, last downloaded 14/08/2018.

233 See https://www.csiro.au/en/do-business/futures/reports/low-emissions-technology-roadmap.

234 U.S. Energy Information Administration (2015), available at https://www.eia.gov/beta/international/rankings/#?cy=2015&pid=7&aid=4, last downloaded 14/08/2018.

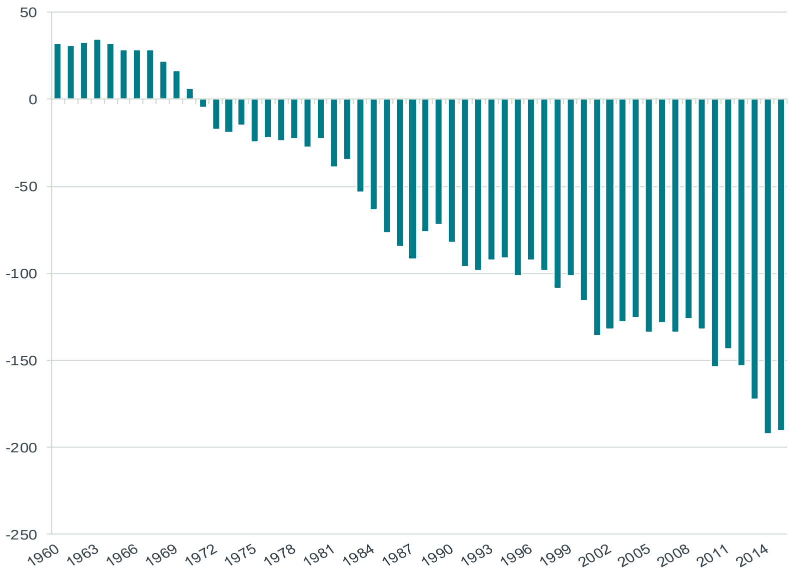
235 Statista (2016), available at https://www.statista.com/statistics/264771/top-countries-based-on-natural-gas-production/, last downloaded 14/08/2018 for production and Statista (2017), available at https://www.statista.com/statistics/274528/major-exporting-countries-of-lng/, last downloaded 14/08/2018 for export of LNG.

- Australia possesses some minor oil reserves[236] and refineries[237].

Overall, Australia is effectively a net energy exporter since the 1970ies (**Figure 67**), and the total natural resources rents adds up to a share of 5% to 10% of GDP[238].

In conjunction with the huge RES potential and the development towards a climate-neutral global economy, Australia could be incentivised to convert from exporting fossils to green fuels via PtX. However, given that energy importing countries in Asia, such as Japan or South Korea, already show a strong interest in future imports of PtX – mainly hydrogen – from Australia, it is uncertain whether Australia would realistically export to far-away destinations such as Europe.

Figure 67. Net energy imports 1960-2015, Australia



Source: The World Bank Databank, Indicator: Energy imports, net (% of energy use).

Australia may well become a key player worldwide

It is apparent that Australia has the potential to become a key player due to its disproportionately vast RES potential, the availability of further key inputs and the good investment conditions. At the moment, PtG/PtL is not yet on top of mind of (energy) political discussions, but, hydrogen production has become more important last year due to the "low emissions technology roadmap". If the government starts facilitating these initiatives, the export of hydrogen may well be a prospect of the near-future. Likewise, if demand continues to grow from abroad, as is demonstrated from Japan and South Korea, market forces will likely drive PtX production as export would proof profitable (at the start the export of hydrogen).

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236 U.S. Energy Information Administration (2015), available at https://www.eia.gov/beta/international/rankings/#?cy=2015&pid=57&tl_id=5-A&aid=6, last downloaded 14/08/2018.

237 See https://www.industryabout.com/industrial-maps, last downloaded 14/08/2018.

238 The World Bank Databank, Indicator: Total natural resources rents (% of GDP).

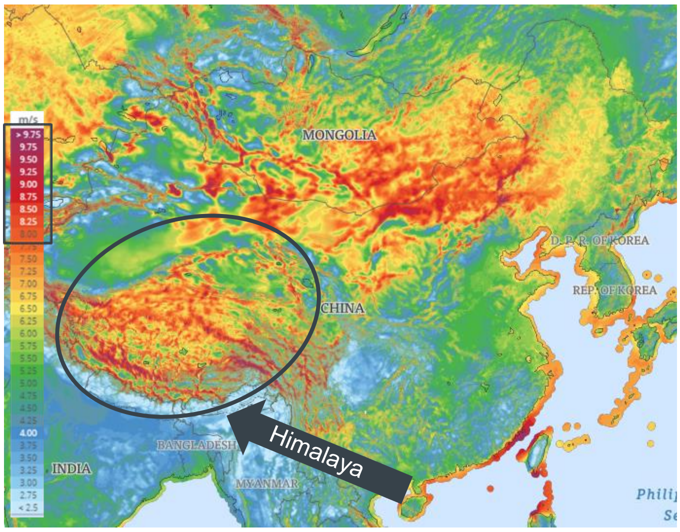
B.6 China – the uncertain candidate

China shows huge and still unexplored RES potential, however climate change targets are only moderate

