Exporting Renewable Energy from South Africa

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Abstract: Due to high population density and low renewable resources, Europe will struggle to meet its energy needs only from internal renewable resources. This presents a very significant export opportunity for South Africa. Much of Asia has the same renewable potential that Europe has and a market larger than that of Europe. South Africa is in a favourable position to be able to provide a significant amount of renewable energy to Europe and other solar resource deficient areas by exporting some of its abundant renewable energy. The challenge has been the conversion of this energy into a form that can be transported and stored conveniently. Renewable generated hydrogen may offer the best option for this. Besides being used for electricity generation and as a transport fuel, hydrogen also has an opportunity to be used directly in other energy requirements where electricity is not the best alternative, such as in steel and cement production.

With its significant solar and wind resources and low population density, South Africa can become a significant participant as a renewable energy exporting country supplying the growing market in Europe and Asia. This can become a major new export opportunity. However, to reach this point, it will be important to be part of the research and development work needed to optimise the associated processes. South Africa should endeavour to find ways to utilise the progress that is being made around the world to determine how best to utilise the international work to build towards this opportunity.

Keywords: Hydrogen; Renewable Energy; Energy Market; Export Opportunity; Hydrogen Research

1. Introduction

In his 2008 book entitled "Sustainable Energy – without the hot air", John MacKay performed a bottom-up analysis of the energy usage by the average person in the UK [1]. He then did the same calculations for the amount of renewable energy that could technically be provided in the country with full development of the resources. He concluded that it would not be feasible to produce enough energy in the UK to supply all of the energy requirements of the country. From inference, he extended this conclusion to all of Europe. He stated that, "*Well, how about living on someone else's renewables? (Not that we have any entitlement to someone else's renewables, of course, but perhaps they might be interested in selling them to us.)*" [1, p. 177]. This indicates the potential for areas with excess solar and wind resources to be able to export the energy to meet this shortfall. Much of the major population centers of the world – Europe, Asia and part of North America have this potential shortfall for sustainable energy production.

This book was written in 2008, and since then, there has been much progress on renewable generation. It is important to revisit the basic assumptions to see whether the conclusion he reached at the time is still valid. Assuming that this conclusion is generally correct, there is an opportunity for South Africa that should be explored, which will be done in the following discussion.

2. Background

South Africa currently has an annual energy balance, (that is imports, exports and production), of approximately 8 000 PJ with energy exports of 2 000 PJ [2]. The energy balance in the European Union (EU) countries is 61 900 PJ per year [3]. Thus, the European market is over ten times larger than that of South Africa. Of this total, the EU imports over 37 000 PJ of their energy requirement, mainly in the form of oil and gas [3].

These numbers indicate that the EU is a very large energy market. It is not as large as the energy usages in China, at over 140 000 PJ per year and the USA at over 115 000 PJ [2]. However, the amount of energy that is imported into the EU, at 37 000 PJ, is larger than either of these markets (Figure 1) [2][3]. The total importation market for energy from China, Japan and Europe is over 70 000 PJ. These large energy markets present opportunities for countries with excess renewable resources.

In South Africa, the electricity portion of the energy usage is 1 900 PJ with a electricity output of 900 PJ [2]. In the more common expression of electricity usage, this corresponds to approximately 250 TWh of electricity production per year. In the EU, the numbers are 24 900 PJ of electricity energy usage with a electricity production of 10 600 PJ or 2 900 TWh [3]. The ratio of EU electricity to SA electricity is over eleven times larger.

Germany is the largest economy in the EU and is known for its efforts in renewable power generation. To understand the ability for the EU to meet its energy needs, it might be easier to look at Germany than looking at the entire group of countries. The total energy usage in Germany is 14 000 PJ per year, with net imports of 7 000 PJ, mainly oil and gas. Electricity production is 647 TWh [3].

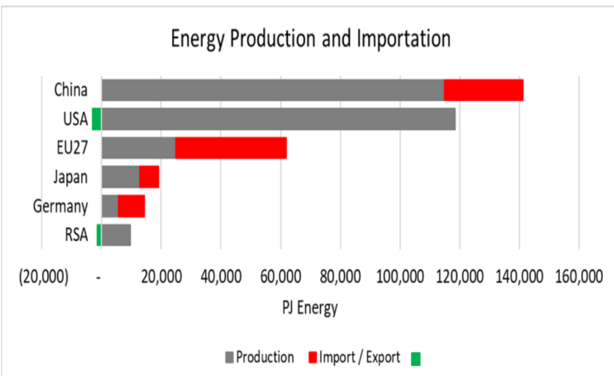

Figure 1- Energy Consumption of major countries [2][3]

