**Supplementary Material**

**Hydrogen export competitiveness index for a sustainable hydrogen economy**

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# Appendix A

## A.1. Summary of study and interview questions addressed to experts

### A.1.1. Background

The growth in global energy demand resulting from growing populations and developing economies has caused CO2 emissions to increase constantly. The COVID-19 pandemic caused a decrease in emissions in 2020, but the following year saw a rapid increase to previous levels, reaching 36.3 Gt in 2021 (IEA, 2021). Although renewable energy sources provide a carbon-free alternative, their adoption depends on various factors that reduce their reliability. The biggest of these challenges is their intermittent nature which necessitates the integration of energy storage systems.

Hydrogen is one of these energy storage options that has gained significant attention and advocates in the past few years. Hydrogen is an energy carrier that can be produced through different methods, stored, transported, and used to generate power. The resulting carbon footprint depends primarily on the production and transportation methods used. For example, hydrogen production results in minimal emissions through water electrolysis using renewable energy sources (green) or conventional carbon capture methods (blue).

More than 20 countries have announced their hydrogen strategies since 2018, and more than 19 are preparing them. National hydrogen strategies indicate the willingness of countries to develop the global hydrogen market and their eagerness to participate in a hydrogen economy. These strategies signal an upcoming shift in the global energy market that can cause a decrease in CO2 emissions if appropriately managed. The growing momentum for hydrogen can also be seen in the number and value of planned hydrogen projects. As of September 2022, more than 680 large-scale hydrogen projects have been announced globally, with investments of 240 bn USD until 2030 (Hydrogen Council and McKinsey & Company, 2022).

### A.1.2. Objectives

This study aims to introduce a hydrogen competitiveness index (HCI) used to evaluate and compare the hydrogen export potential of energy exporters. The HCI score is indicative of a country’s ability to participate in the global hydrogen market as an exporter. Different sub-scores are to be calculated from publicly available data and expert opinions. Categories currently include resource capacity, political status, adaptability, economic potential, geographical location, and human/business capability.

We also intend to assess the current situation for Qatar using its existing strengths, weaknesses, competitors, and clients within the global hydrogen market. The situation analysis will be a starting point for our hydrogen energy models. The agent-based model we will develop will help us guide policies and strategy options for Qatar based on different scenarios.

### A.1.3. Interview Questions

The following are the questions we will ask in the interview:

1. Are the selected categories and sub-categories suitable? What changes, omissions, or additions do you suggest for a better evaluation?
2. How significant is each category? What weight/percentage should we assign to each category and sub-category?
3. How competitive do you think certain countries will be in a global hydrogen market?
4. What are the strengths, weaknesses, opportunities, and threats of hydrogen export from Qatar?

In the follow-up survey, we will ask you to assign a weight to the different sub-categories based on your opinion

### A.1.4. FAQ’s

*Is this study confidential?*

Yes, this study will maintain respondent confidentiality. We will not share your details (including name, position, and affiliation) with anyone outside our small research group or publish them anywhere. Your contribution will be used solely to guide and enrich our research.

*Whose opinion do we expect?*

We acknowledge that your answers only represent your opinion as an expert in the energy field. They do not represent your institution/company’s opinion or its official viewpoint in any way.

*How long is the interview?*

Depending on the discussion, we expect the interview to take 40-60 minutes.

*Will the interview be recorded?*

Yes, we prefer to record the interview audio for better internal analysis of the answers. However, kindly let us know if you prefer not to be recorded.

## A.2. Excerpts from expert interviews

The following is a summary of important excerpts from the interviews conducted with energy experts. The excerpts were selected to show a wide range of expert input based on the authors’ best judgment. The statements are rephrased, but they capture the main opinions expressed by each expert. The expert numbers do not match the expert numbers presented for the survey results since the survey entries were anonymized.

