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INFORMATION PAPER

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Classification of different paths to hydrogen production ('hydrogen rainbow')

1 BACKGROUND

Establishing a hydrogen market is an essential step in the transition to a climate-neutral economy. In this context, hydrogen is not just a new energy source or raw material for the energy system or industry. It is also a platform due to the wide-ranging options available for producing hydrogen and owing to the numerous possibilities in terms of further processing and use.

There are competing views within the National Hydrogen Council as regards to the options for supplying hydrogen and whether it is eligible for funding within the context of the transition to a climate-neutral economy. These include questions relating to the environmental assessment of hydrogen, the potential for production, the costs involved, opportunities and risks in terms of industrial and innovation policy as well as geostrategic implications, in each case also with a view to different time horizons.

There are several reasons for disagreement regarding contentious aspects of the various hydrogen production routes. These are based partly on core beliefs that are difficult or impossible to change and partly on different analytical assessments or expectations. Taking an objective approach to these different positions is a logical and necessary step in order to create the basis for better decisions on a policy level.

This paper is intended to present various analyses and assessments in a clearer, more comprehensible manner. It is not intended to describe majority or minority positions held by members of the National Hydrogen Council. Instead, it should make it easier to assess positions based on experience from discussions of the National Hydrogen Council.

2 SPECIFICATIONS FOR HYDROGEN PRODUCTION PATHS

During discussions on the paths to hydrogen production, a process to categorise certain technology paths using the colours of the rainbow has emerged, especially in Germany. However, this categorisation is not always consistent or uniform.

These exemplary classifications can sometimes occur in hybrid form under real-life conditions, especially in the transition or ramp-up phase or based on the system boundaries that were selected.

However, regardless of what colour hydrogen you are talking about, hydrogen is hydrogen. It has been produced from the corresponding source (water, fossil fuel, biomass, bound otherwise organically and inorganically) using the related process (electrolysis, reforming, pyrolysis, biochemical and photochemical processes, etc.) and therefore has an environmental and economic footprint. The relevant paths to hydrogen production are influenced by a variety of constraints. Reliable specifications at this point are only possible on the basis of the environmental parameters, primarily the carbon footprint (greenhouse gas emissions – CO_2). Economic factors are constantly changing over time and in terms of the technologies and therefore only present the situation at that time.

The National Hydrogen Council bases its discussions on the following classifications that look at the ecological footprint:

- Grey hydrogen is hydrogen produced from fossil fuels such as natural gas without measures to directly or indirectly mitigate greenhouse gas emissions, i.e., it is associated with high greenhouse gas emissions;
- Blue hydrogen is hydrogen made from fossil fuel, whereby a (very) large portion of the CO_2 generated during its production is captured and stored in geological formations;
- Turquoise hydrogen is hydrogen made from fossil fuels. Solid carbon is generated during its production that can be re-used as a raw material or can be stored so that no CO_2 is released into the atmosphere either directly or during the use or disposal of the products;

In the area of electricity-based methods, there are three exemplary paths, whereby the different colours are based on the relevant method of power generation[1]:

- Yellow: The electricity to produce hydrogen is obtained from the power grid and typically represents a corresponding electricity mix.
- Red: The electricity to produce hydrogen is from nuclear power.
- Green: The electricity to produce hydrogen is from renewable energy plants.

In addition to these main categories, there are a number of other production paths that are described here but will not be explored in greater detail:

- Excess hydrogen from corresponding technological processes (hydrogen from chlor-alkali electrolysis, hydrogen from ethane-powered olefin plants);
- Hydrogen from the thermochemical or biochemical conversion of biomass);
- Hydrogen from natural sources.