Germany has been in the lead for development of its wind and solar resources for the last decade. It has installed significant amounts of both of these generation sources. For wind electricity production, there are over 27 000 wind turbines installed in Germany, covering over 7% of the land area in the country [4]. The total installed wind generation capacity is over 58 GW on land with an additional 4 GW in the German North Sea [5]. In 2019, this resource provided 110 TWh or 17% of the total electricity consumed in the country [5]. With 7% of the land already covered with wind generation, the upside for additional wind generation is limited. The debate in Germany is around the expectation that this limit could be as high as 80 GW or as low as 65 GW, depending on offsets between turbines and distance from populated areas [4]. This implies that the maximum expected wind generation would be something less than 22 % of the total electricity generation. For solar energy, the installed PV capacity is 49 GW, with generation of 39 TWh, 6% of the total electricity generation [6]. Solar installations do not cover much of the country and the limitations are unlikely to be on land usage, but on useful output. IRENA has forecast that solar PV could eventually expand to supply approximately 22% of the electricity in Europe by 2050 [7]. This would imply that PV in Germany could grow to nearly 200 GW.

If we assume that wind capacity is expanded to the estimated limit of 80 GW and solar is increased to 200 GW with storage to make maximum use of the generation, the generation would be 300 TWh, or 46 % of the overall electricity generation. This has not made any inroad into the energy usage outside the electricity sector.

With Germany, even after all of its efforts, unable to meet its energy needs, people have pointed to the wind generation potential from the North Sea as a potential solution, with high-capacity factors and less restriction on “land” usage. The area of the North Sea is 570 000 km^2, [8] somewhat larger than the 357 000 km^2 of Germany [9]. If it is assumed that the installed wind capacity could be 3 MW per km^2, covering the entire North Sea with turbines could accommodate up to 1 700 GW of capacity with an output of 4 000 TWh [5]. This would meet the current electricity generation requirement in Europe but not have any impact on meeting the remaining energy demand. However, it would not be feasible to cover the entire North Sea with wind generation, so the real limit is much lower than this.

Even with all of the advances that have been made in solar and wind generation since 2008, the conclusions that were made at that time are still valid for the UK, Europe and for much of the developed world. As noted in that book, this should create opportunities for renewable energy resource rich countries to develop export systems to supply these energy shortages. South Africa should be able to benefit from this opportunity.

As noted above, the energy demand in Europe is about ten times the energy utilisation of South Africa. The population of the EU is 447 million people compared to 59 million in South Africa [11][12], with an area of 4.2 million km^2 in the EU and 1.2 million km^2 in South Africa [3][12]. The solar resource in South Africa averages approximately 2 500 Wh/m^2 per year compared to less than 1 000 Wh/m^2 per year in the EU [13]. Due to lower population density and higher solar irradiance, the solar energy density per person in South Africa is over five times larger than in Europe.

With South Africa able to meet its energy demands from its local wind and solar resources, the question is how to export the excess energy that it can produce. The simplest method of exporting solar energy is by exporting electricity. However, this is limited in the range of markets that can be supplied by the limits of the length of the transmission lines. While northern Africa can supply much of Europe directly with electricity [14], this is not realistic for South Africa. None of the major potential markets, Europe, the United States or Asia, are within a range that would allow export of solar energy from South Africa in the form of electricity. The longest transmission line in the world is currently 2 350 km [15], compared to the distance between Cape Town and London of more than 9 000 km. The alternative to this is conversion of the generated electricity into a gas, liquid, or solid fuel. The most widely discussed alternative is hydrogen. Hydrogen derived from renewable energy sources is termed as green hydrogen which emits no CO_2 in the production process.

Hydrogen is the most common element in the universe. Hydrogen combines easily with many elements and is stable with those combinations, such as water, ammonia and hydrocarbons. It takes a significant amount of energy to break the hydrogen from these molecules. Hydrogen can be derived using a number of different processes; thermochemical, electrolytic, direct solar water splitting as well as biological processes [23]. Currently, the majority of hydrogen is derived from natural gas using steam reforming, a thermochemical process. This is termed as grey hydrogen and produces significant volumes of CO_2 in the production process.

Hydrogen can be used for electricity generation and as a transport fuel. Hydrogen also has an opportunity to be used directly in other energy requirements where electricity is not the best alternative, such as in steel and cement production. Direct use of hydrogen in steel and cement production presents pathways to decarbonise these production processes [16]. Various uses for hydrogen in these activities are currently under investigation.