Table A.. Summary of comments, suggestions, and recommendations given by experts during interviews

|  |  |  |  |
| --- | --- | --- | --- |
| Expert | | Comments, suggestions, and recommendations | |
| Expert #1 | | * Research center expenditure is not as important as previous experience for evaluating competitiveness. * Human capital is not enough for a country to compete globally. * Building renewable energy capacity is important for all countries. * Excess electricity can be shifted towards hydrogen, but it should remain for internal use when needed. | |
| Expert #2 | | * The domestic energy market needs should be evaluated before considering export potential. * Access to international markets is very important and should be included as a criterion when evaluating the potential of different countries. For example, some countries have sanctions and restricted access to technology. * The import of technology is easy and should not be a major category. * The cost of hydrogen production should be highlighted as an advantage for market competition. | |
| Expert #3 | | * Water usage can be a significant barrier to developing renewable energy and hydrogen production. * Economic potential and resource availability are the two most important categories * Knowledge from the LNG sector can be upgraded to the hydrogen market in one year or so, so the knowledge category is not as important as other categories. * Safety is the biggest concern for adaptability, especially regarding consumer safety. * Technology development capacity is unimportant; China will always produce cheaper solar panels and batteries. | |
| Expert #4 | | * Data from 2019 should be used since 2020-21 data is affected by COVID-19, while 2022 trade data is partly affected by the Russian war on Ukraine. * Cost and profitability determine demand and investments. * The cost of green hydrogen without governmental support/incentives is much higher than the conventional production of grey hydrogen. * Producing hydrogen for energy from natural gas is a waste of efficiency. Ammonia production is a better option due to its more efficient transportation. | |
| Expert #5 | | * In order of importance, the categories are economy (35%), resources (25%), political status (20%), knowledge (10%), and adaptability (10%). * Knowledge can be rented, so it is not as important as other categories. * Technology development can be done externally through investments in technology and research. * Policies follow economics, so economic factors are essential in driving hydrogen exports. | |
| Expert #6 | | * Opportunities for hydrogen use exist in the transportation, heating, industrial, and power generation sectors. * Challenges for the application exist in hydrogen’s transportation, distribution infrastructure, demand, and the price of green hydrogen. * Hydrogen demand evolution by region is the most important factor driving markets. * National hydrogen policies, if announced, may not be applied. * Demand will impact production capacities. * Blue hydrogen production potential (Demand, cost, lifecycle) should be evaluated in oil and gas-producing countries. * The hydrogen market needs appropriate business models (blue/green), international cooperation, and investments in research and development * Strategies to develop hydrogen trade include investment in other countries (hydrogen production at importers) since the export depends on customers. | |
| Expert #7 | | * Water requirement should not be an issue since desalination plants can be added whenever more water is needed. * LNG experience should only be considered an advantage if hydrogen is exported as a liquid. * Chemical/ physical adsorption is the predicted method for initial hydrogen export. * Retrofitting LNG ships for hydrogen transport would be difficult because of differing liquefaction temperatures and used metal. * Research should focus on clean hydrogen production for the long term. | |
| Expert #8 | | * The most important categories are resource availability and economic potential. * Knowledge is not an important category since it can be easily obtained. * Ease of business indicator can be moved under the economic category. * Governmental effectiveness can be moved to the political status category. * Water is the main concern for green hydrogen production and not solar potential. | |
| Expert #9 | | * The adaptability category is confusing and not clear. The adaptability of a country can be difficult to evaluate and, therefore, should be removed. * All other categories are applicable and contribute to the competitiveness of hydrogen export * An overlap in categories should be avoided so that no double counting takes place * Economic potential and resource availability might slightly overlap * Gas reserves are also correlated with GDP and financial status. | |
| Expert #10 | | * Technology and knowledge can come with time or be imported, so they are not as important for evaluating future competitiveness. * Strategy is not based solely on profits; diversification and stability of income are as important * A small country area is detrimental to renewable energy and should be added when evaluating potential hydrogen production. | |
| Expert #11 | | * Electricity is needed for economic development, so it would be disadvantageous to produce green hydrogen if the economy is underdeveloped. * The role of ammonia in coal plant switching/blending should be better investigated. * Critical minerals for electrolyzers can become a chokepoint for hydrogen production. * International investments can reduce the risk from resource concentration. * Resource upgrade: Green steel/industry and ammonia are premium products that are better to export than pure hydrogen. | |
| Expert #12 | | * Research and development are essential indicators. * There should be a distinction between categories that can be controlled by a country and those that cannot be controlled (political status vs. location) * Index ratings do not mean a country is locked; policies can change many aspects. * Country targets can greatly affect their future in a hydrogen economy; index ratings can be too simplistic. * Technological challenges for hydrogen transport and application will not be an issue long term. | |