China shows huge RES potential, the technical potential is estimated at 2,500 GW for wind and 500 GW for solar.[239] Installed wind capacity is only about 164 GW, installed solar capacity about 131 GW in 2017[240] – massive projected capacities are still unexploited.

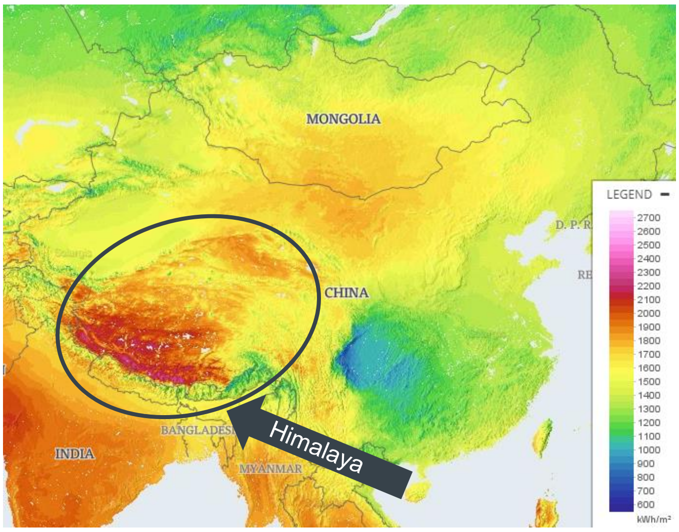
This is true despite the fact that a large area demonstrating some of the strongest wind speeds and solar power potentials are set on the rocky steep walls of the Himalaya, which impedes the construction of wind and solar plants (**Figure 68** and **Figure 69**). Additional strong wind speed locations – besides those on top of the Himalaya – are in the north of the country and along parts of the coastline (including offshore potential). Most PV modules are currently installed in the north and in the middle of the country[241] and solar irradiation levels still range from 1,700-2,000 kWh/m^2.

Figure 68. Heat map of wind speed, China



Source: World Bank Group, https://www.globalwindatlas.info/.
Note: Wind Speed @ 100 m – [m/s].

Figure 69. Heat map of solar power, China



Source: World Bank Group, http://globalsolaratlas.info/.
Note: Global Horizontal Irradiation (GHI) – [kWh/m²].

The figures for installed electricity generation capacity by wind and solar plants previously shown are very high compared to the installed wind and solar plants in other countries of the world – in fact, China is one of the frontrunners.[242] However, compared to the huge potential, the amount of installed wind and solar plants is rather low. In addition, the share of electricity generated by the installed wind and solar generation plants is currently very low (1% in 2010), but is at least predicted to rise – depending on the scenario – up to 9% or 18% (**Table 3**).

[239] According to IRENA (2014), p. 47.

[240] IRENA available at http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=19, last downloaded 08/08/2018.

[241] IRENA (2014), p. 13.

[242] IRENA (2014), p. 1, and REN21 (2018), p. 13.

Table 3 simultaneously shows that coal plays a major role in electricity generation and this is also true for supplying national energy demand[243].Coal is predicted to play a major role in China's electricity generation as well as national energy supply well into the future, even if the relative share is expected to fall.[244] Despite growing concerns over the environmental impacts of coal and the ratification of the Paris agreement[245], as well as incentives to reduce the coal dependency, the top priority of China's government remains the economic development. Therefore, only moderate renewable energy and climate targets are envisaged, e.g. within the 13th Five-Year Plan[246] and the "Energy Development Strategy Action Plan 2014-2020".[247]

Table 3 Electricity generation (in TWh) in China

Energy Source	2010	Business as usual 2030	Remap 2030
Coal	3,262	5,099	4,269
Natural gas	83	663	663
Oil	13	12	12
Nuclear	74	878	878
Biomass	33	192	358
Geothermal	1	9	9
Solar PV	1	197	445
Concentrated Solar Power	0	18	46
Wind	43	647	1,263
Hydropower	722	1,600	1,600

Source: IRENA (2014), p. 98.