Europe currently imports over 37 000 PJ of energy in the form of oil and natural gas, and China and Japan combined import a similar amount. Thus, there is currently an international market of over 70 000 PJ of energy. These areas are unlikely to be able to reduce these values with local renewable energy.

In 2019, the IEA performed an analysis of the cost of generation of green hydrogen around the world based on the available wind and solar resources in the region. The results can be seen on the map where the projected costs of hydrogen production are shown (Figure 2), Europe will have an expected generation cost of over USD 3 per kg of hydrogen. As can be seen from this map, the expected cost of generation of green hydrogen from South Africa is amongst the lowest in the world with costs less than USD 1.6 per kg [17]. This presents a large opportunity for those areas that can produce excess sustainable energy. Other than South Africa, the locations with this potential have been identified as northern Africa (extending into middle East countries such as Saudi Arabia), Australia and Chile [18].

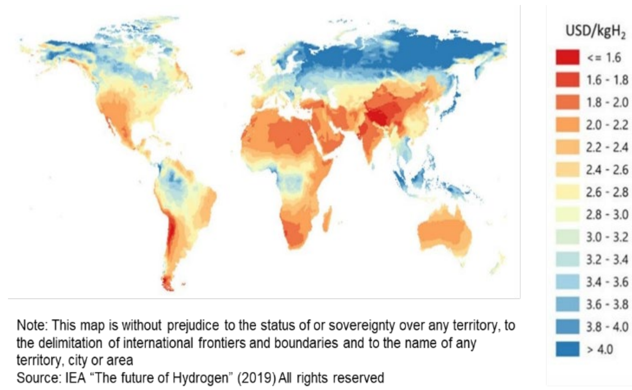

Figure 2 - Potential hydrogen costs in long term [17]

South Africa currently exports approximately about 2 000 PJ of energy per year mainly through coal exports [2]. As the world moves away from coal generated electricity, these exports are likely to decrease significantly. Exporting 2 000 PJ of solar and wind derived hydrogen would meet 3% of the current international energy market. Even if all of the potential supply countries develop their export potential, the market should easily be able to absorb this production. It is probable that the ultimate opportunity for hydrogen export from South Africa could be much larger than this.

The price of natural gas in the international market ranges around the USD 10 per GJ price [19], so meeting this price would indicate an export opportunity of approximately USD 20 billion per year for the export of 2 000 PJ of hydrogen per year from South Africa. Assuming a carbon tax premium on fossil fuels, the competitive price target could be as high as USD 15 per GJ, which would indicate that this could be a USD 30 billion per year export opportunity or larger.

To develop 2 000 PJ of hydrogen per year, South Africa would have to generate 800 TWh of energy from wind and solar sources dedicated to this export. Based on the size of current PV and CSP projects in the Northern Cape, this would require approximately 8 000 km^2 (90 x 90 km), or about 2 % of the land area of the province [20]. It is also expected that wind energy would be utilised, so the amount of land for solar generation would be reduced by a proportional amount. Wind generation is more disperse, so the area that would be involved in wind generation would be more extensive, but with lower impact. Assuming that half of the energy would come from wind, the area for wind development, based on 3 MW per km^2, would be 33 000 km^2 (182 x 182 km) and involve the installation of 33 000 turbines. This would occupy about 8 % of the land in the province – similar to that currently involved in wind generation in Germany with a similar number of wind turbines.

3. The Hydrogen Export Opportunity

Production of hydrogen from solar and wind generated electricity is not complex, but it requires a significant amount of electricity. Straight electrolysis requires about 50 kWh of electricity to produce one kilogram of hydrogen – which has an energy value of about 120 MJ, thus 8 kg of hydrogen must be produced for 1 GJ of hydrogen fuel, requiring about 400 kWh of electricity. With higher temperature, the amount of power drops, presenting a possibility to use solar generated heat directly in the process [21].

As the price of electricity generated from solar and wind resources has dropped to bring them to the lowest cost generation options, the associated cost of hydrogen produced from these sources has declined significantly. It is expected that with this low-cost electricity and the declining cost of the electrolysis systems, the cost of hydrogen on an energy basis will become competitive with fossil fuels on a cost for energy basis by 2030 [18].