## A.3. Survey questionnaire

The following questionnaire was prepared as a Google form and sent to experts. The questionnaire includes objectives, instructions, category explanations, and an AHP classification guide.

### A.3.1. Objectives

This study aims to introduce a hydrogen competitiveness index (HCI) used to evaluate and compare the hydrogen export potential of energy exporters. The HCI score indicates a country’s ability to participate in the global hydrogen market as an exporter. Different sub-scores are to be calculated from publicly available data and expert opinions.

### A.3.2. Instructions

Kindly answer the 10 questions below based on the Analytic Hierarchy Process (AHP) methodology. For example: If you think “Resource availability” is “extremely” more important than “Political status” in our evaluation of competitiveness, select “Resource availability is more important” and “9” (Goepel, 2018).

### A.3.3. Category explanations

Resource availability: Resources required for blue hydrogen production from SMR include natural gas and water. As for green hydrogen production, water and electricity from renewable energy sources are needed. The water stress index (WSI) is selected to evaluate water resources available for hydrogen production. To evaluate the potential production of hydrogen from renewable energy-powered electrolysis, we examine the potential for solar and wind energy production in each of the selected countries.

Political status: For a successful economic transformation and transition to hydrogen export, a relatively stable government is needed to adopt and implement the required changes. Transparency in government institutions is also a competitive advantage as it allows investors and companies to follow up on these processes and policies. Existing trade relations with countries planning to import hydrogen are considered an advantage.

Economic potential: The ability of governments to command a leading role in hydrogen exports can hinge on leveraging their existing economic advantages. These include existing infrastructure that facilitates hydrogen production and export, financial reserves that can be used to invest in developing projects, the ease with which private companies can do business, and the distance to potential clients.

Knowledge: How governments respond to changes in the global energy market can depend on the available human capital with its experience, education, and ability. The value of research and development cannot be understated as it is a good measure of the potential to prosper in a hydrogen economy. Experience in handling large quantities of natural gas and dealing with international trade partners and clients can also positively affect the developing hydrogen industry.

Adaptability: A nurturing business environment and a government that effectively promotes change should exist for economies to undergo a complete transformation. The ease of doing business is a benchmark of the different aspects of business regulation in a country that can be used to rate the strength of the business environment. The government’s effectiveness captures the quality of policy formulation and implementation and how committed the government is to such policies.

### A.3.4. AHP classification guide (Saaty, 1987)

Table

Description automatically generated

### A.3.5. Survey questions

1. Resource availability vs. Political Status

Resource availability is more important

Political status is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Resource availability vs. Economic Potential

Resource availability is more important

Economic Potential is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Resource availability vs. Knowledge

Resource availability is more important

Knowledge is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Resource availability vs. Adaptability

Resource availability is more important

Adaptability is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Political Status vs. Economic Potential

Political Status is more important

Economic Potential is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Political Status vs. Knowledge

Political Status is more important

Knowledge is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Political Status vs. Adaptability

Political Status is more important

Adaptability is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Economic Potential vs. Knowledge

Economic Potential is more important

Knowledge is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Economic Potential vs. Adaptability

Economic Potential is more important

Adaptability is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

1. Knowledge vs. Adaptability

Knowledge is more important

Adaptability is more important

They are equally important (please also select “1” in the next question)

How much more is it important?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  |
| Equal importance |  |  |  |  |  |  |  |  |  | Extreme importance |

## A.4. Survey - AHP results

The category weights for individual and group expert survey preliminary results are shown in Table A.2, and the consolidated decision matrix for the preliminary results is shown in Table A.3. After removing the adaptability category and re-analyzing the data, the results are shown in Table A.4, and the consolidated decision matrix for the final categories is shown in Table A.5.