In addition to classification of production paths based on greenhouse gas emissions, there are further influencing factors. The focus will be on several hydrogen colours, which will be examined below:

- Grey hydrogen is available commercially on an industrial scale, and the technologies are mature. The cost of energy generated from fossil fuels (esp. natural gas) is a core reference value for other hydrogen production paths. In the case of grey hydrogen, the potential to reduce costs that can be achieved through technological advances is rather low; produc-tion costs are heavily dependent on current prices. No significant limitations for the production of grey hydrogen can be identified in the short and medium term, with the exception of the requirements to reduce greenhouse gas emissions.

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[1] The described paths also permit hybrid forms in terms of definition and implementation. It is clear at this point that no legally established definitions exist. Regulatory-compliant definitions are needed (cf. delegated acts on REDII).

- Production of green hydrogen is possible using mature technologies, likely on a large scale in the near future. In principle, green hydrogen can be produced in highly centralised and more localised structures. There is significant cost-cutting potential in the short, medium and long term, especially with regard to the electrolysis plants (CapEx) as well as the purchase costs of renewable power. That means that cost parity with grey hydrogen is expected, at least in the long term, subject to appropriate CO_2 pricing. Domestically, there are restrictions to the widespread availability of green hydrogen or an increase in its avail-ability primarily determined by the availability of renewable electricity. From a European perspective, there are significantly fewer restrictions in this regard and they are not relevant on a global scale in the long term. On an international scale, production of green hydrogen is a legitimate option for some of today's fossil fuel suppliers as well as for new producer regions.

- Production of red hydrogen is possible using mature technologies, likely on a large scale in the near future. Production of hydrogen using new reactor technologies, which are currently still in the low TRL range (SMR, HTR)[2], is also being discussed. There is significant cost-cutting potential with regard to electrolysis plants. With regard to the price to purchase electricity generated by new nuclear power stations, it is reasonable to assume that costs will rise due to the increasingly stringent safety requirements and lengthy approval processes. There are constraints on the large-scale production of red hydrogen or any increase in its production primarily due to low public acceptance for nuclear power generation, associated process chains, disposal of nuclear waste and due to long approval processes. This means that significant volumes of red hydrogen will likely not be available until well after 2030. On an international level, production of red hydrogen is only a legitimate option for countries where nuclear power enjoys widespread acceptance.

- Production of blue hydrogen is possible using fully developed technologies, likely on a large scale. There is limited (moderate) cost-cutting potential in selected process phases (certain CO_2 capture processes). Nevertheless, the cost of producing blue hydrogen is highly dependent on the cost of purchasing the fossil fuels used. Subject to appropriate CO_2 pricing, cost parity with grey hydrogen can be achieved in the short to medium term. Aside from the residual emissions of greenhouse gases, other strategic constraints on the production of significant quantities of blue hydrogen or a major increase in production primarily include the availability of safe and long-term geological storage facilities for CO_2 and the creation of the necessary transport and storage infrastructures. On an international level, production of blue hydrogen is a legitimate option especially for countries that are capable of producing large quantities of fossil fuels in the future and are active on these markets today.

- Turquoise hydrogen is currently in the transition phase from laboratory to pilot-plant scale production (technology readiness level TRL 3–4). It is difficult to predict when it will be available on a large scale and what the cost will be. With regard to the use or disposal of the solid carbon that is produced, there are still a large number of questions that need to be answered. The associated challenges, however, do not appear to be insurmountable and have the potential to open up new value chains. Furthermore, expectations are that it will be considerably easier to store solid carbon than gaseous CO_2. In addition to the residual emissions of greenhouse gases, the main constraints on the production of significant quantities of turquoise hydrogen or increased production of it are the climate-neutral use or disposal of the solid carbon that is generated. On an international level, production of turquoise hydrogen is a legitimate option especially for countries that are capable of supplying large quantities of fossil fuels in the future and are active on these markets today.

[2] SMR = small modular reactor; HTR = high temperature reactor

3 CLASSIFICATION DIMENSIONS

3.1 CLASSIFICATION IN TERMS OF ENVIRONMENTAL POLICY

The impact of hydrogen production on the growth of greenhouse gas emissions is a key dimension in the classification of the different production paths for hydrogen[3].