The main components to the export of hydrogen are the production of the hydrogen, its storage and then the transport of the hydrogen to the market (Figure 3) [22]. Each of these areas is currently reasonably understood but each will require innovation and optimisation to be able to develop a reasonable cost supply opportunity. All of the areas are subject to international and local research programmes. To develop the opportunity in South Africa it will not be necessary to replicate all of the work done elsewhere, but it will be necessary to put all of the elements together into a process that works well in the South African context.

As noted by IRENA, for production of green hydrogen, the two major factors are the cost of electricity and the capital and operating cost of the electrolysis system [18]. As noted above, each kg of hydrogen takes nearly 50 kWh of electricity, which means that at a cost of USD 0.02 per kWh, the electricity for one kg would be USD 1.0 and at USD 0.06, the cost would be USD 3.0. Internationally with wind and solar generation heading towards the USD 0.02 range, these costs indicate that green hydrogen could be produced at a cost competitive to fossil fuels. As will be seen in Figure 4 below, even with a cost of USD 0.02 per kWh, the cost of electricity will be approximately half of the overall cost of green hydrogen production. Optimising the cost of this supply will be the fundamental factor in creating a commercial opportunity.

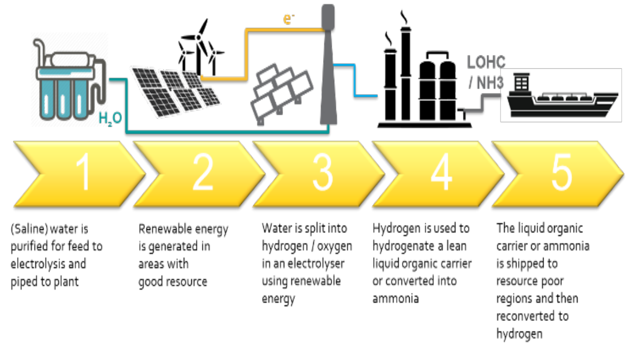

Figure 3 - Steps in green hydrogen export

Water can be split into hydrogen and oxygen using electrolysis with heat and electricity being applied to raise the energy level to the point where the oxygen and hydrogen break apart. Electrolysis is considered the most probable method for commercial green hydrogen production, with no CO2 production in the process. Currently, there are three main types of electrolysers under development: alkaline, polymer electrolyte membrane (PEM), and solid oxide electrolyser cells (SOEC). The most developed to date are alkaline electrolysers. These use a solution of potassium hydroxide as the electrolyte and have been in commercial use for many years.

The second type of unit is a PEM electrolyser. Unlike an alkaline electrolyser, the electrolyte is a solid ion conducting membrane. This membrane has a polymer structure with sulphonic acid groups attached that allow for proton transfer. Internationally, much of the current research is focused on improving PEM electrolyser performance [24].

SOEC electrolysers use a solid ceramic material as the electrolyte. SOECs have gained attention as they operate at high temperatures (approximately 500–950 °C) which reduces the electrical energy requirements by application of heat energy which might lower the energy input cost [21].

In the United States, the National Renewable Energy Laboratory (NREL) recently performed an analysis of the cost for PEM electrolysers and concluded that in the coming years the capital cost for these systems will drop to approximately half of the current cost - from nearly USD 600 per kW of capacity to slightly above USD 200 per kW. These changes will not be due to technological improvements but rather from manufacturing improvements once the systems achieve industrial scale production. This is a similar cost improvement curve to that seen in wind and solar PV as these technologies shifted to industrial level development [24].

Hydrogen storage conceptually is similar to natural gas storage and this is a well-developed technology with a large international market. It is not expected that there will be major technological advances in this area, but there are a number of areas where the particular properties of hydrogen require unique solutions. For South Africa, with minimal natural gas business, this will be a matter of determining what works best in this environment.

It appears at this time that the most economical solution for both storage and transport of hydrogen is to convert the hydrogen into ammonia or to hydrogenate an oil substance to hold a given amount of hydrogen within the oil bonds. This is termed to be a Liquid Organic Hydrogen Carrier (LOHC). At the end use location, the hydrogen would be removed from the LOHC and the uncharged oil taken back to the generation point for recharge. The LOHC can be stored and transported in the same way as oil. It is estimated that the hydrogen content of an LOHC can be up to approximately 8% by volume [25].

For ammonia storage and transport, the hydrogen is converted into ammonia (NH_3) with the addition of nitrogen. Once converted into ammonia, it can be used directly as a fuel or have the hydrogen removed to use as a fuel with the nitrogen being released into the atmosphere. Nothing is returned to the generation location. Tests are currently being conducted to verify the direct use of ammonia as a marine fuel [26]. There are also tests being conducted for ammonia based fuel cells [27].