Infrastructure for PtX already exists in parts, and further resource inputs for production are also generally available

Water as a key input to the water electrolysis is generally not critical in China,[248] however this is not true across all regions (**Figure 70**). There is a high to extremely high risk of water scarcity in the northern and north-eastern part of China and those areas overlap for the most parts with those regions with high RES potential. Scarce water resource could be a constraint to PtX production with plants located inland, whereas saltwater desalination plants can be built along the coastline.

243 The share of coal used for covering the total final energy consumption is about 44% in 2010 according to IRENA (2014), p. 98.

244 The share of coal used for covering the total final energy consumption will decrease to 28% or 26% according to IRENA (2014), p. 98.

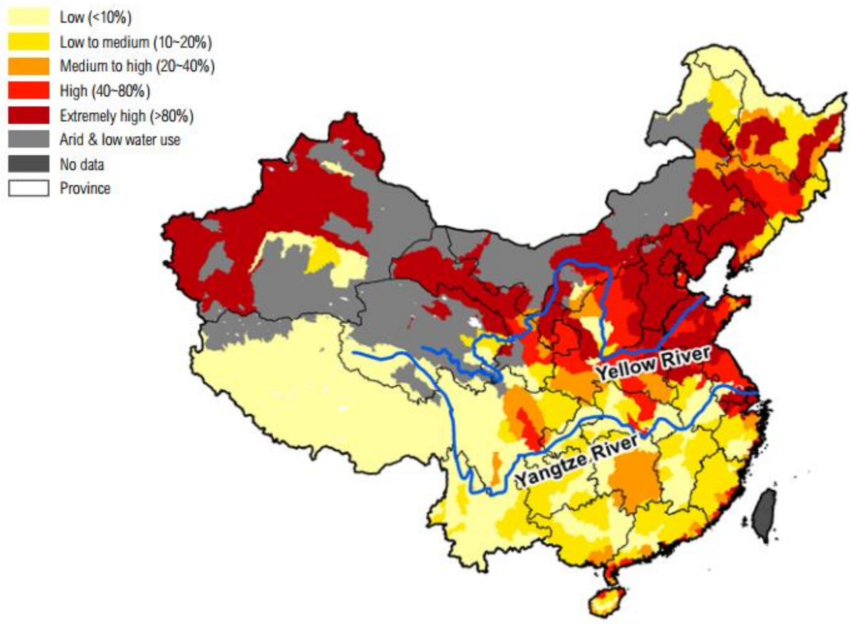
245 China committed itself to reduce the Greenhouse Gas emissions to 60.65% below 2005 by 2030.

246 The plan envisages a 15% share of non-fossil fuel energies in the primary energy consumption in 2020 and contains some moderate restrictions on coal. Climate Policy Observer, available at http://climateobserver.org/country-profiles/china/, last downloaded 09/08/2018.

247 Further detailed RE and climate targets are listed at the homepage of the Climate Policy Observer, available at http://climateobserver.org/country-profiles/china/, last downloaded 09/08/2018.

248 The World Energy Council (2016), p. 107, classified the water stress in China as medium to high.

Figure 70 Water stress in China



Source: Wang, Zhong, Long (2016), p. 11

For the second-stage conversion processes, CO_2 is a key input which can either be captured from the air or from industrial processes. China is one of the biggest CO_2-emitters worldwide and a large part of the emissions arise from industrial combustion/non-combustion (about 4,000 million tons from 10,000 million tons in total).[249] The industries emitting most, i.e. especially the cement and iron/steel industry, are mainly spread across the eastern part of the country (**Figure 71**).

Figure 71 Location of cement and iron/steel industry in China

Source: https://www.industryabout.com/china-industrial-map, last downloaded 08/08/2018.

[249] Janssens-Maenhout et al. (2017), p. 58.

Developing PtX technology could be on China's strategic agenda, and existing energy partnership may reinforce the development

Economic development remains a top priority for China, and technological know-how is on the country's political agenda. China's strategy is to become a high technology country, which means exploring PtX could fit to its political agenda. PtX is a topic that is discussed within China's energy framework and PtX pilot projects may already be underway. Energy partnerships with Germany may also facilitate the development of PtX technology with China, such as the Sino-German Energy Partnership since 2007 (with focus on renewable energy and energy efficiency)[250]. The partnership aims to support China with the liberalisation of the energy market as key for the Chinese energy transition with a strong focus on renewables and energy efficiency. Finally, China is well integrated into world markets and a very important trading partner for the EU. However, the idea of reciprocity pursued by the EU could affect the trade relationship negatively due to China's protective behaviour of national sectors and companies.