System boundaries for the corresponding assessments are highly relevant on an analytical level and for the corresponding tools to implement hydrogen strategies (for example, for certification and creditability). In principle, there are three distinct types of greenhouse gas emissions:

- Direct greenhouse gas emissions from hydrogen production can be calculated with a high degree of certainty. This also concerns the location where greenhouse gas emissions are released into the atmosphere[4]. Direct greenhouse gas emissions are generated during the production of grey, blue and turquoise hydrogen.

- In principle, greenhouse gas emissions in the upstream and downstream process phases (electricity generation for electrolysis, greenhouse gas emissions from the provision of natural gas, greenhouse gas emissions from CO_2 storage) can be calculated with a high degree of certainty. However, they are largely dependent on a small set of parameters or defined limits. Evaluation of the electricity system, in part or in whole, with regard to the additionality of electricity generation and data availability/reliability for the upstream chain emissions from the provision of natural gas and the time frame for the evaluation or corresponding temporal dynamics are two examples of this. The location at which the greenhouse gas emissions are released into the atmosphere can also be calculated with a relatively high degree of certainty here, too. Greenhouse gas emissions defined in this way are primarily relevant for grey, yellow, blue and turquoise hydrogen and, in some cases, for green and red hydrogen.

- Modelling can be used to calculate the greenhouse gas emissions from the end-to-end life cycle analysis (including all energy and material inputs, etc.). However, this is dependent on a large number of system boundaries and parameters. Along with this, evaluation of temporal dynamics and the spatial allocation of greenhouse gas emissions are only possible with a high level of uncertainty. Greenhouse gas emissions defined in this way are relevant for all hydrogen production paths.

Green hydrogen is seen as necessary to achieve comprehensive climate neutrality, i.e., the transition of all value chains over to climate-neutral processes.

It is unclear what role the different hydrogen production paths can or should play in the processes during the transition to comprehensive climate neutrality. In basic terms, there are three definable positions:

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[3] This paper will only explore a selected number of production paths with regard to their greenhouse gas intensity. To learn more about other aspects, please refer to the sustainability paper published by the NRW, which describes environmental classification in full detail.

[4] The location at which greenhouse gases are released into the atmosphere is primarily relevant from the perspective of climate protection governance. That is because emissions are attributed to the countries on whose territories they occur. Within (industrialised) states with robust climate change governance, cross-border effects are appropriately reflected at a market process level. Except for these countries, however, there may be significant challenges in terms of political integrity and fairness arising from the transfer of emissions effects. Cross-border emission effects are also highly relevant for public acceptance of hydrogen applications.

- In terms of greenhouse gas emissions, the first position considers green hydrogen to be the only acceptable option during the transitional phase, provided that there are no technical planning limitations that make this impossible.
- The second position considers the use of blue or turquoise hydrogen to be reasonable and necessary if significant emission reductions are achieved compared to the provision of competing fossil fuels.
- The third position also considers the use of blue or turquoise hydrogen to be a reasonable option if sufficiently ambitious emission reductions are achieved for the direct emissions in production and the emissions from upstream process stages are not further considered. That's because other countries are responsible for reducing these emissions under their climate neutrality strategies.

Specifically regarding the evaluation of blue hydrogen, reliable, long-term carbon capture and storage (CCS) is controversial:

- The first position regards the use of CCS in general as insufficiently reliable and for this reason rejects any production path based on CCS.
- The second position regards the use of CCS as acceptable in principle and within certain limits. However, it sees competition between the use of geological storage formations for CCS for the production of hydrogen and for CCS applications in other industrial sectors (e.g., the cement industry).
- The third position regards the use of CCS as feasible in principle and sufficiently secure under the corresponding regulatory framework. However, it does not believe competition with other CCS applications is a critical factor during the period relevant for blue hydrogen. Along with that, it expects that the use of CCS for the production of blue hydrogen will make a (marginal) contribution to the development of the necessary CCS infrastructures.