Table A.. Preliminary category weights from the expert survey by participant and group

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Weights | Resource availability | Political Status | Economic Potential | Knowledge | Adaptability | CR |
| Group result | 0.340795 | 0.184012 | 0.272115 | 0.120768 | 0.08231 | 0.027438 |
| Expert #1 | 0.070377 | 0.257359 | 0.270234 | 0.133189 | 0.268841 | 0.103933 |
| Expert #2 | 0.409823 | 0.136489 | 0.354461 | 0.036209 | 0.063018 | 0.129678 |
| Expert #3 | 0.485223 | 0.241656 | 0.132035 | 0.040038 | 0.101048 | 0.086988 |
| Expert #4 | 0.439024 | 0.233969 | 0.209424 | 0.090919 | 0.026665 | 0.403541 |
| Expert #5 | 0.095947 | 0.104723 | 0.204273 | 0.548484 | 0.046573 | 0.188711 |
| Expert #6 | 0.329261 | 0.180774 | 0.157962 | 0.225357 | 0.106646 | 0.295825 |
| Expert #7 | 0.282795 | 0.039911 | 0.278352 | 0.252484 | 0.146458 | 0.165563 |
| Expert #8 | 0.423912 | 0.184222 | 0.334325 | 0.032076 | 0.025465 | 0.305035 |
| Expert #9 | 0.594707 | 0.158883 | 0.174782 | 0.046578 | 0.02505 | 0.195794 |
| AHP Consensus | 0.641627 |  |  |  |  |  |

Table A.. Consolidated decision matrix for preliminary categories

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Resource availability | Political Status | Economic Potential | Knowledge | Adaptability |
| Resource availability | 1 | 2.723053 | 1.544452 | 2.212433 | 2.632655 |
| Political Status | 0.367235 | 1 | 0.636483 | 1.719271 | 3.071069 |
| Economic Potential | 0.647479 | 1.571133 | 1 | 2.568185 | 3.670608 |
| Knowledge | 0.451991 | 0.581642 | 0.38938 | 1 | 1.591042 |
| Adaptability | 0.379845 | 0.32562 | 0.272434 | 0.628519 | 1 |

Table A.. Revised weights from the expert survey by participant and group

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Weights | Resource availability and potential | Political and regulatory status | Economic and financial potential | Industry knowledge | CR |
| Group result | 0.396214 | 0.184289 | 0.288852 | 0.130645 | 0.019103 |
| Expert #1 | 0.064396 | 0.385618 | 0.370263 | 0.179723 | 0.070871 |
| Expert #2 | 0.452244 | 0.112357 | 0.389486 | 0.045913 | 0.113972 |
| Expert #3 | 0.546566 | 0.262024 | 0.139246 | 0.052164 | 0.104409 |
| Expert #4 | 0.483633 | 0.240156 | 0.202495 | 0.073715 | 0.66328 |
| Expert #5 | 0.114202 | 0.076295 | 0.179596 | 0.629907 | 0.126085 |
| Expert #6 | 0.412817 | 0.143381 | 0.221901 | 0.221901 | 0.185625 |
| Expert #7 | 0.396813 | 0.061693 | 0.29473 | 0.246765 | 0.0844 |
| Expert #8 | 0.453628 | 0.176622 | 0.336415 | 0.033335 | 0.564015 |
| Expert #9 | 0.661419 | 0.145812 | 0.155887 | 0.036883 | 0.219007 |
| AHP Consensus | 0.627561 |  |  |  |  |

Table A.. Consolidated decision matrix for revised categories

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Resource availability and potential | Political and regulatory status | Economic and financial potential | Industry knowledge |
| Resource availability and potential | 1 | 2.572802 | 1.544452 | 2.212433 |
| Political and regulatory status | 0.388681 | 1 | 0.636483 | 1.719271 |
| Economic and financial potential | 0.647479 | 1.571133 | 1 | 2.568185 |
| Industry knowledge | 0.451991 | 0.581642 | 0.38938 | 1 |

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