Uncertainty remains: PtX export in competition with growing national energy demand and barriers to foreign investment remain fairly high

China is the world's largest energy user [251] and IRENA projects that China's energy consumption will even grow considerably in the future[252] due to economic growth and energy demand from transport and residents. To cover the large and increasing national energy demand over the last 10 years, China has been heavily importing energy from abroad[253]. Given its import dependency and China's strategy to reduce this dependency, additional electricity generated by RES might be absorbed by the estimated growth in China's energy/electricity consumption. It is uncertain whether China will be prepared to export any green energy in the short and medium term.

Foreign PtX investments in China – at least in the short term – might be hampered by certain barriers to international investment as China's attitude is ambiguous. On the one hand, China has long relied (and still relies to certain extent) on foreign investment to develop key sectors of its economy. On the other hand, a considerable number of prohibitions and restrictions on FDI in different sectors exist. China's protective behaviour also leads to strong reactions of actors like the EU, which pursue the idea of reciprocity. Furthermore, aspects like the discriminatory bureaucracy towards foreign investors, the endemic corruption[254] or the absence of judicial independence/transparency and the absence of protection

[250] Federal Ministry for Economic Affairs and Energy (2017), pp. 18 f.

[251] IRENA (2014), p. 1, and Enerdata (2018): Global Energy Statistical Yearbook, available at https://yearbook.enerdata.net/, last downloaded 09/08/2018.

[252] IRENA (2014), p. 31.

[253] World Bank Indicator 'Energy imports, net (% of energy use)'.

[254] China has a score of 41 (whereby 0 is highly corrupt and 100 very clean) and is on place 77 out of 180 countries of the Corruption Perception Index. Transparency International, available at https://www.transparency.org/news/feature/corruption_perceptions_index_2017#table, last downloaded 13/08/2018.

of intellectual property rights might hamper international investment in PtX.[255]

Overall this leads to a mixed evaluation of the climate for international investment in PtX, which corresponds to the "upper medium grade" country ranking of different rating agencies[256] and the Ease-of-Doing-Business-Index of China (rank 78 of 190 countries)[257]. Compared to countries like Norway or Australia, China has a need for development in several areas in order to provide a good investment climate.

Growth strategies in the energy sector could support PtX technology development and infrastructure/production abroad

China might be incentivised to drive the scale up of PtX technology abroad, especially e.g. through partnerships with the EU/DE in order to meet climate change targets and growing national energy demands.

China has in the past shown geographically expansive growth strategies in the energy sector (e.g. large investment in UK nuclear power plant at Hinkley point in southern England by Chinese General Nuclear Power Group (CGN), a state-run Chinese energy company)[258]. China is currently heavily investing in its economic relations with Africa, financing large scale projects in infrastructure, securing energy supply, thereby securing access to natural resources.[259] The 2018 Forum on China-Africa Cooperation (FOCAC) summit[260] was held in Beijing this month and leaders from almost 50 African states attended to discuss a wide range of topics – from enhanced Sino-African military ties, health agreements, and academic exchanges. However, a key announcement was a financing package of $60 billion for African states to build infrastructure.[261]

China might use its position to set up PtX production sites in African countries (such as Morocco or Algeria), to develop the technology and build up comprehensive know-how. In later stages, the knowledge could be transferred to other countries including China itself for building up a PtX production and export infrastructures to supply domestic as well as world markets.

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[255] Country Commercial Guide of China provided by the U.S. Department of Commerce's International Trade Administration, available at https://www.export.gov.

[256] The rating agencies Moody's, Standard & Poor's and Fitch rank China as upper medium grade (2018). The OECD classifies China's risk for export credits as relatively low (2 out of 7), OECD Country risk classification for export credits, available at http://www.oecd.org/trade/xcred/crc.htm, last downloaded 06/08/2018.

[257] World Bank, Doing Business, available at http://www.doingbusiness.org/rankings, last downloaded 13/08/2018.

[258] See https://www.theguardian.com/business/2016/sep/15/hinkley-point-chinese-firm-to-submit-essex-nuclear-plant-plans

[259] See, for example, http://www.chinafile.com/library/china-africa-project

[260] See http://www.xinhuanet.com/english/2018-08/30/c_137431608.htm

[261] See http://www.chinafile.com/library/china-africa-project/should-african-governments-welcome-or-be-wary-of-chinese-infrastructure

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