For reliable balancing and certification of the different greenhouse gas emissions and the accompanying assessment, the precision, transparency and reliability of the emissions data must be significantly improved, at least in some areas. This applies not only but above all to the process chain emissions of natural gas supplies from Russia and other non-European regions of origin and the accompanying assessment from a climate policy perspective (with a view to the specific global warming potential to be estimated) as well as the secure, long-term storage of CO_2.

A question relevant specifically to hydrogen produced using electrolysis relates to the classification of the nuclear-based electricity generation route:

- The first position regards the use of red hydrogen as unacceptable in view of the risks specifically associated with nuclear power (scale of damage caused by major accidents, transport, safe operation, dismantling and disposal issues, uranium supply, proliferation).
- The second position regards the use of red hydrogen generated by using new production technologies to be possible in theory in this area. However, the technology for new reactor designs (SMR) is not sufficiently advanced at this time to permit serial production. In the best case scenario, the learning effects and economies of scale can only be achieved in the long term. As far as generation IV reactors (alternative reactor designs) are concerned, this position suggests there are doubts as to whether they will achieve technological maturity in the next two decades.

- The third position regards the use of red hydrogen as acceptable, primarily with reference to the lower probability of major accidents occurring, the fundamental ability to solve the issue of permanent storage through technology, the containment of proliferation risks through regulation, for example, and because it will be available on the international market anyway.

The future role of and potential for production and use of red hydrogen outside of Germany (especially in the US, UK, Middle East, China) and the EU (France, Poland, the Czech Republic) remains controversial.

The different positions with regard to the classification of production routes from a climate policy perspective are in part due to core beliefs (residual emissions, CCS, nuclear energy, etc.). They can therefore not be significantly influenced even through a decisive improvement in the base data. However, some of the previously described differences relating to classification (especially with regard to the limits of the emission reductions) could be nar-rowed by having more detailed or more reliable base data.

3.2 VOLUME-BASED CLASSIFICATION

Green hydrogen and its derivatives from European and non-European production, in addition to domestic production, should cover the demand required to achieve climate neutrality in the long term.

When it comes to the medium-term production of hydrogen, the following picture emerges:

- The first position regards the volume of green hydrogen that can be produced domestically or imported to be sufficient, even over the medium term (2030/2035), to achieve the corresponding climate targets. In other words, the dynamics of green hydrogen are deemed to be sufficient in order to implement the ramp-up and create the necessary infrastructures.

- The second position regards the risk of an insufficient supply of green hydrogen as too high if there are no plans to produce at least a certain quantity of blue hydrogen. Nevertheless, this quantity is limited by the transport and storage infrastructures that can be created. Whether turquoise hydrogen can also play a significant role during the relevant planning intervals and from a volume perspective is uncertain.

- The third position advocates the use of all currently available hydrogen production paths and the expedited construction of facilities, infrastructures and logistics chains in order to develop downstream applications and transport routes for the use of green hydrogen as quickly as possible.

All three positions differ not only from a production perspective, but also with regard to the volume of demand that is assumed to be reasonable and necessary.

The different positions are less due to core beliefs and more to a lack of data and could therefore be more closely aligned by obtaining more detailed base data.

3.3 COST CLASSIFICATION

There are three key variables that determine the cost of hydrogen. Firstly, there is the cost of the energy sources used (natural gas for grey, blue and turquoise hydrogen; electricity for green, yellow and red hydrogen). Secondly, there are the investment costs relating to conversion plants (steam methane reforming, pyrolysis plants, CO_2 separation facilities, electrolysis plants). Thirdly, there is the capacity utilisation of the conversion plants. Special factors relevant for blue hydrogen are the cost of CO_2 removal and the safe, long-term storage of CO_2 in geological formations.

Grey hydrogen is an important benchmark for the cost classification of other colours of hydrogen.