While the entire process of green hydrogen is well understood, the current costs for electricity and the hydrolysis equipment is too high for commercial application. It will be necessary to minimise the cost of electricity as well as the capital cost of electrolysis to make this a competitive alternative. With the expected costs for each of the major portions of the process, the cost of hydrogen production in South Africa can be forecast to come up to slightly over USD 2 per kg delivered to Europe, as shown in Figure 4. There is extensive research being done around the world in all aspects of this process. With the size of the South African research budgets, it is not likely that South Africa will match the research efforts being done elsewhere, so the best alternative should be to closely follow the work being done around the world and determine what would work best in a South African based export system.

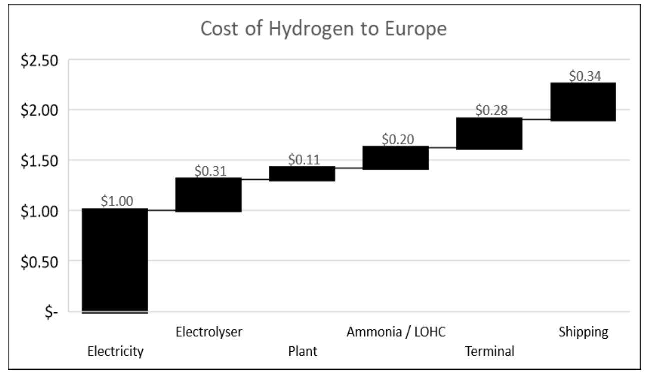

Figure 4 - Forecast cost of hydrogen export from South Africa

4. Research Requirements

As noted above, South Africa is unlikely to be able to match the research efforts that are being done elsewhere to develop new technologies for electrolysis as well as the storage and transport of hydrogen fuels. The choice of technology for the production of hydrogen will be something that can be optimised for South Africa specific conditions. There will be considerations for capital cost, operating cost and life span. System operating flexibility is a requirement as the input from renewable sources is likely to have considerable daily and seasonal variation.

As the intent is to be part of the international market, the form for storage and transport of hydrogen, whether as ammonia or via an LOHC or other forms, will be dictated more by the major markets than by individual supply countries. Development of LOHC or ammonia technologies in South Africa will not be useful if not accepted by the European or Asian markets.

The number of inputs into the optimisation of the green hydrogen process are extensive and changing rapidly as the costs of all of the elements decline over time. It will be essential to build models for the system that incorporate all of the inputs and model the optimisation points within the framework of changing variables over time. The inputs include the cost and generation capacity of wind and solar generation – PV and CSP as well as diurnal energy storage plus the capital cost, operating cost, life and operational flexibility of the electrolysis systems. Building a complete and flexible model will allow the researchers to advise policy makers and investors on areas that must be optimised to make this opportunity effective.

With time, the relationship of the input variables into a South African green hydrogen export model will change and the model must be able to address the changing relationships in the variables to keep the system optimal. One of the benefits of the renewable energy sphere is short lead times and the ability to incorporate revisions into the system as changes develop. This should be carried into the green hydrogen system and modelled accordingly. In addition, it is essential to establish the accuracy of the input information as well as the conclusions developed from the model. This should involve collection of data from developed projects as well as the development of pilot programmes as deemed appropriate.

As this work is just being started, it is not possible to accurately predict what results will come from this effort. However, the intent is to build a model that will be useful in assisting to optimise green hydrogen projects for the export market in South Africa.

5. Conclusion

It has been noted that much of the developed world will have significant challenges to meet their energy needs from local renewable resources. On the other hand, some regions have more solar and wind resources than are needed to supply local needs. South Africa fortunately falls in this second group. This provides a significant opportunity for the country to create an export business that can provide renewable energy to this market in the form of green hydrogen. This is an opportunity that should be pursued in the country. To develop the appropriate systems doesn't require research for all of the involved technologies. Relevant research is being done all around the world. What will be required is a good understanding of the available technologies for all parts of the process; electricity generation, hydrolysis, hydrogen storage and transport. The ability to combine all of these elements optimally in South Africa to ensure least cost is the requirement that must be met for commercial development. To be ready to develop this opportunity, the systems integration analysis must commence.

The area where South African research can add the most value into the green hydrogen process is the optimisation of the energy input which is the major cost factor in the production process. South Africa has excellent wind and solar resources and the expertise to exploit these resources in the most economical and effective way.

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