For green hydrogen to become marketable, it will be necessary to offset the cost differences on a larger scale than for blue hydrogen in the short and medium term. This is at least true for the price of natural gas prior to 2021. However, the cost of green hydrogen is exposed to a lower risk of volatility, whereas the price of blue and turquoise hydrogen is linked to movements in price on the international fuel markets. However, it is also clear that changes in natural gas prices will also be reflected in the purchase price of electricity-based hydrogen production procured via the electricity markets and that the advantages of green hydrogen from a cost perspective that occur when natural gas prices are high can only be realised on the price side.

Differences in cost between green hydrogen and hydrogen from other production routes in the medium term (2030/2035) and potentially also in the longer term are at least in part categorised differently and only reflect the situation at the given time:

- The first position regards the cost differences in the foreseeable future as so small that higher offsets would be acceptable.

- The second position regards the corresponding cost differences to be so significant that it believes that making quantities of hydrogen available outside the green production route is the logical course of action.

The different positions on cost classification are due less to core beliefs and more to different expectations regarding actual trends. Detailed trend monitoring and gradual improvements in forecasting can help at least in part to reduce the gap between the different classifications.

3.4 CLASSIFICATION ON AN INDUSTRIAL POLICY BASIS

Hydrogen plays an important role in industrial policy and thus in society as well, especially for Germany as a country with a large value-adding and export component to its industrial sector.

While the prominent position of green hydrogen is undisputed in industrial policy, this aspect is understood differently for other production routes:

- The first position regards the trajectory of industrial policy as not sufficiently relevant due to a lack of acceptance for other production routes or does not deem measures to support other production routes necessary.

- The second position sees an advantage on an industrial policy level, both from the perspective of users and plant manufacturers (and their suppliers), provided that it is possible to ramp up the market at home and abroad more dynamically and flexibly than would be the case if the focus were on green hydrogen due to acceptance for a wider range of hydrogen production paths.

The different positions on classification on the basis of industry policy are less due to core beliefs and more to different expectations regarding actual trends. Detailed trend monitoring and gradual improvements in forecasting can help at least in part to reduce the gap between the different classifications.

3.5 CLASSIFICATION ON AN INNOVATION POLICY BASIS

The development of a hydrogen market in the German, European and global economies is contingent on major progress in innovation. For an economy like Germany, there are considerable opportunities in production, transport, conversion and use if progress in innovation can be made and the corresponding economic and social benefits can be achieved. At the same time, corresponding innovation effects are also dependent on the extent to which the commercialisation of innovation can be achieved, especially on an international level.

Electrolysis (green and potentially red hydrogen), renewable energy generation and the production processes for turquoise hydrogen are all relevant factors on an innovation policy level. Apart from the production of hydrogen, the generation of hydrogen derivatives, especially in plant and process engineering, is also of considerable importance to innovation policy.

While the key role of green hydrogen and hydrogen derivatives is undisputed in all facets of innovation policy, this aspect is understood differently with respect to the turquoise hydrogen production path:

- The first position regards the trajectory of innovation policy to be insufficiently relevant from a German perspective due to the lack of acceptance for production routes other than green hydrogen, or it does not consider this to be very significant here for a broadening of measures in Germany to support production routes other than green hydrogen.

- The second position primarily sees an advantage from an innovation policy perspective if a broader range of hydrogen production routes is funded under innovation policy. This is especially true in light of the fact that demand for other technologies (CCS/methane pyrolysis) is higher outside of German than in Germany itself.

The different positions with regard to the classification of hydrogen in innovation policy are based on different expectations for the future. There is limited scope to more accurately quantify the differences, or it is difficult to reduce the disparities due to early decisions made on innovation policy.

3.6 CLASSIFICATION IN GEOPOLITICAL TERMS

The ramp-up of a hydrogen market in European and international economies, the corresponding decline in demand for fossil fuels and/or rising demand for commodities will shift trade relations and the geopolitical balance of power. Therefore, considerable uncertainty and risks are to be expected during the transformation phase along with a major shift in the balance of power over the long term.

Owing to highly divergent strategies on energy and economic policy, different technological production routes will play a role during the adjustment phase. Countries with a heavy bias towards fossil fuels will also focus on production of hydrogen on the basis of fossil fuels (especially natural gas) and serve markets that emerge for this product.

Blue (and turquoise) hydrogen production is likely to become more attractive to countries that can build on their strong initial position in CCS and have transport and other infrastructure that can be adapted. Over time, it will become less attractive, especially for countries where conditions for electricity or hydrogen production based on renewables are less favourable, especially once the cost of green energy has declined noticeably.

A similar situation may arise with regard to red hydrogen for countries with a clear preference for nuclear energy if they are able to make large amounts of nuclear power available for hydrogen production at low cost.

There is general consensus that the provision of green hydrogen in a European and international context opens up a market that can be served by a large number of new and established suppliers. This offers the opportunity for diversification even with a high proportion of imported hydrogen.

However, from a geopolitical perspective, whether and in what way corresponding measures to support production routes other than green hydrogen could be useful and beneficial is still up to debate:

- The first position does not expect that opening up the corresponding supporting mechanisms to other production routes will make the necessary transition and adjustment process any easier. Furthermore, a lack of focus on green hydrogen is seen as sending too weak of a signal on direction on an international level, thereby delaying the adjustments that are inevitable in the long term.

- The second position expects that opening up the corresponding supporting mechanisms to other production routes will mitigate issues faced during the transition to a climate-neutral economy. The transition to green hydrogen production is expected primarily as a result of international market processes. The signalling effects of European actions are not considered sufficiently strong.

Central aspects of the different positions on geopolitical classification are based on different core beliefs regarding international relations. These are difficult to reconcile and, above all, would require a broad-ranging, long-term dialogue with the very different supplier regions.

Setting this aside, however, it is essential to start a European coordination process. Building a resilient energy system in Europe and establishing a long-term international network of like-minded partner countries are necessary goals in order to have a reliable hydrogen supply and strong hydrogen markets even in a world marked by geopolitical conflict.

3.7 LOCK-IN EFFECTS

Lock-in effects play an essential role in discussions regarding the different technological production routes. A lock-in effect involves a situation where the decision to make a specific investment acts to prevent the switchover to other products or suppliers due to the unacceptably high costs of doing so or due to other obstacles, even if the other products are cheaper or otherwise preferable. Lock-in effects can occur due to standards, infrastructure links, limited investment funds and/or funding and so forth.

It is unclear whether and to what extent lock-in effects may occur in a rapidly growing market for a commodity like hydrogen:

- The first position anticipates that opening up the hydrogen ramp-up (or the corresponding support mechanisms) to technological production routes outside of green hydrogen will act as a significant drag on the ramp-up dynamics for green hydrogen due to limited (accompanying) funding and, where applicable, other infrastructures. For that reason, it is expected to be counterproductive in the medium and long term.

- The second position cites the clearly limited role of technological production routes outside of green hydrogen, the correspondingly limited effects on costs and funding, and the general qualities of hydrogen as a commodity. It also sees the possibility of supplier diversification and rates the risk of lock-in effects as low, especially in view of the long-term prospects of the hydrogen economy.

The different views on lock-in risks can help reduce the gap between the various classifications through detailed monitoring of actual trends and gradual improvements in forecasting, at least in part. In some cases, appropriate safeguards can help lessen the role played by lock-in effects where there is disagreement on classification.

4 OUTLOOK

Classification of the different production routes for hydrogen and hydrogen derivatives is the result of complex and, in part, highly differentiated individual assessments as well as the underlying interplay between them. These lead to very different, and sometimes controversial, positions.

To explain the widely divergent overall assessments, it is both useful and necessary to take a differentiated look at the individual assessments, specifically with regards to aspects like environment/climate/risk, volumes, cost, industrial policy, the potential for innovation, lock-in effects and geopolitics. The individual assessments are partially shaped by different analytical findings in the scientific and technical field and partially by different economic, strategic and political considerations and their contextualisation.

In some areas, the disparities between the individual assessments can and should be narrowed through deeper or broader fact-finding or improved monitoring processes. In other areas, however, the differences in the assessments are due to vastly different expectations for the future, some of which are difficult to quantify, or core beliefs that are difficult to change, which ultimately make it necessary to strike a balance when it comes to decisions on policy direction. These policy decisions should be taken as soon as possible in spite of existing uncertainties.

In addition, prioritisation of the previously described aspects regarding classification and decisions on policy direction can be done in many different ways. Alongside improvements to fact-finding and monitoring processes, political decisions will ultimately need to be made here, too.

There are extensive requirements and implications of the highly varied structure of the decisions on the portfolio of predicted and accepted production routes in the short, medium and long term. Initially, this relates to the (broader or more narrow) range of funding and supporting measures across the entire value chain:

- What impact does the portfolio of accepted or preferred production routes have on (German) measures to fund and support hydrogen production (at home and abroad)?
- What impact does the portfolio of accepted or preferred production routes have on (German) measures to fund and support the development of a hydrogen infrastructure (in Germany and potentially in Europe)?
- What impact does the portfolio of accepted or preferred production routes have on (German) measures to fund and support hydrogen applications (in Germany and potentially in Europe)?

Taking a transparent, differentiated approach to making and justifying the corresponding policy decisions is also key with regard to the social, economic and geopolitical acceptance of a ramp-up of the hydrogen economy and for the development and integration of the markets for hydrogen and hydrogen derivatives.

To more effectively assess the consequences of policy decisions for or against a technology or production path, it is important to be aware of the different contexts of climate and environmental protection, social acceptance, the economy, industrial and innovation policy, as well as geopolitical issues and possible lock-in effects, and place them in the context of the European and global debate.

In this respect, it is important with regards to urgent policy decisions to recognise that some of the differences in classification result from expectations regarding future developments that are difficult to quantity as well as core beliefs and fundamental interests. New policy decisions are needed in this area. The system of coordinates, or classification dimensions, and descriptions of the various positions presented here offers a suitable frame of reference and justification for this policy decision in two respects:

1. There is a need for transparency in policy prioritisation or hierarchisation between the different coordinates;

2. Policy prioritisation should be accompanied by a systematic and comprehensible weighing of possible trade-offs regarding aspects classified as having lower priority.

It is important, useful and ultimately necessary to provide full and transparent information on how and why fundamental basic decisions have been made.

Classification dimensions	Core positions	Remarks/comments
A. Environmental policy		
Greenhouse gas emissions	**c)** Only green hydrogen acceptable. **d)** Blue and turquoise hydrogen are also acceptable if significant emission reductions can be achieved across the process chain compared to the use of fossil fuels. **e)** Blue and turquoise hydrogen are also acceptable if significant reductions in direct emissions can be achieved across the process chain compared to the use of fossil fuels.	Fact-finding to reveal relevant potential to narrow gap between positions, role of core beliefs limited
CO_2 capture and storage (CCS, relevant for blue hydrogen)	**a)** CCS fundamentally unsafe, rejection of any hydrogen route that includes CCS (blue hydrogen). **b)** CCS acceptable in principle and within certain limits, though competition of blue hydrogen with other CCS applications is relevant. **c)** CCS acceptable in principle and with an appropriate regulatory framework; blue hydrogen does not compete in any meaningful way with other CCS applications/helps facilitate CCS ramp-up.	Limited potential of fact-finding to narrow gap between positions, core beliefs play a major role
Nuclear energy (relevant for red hydrogen)	**a)** Red hydrogen not acceptable due to accompanying risks. **b)** Red hydrogen produced using new technologies potentially acceptable, but not within the next two decades. **c)** Red hydrogen acceptable in principle, also owing to the expected supply that will be available on the international market anyway.	Significant potential for fact-finding to help narrow gap between positions, core beliefs play a major role
B. Quantity/volume		
Demand and availability	**a)** The amount of green hydrogen that can be produced is also sufficient in the medium term (2030/35) to achieve the climate targets and the infrastructure ramp-up. **b)** Risk of not being able to secure a sufficient supply by focussing solely on green hydrogen is too high, having blue hydrogen as part of the mix desirable, role of turquoise hydrogen uncertain here. **c)** All production methods with a minimum emission reduction potential should be allowed to ensure the fastest possible hydrogen ramp-up on the application and infrastructure side.	Fact-finding to reveal relevant potential to narrow gap between positions, role of core beliefs limited
C. Costs		
Costs associated with different production routes	**a)** The difference in costs between green hydrogen and blue, turquoise (and possibly red) hydrogen is so small, even in the medium term, that the additional costs of focussing solely on green hydrogen are acceptable. **b)** The difference in costs between green hydrogen and blue (and possibly also turquoise as well as red) hydrogen are so significant, especially in the medium term, that it makes sense to make quantities of hydrogen available outside the green production route.	Fact-finding to reveal relevant potential to narrow gap between positions, role of core beliefs limited

Classification dimensions	Core positions	Remarks/comments
D. Industrial policy		
Potential for industrial policy development in Germany	**a)** Momentum in industrial policy driven by production routes other than the green one is and remains low. **b)** There are advantages from an industrial policy perspective for both application and equipment manufacturers (incl. suppliers) by having a wider range of production routes, also with a view to developments abroad.	Significant potential for fact-finding to help narrow gap between positions, different expectations for the future plays a large role, role of core beliefs small
E. Innovation policy		
Potential for innovation policy development in Germany	**a)** Momentum in innovation policy driven by production routes other than the green one is and remains low. **b)** Advantages in terms of innovation policy by having a broader focus, also in view of the expectation that technologies such as CCS and methane pyrolysis will also be in high demand internationally.	Significant potential for fact-finding to help narrow gap between positions, different expectations for the future plays a large role, role of core beliefs small
F. Geopolitics		
Geopolitical adjustments in the context of the transition to climate neutrality	**a)** Transition and adjustment processes will not be made simpler by expanding production routes beyond green hydrogen, international signal of direction too weak without a focus on green production routes. **b)** Mitigation of problems that occur during the transition phase by expanding other production routes, signal of direction from Europe has minimal impact	Limited potential for fact-finding to help narrow gap between positions, different expectations for the future/core beliefs play a major role
G. Lock-in effects		
Long-term spillover effects from medium-term portfolio decisions	**a)** Damping of long-term ramp-up dynamics for green hydrogen by opening it up to other production routes. **b)** No relevant damping of the long-term ramp-up dynamics for green hydrogen due to the limited potential from a volume perspective of other production routes in the long term.	Limited potential for fact-finding to help narrow gap between positions, different expectations for the future/core beliefs play a major role

THE GERMAN NATIONAL HYDROGEN COUNCIL

On 10 June 2020, the German Federal Government adopted the National Hydrogen Strategy and appointed the German National Hydrogen Council. The Council consists of 26 high-ranking experts in the fields of economy, science and civil society. These experts are not part of public administration. The members of the National Hydrogen Council are experts in the fields of production, research and innovation, industrial decarbonisation, transportation and buildings/heating, infrastructure, international partnerships as well as climate and sustainability. The National Hydrogen Council is chaired by former Parliamentary State Secretary Katherina Reiche.

The task of the National Hydrogen Council is to advise and support the State Secretary's Committee for Hydrogen with proposals and recommendations for action in the implementation and further development of Germany's National Hydrogen Strategy.

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