CLEAN ENERGY TRANSITION IN PERU: A GREEN HYDROGEN PERSPECTIVE

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ABSTRACT

For anyone concerned about climate change, fostering the energy transition from fossil-based to low- or zero-carbon energy sources is a must. In this context, this work provides a brief overview of the clean energy transition in Peru, accounting for a green hydrogen perspective. Accordingly, after the corresponding introduction to the subject, the current situation of renewable energies in Peru is highlighted, along with their historical evolution during the last two decades or so, and the prospects for these more environmentally friendly energy sources in the following years. Next, the potential for renewable energy production in Peru is discussed, with especial emphasis on hydropower, wind, solar, and biomass. Finally, green hydrogen and its potential to contribute to the energy transition in Peru is addressed. A particular emphasis is put in this case on the production of green hydrogen and its applications in Peru and worldwide. From the discussions carried out in this work, it is concluded that, although Peru has a large potential to become a green hydrogen producing and exporting country, there is still a long way to go before Peru can achieve the desired carbon neutrality in the coming decades.

Keywords: Clean energy transition; Renewable energy; Wind energy; Solar energy; Biomass; Green hydrogen.

RESUMO

Para qualquer pessoa preocupada com as mudanças climáticas, é essencial promover a transição energética de fontes de energia baseadas em fósseis para fontes de baixo ou zero carbono. Nesse con-texto, este trabalho fornece uma breve visão geral da transição para energia limpa no Peru, focando em uma perspectiva do hidrogênio verde. Assim, após a correspondente introdução ao tema, destaca-se a situação atual das energias renováveis no Peru, sua evolução histórica nas últimas duas décadas e as perspectivas para essas fontes de energia mais ecológicas nos próximos anos. Em seguida, discute-se o potencial de produção de energia renovável no Peru, com ênfase especial em energia hidrelétrica, eólica, solar e biomassa. Por fim, aborda-se o hidrogênio verde e seu potencial para contribuir com a transição energética no Peru. Uma ênfase particular é colocada na produção de hidrogênio verde e suas aplicações no Peru e no mundo. A partir das discussões realizadas neste trabalho, conclui-se que, embora o Peru tenha um grande potencial para se tornar um país produtor e exportador de hidrogênio verde, ainda há um longo caminho a percorrer para que o Peru alcance a desejada neutralidade carbônica nas próximas décadas.

Palavras-chave: Transição para energia limpa; Energia renovável; Energia eólica; Energia solar; Biomassa; Hidrogênio verde.

1. INTRODUCTION

The catastrophic threats that humanity may face due to climate change have been documented on numerous occasions in the past (RIPPLE et al., 2020). In addition, since about three-quarters of the emissions that pushed global average temperatures 1.1°C higher than that of the pre-industrial age have been attributed to the energy sector (IEA, 2021a), any solution to the climate change problem must include this sector. Furthermore, in modern society, energy consumption and human well-being are directly related to each other (INTERACADEMY COUNCIL, 2007; IEA, 2021a). Therefore, considering that by 2050 the world population will increase by about 2 billion people (IEA, 2021a) and that there will be a greater number of people with higher incomes who will demand for additional energy services, it is natural to expect that world energy demand will increase as well. The question now is how to meet this additional energy demand without further exacerbating the climate change problem. In this context, the progressive increase in the use renewable energy sources and more environmentally friendly energy production-related technologies is key.

Currently, in most countries, including Peru, energy production comes from burning natural gas and other hydrocarbon-based fuels. Renewable energies such, as solar or wind represent only a small percentage of the energy matrix. What it is interesting in the Peruvian electricity matrix, indeed, is that at the beginning of this century about

93% of the country's total energy was produced from hydropower, 4% from natural gas, and 3% from other sources, including diesel and carbon (OSINERGMIN, 2019). However, in 2018, 55% of the total electricity came from hydropower and 37% from natural gas. Since during the past two decades the annual growth rate of the total energy produced in Peru was about 7% (OSINERGMIN, 2019), this means that most of the increase in energy demand during this period was covered by natural gas. Although in terms of gaseous emissions natural gas is cleaner than diesel and carbon, this implies that CO2 emissions associated with energy generation in Peru increased significantly during the last twenty years or so. Notice that, in 2018, the share of renewable energies (different from hydropower) in the Peruvian energy matrix was about 7.2% (OSINERGMIN, 2019). Although this share is still small, it represents an advance in terms of use of renewable energy sources because in 2008 this share was 0%.

The potential to produce renewable energy in Peru is relatively large. For instance, for hydropower, solar, and wind, this potential represents about 70, 25, and 20 GW, respectively (OSINERGMIN, 2019). Nevertheless, only about 7.1, 1.1, and 1.8% of this potential is currently utilized. There is a big room then to keep increasing the share of renewable energies in the Peruvian energy matrix. One of the drawbacks of some renewable energy sources, such as wind or solar, is their variability with weather conditions and time of the day (year). A solution to this issue is to use these renewable energy sources to produce hydrogen that can be stored and used when the wind or sun is not available. When involving renewable sources, water electrolysis is the main technology used for producing the so-called 'green' hydrogen. As previously reported (NIKOLAIDIS and POULLIKKAS, 2017; YODWONG et al., 2020), hydrogen production via water electrolysis is a promising technology. Electrolysis can be carried out indeed at both high and low temperatures, but the latter is the most widely used type of electrolysis nowadays (NIKOLAIDIS and POULLIKKAS, 2017). Thus, this specific hydrogen production technology will be accounted for in the discussions carried out in this work.

It is worth noticing here that, as highlighted in the WEO (World Energy Outlook) 2021 (IEA, 2021a), the tomorrow's energy economy is expected to be very different from the one currently in place. In particular, because of the ongoing global decarbonizing process, human society is expected to increasingly meet its energy needs with electricity. As shown in Figure 1, indeed, according to the different long-term scenarios accounted for in the original work (IEA, 2021a) used as reference here, (i) STEPS (Stated Policies Scenario), (ii) APS (Announced Pledges Scenario), and (iii) NZE (Net Zero Emissions by 2050), electricity usage is expected to increase up to 50% by 2050. Similarly,by 2050, the share of (variable) renewable energy sources in electricitygeneration is also expected to increase between 40 to 70%, which is well above the current 10% value (Figure 1). In addition, contrarily to what happens today, the future energy system is expected to involve much more complex interactions between fuels (solid, liquid, and gaseous) and electricity. For instance, according to the NZE by 2050, around 40% of primary energy is expected to be converted at least twice before reaching end-users (IEA, 2021a). That is, energy is expected to travel through batteries, electrolyzers, and fuel cells undergoing conversions from electricity to heat or fuels, and vice versa. In this sense, low- or zero-carbon (green) hydrogen is expected to be key to helping manage the imbalances between variable energy supply and demand.

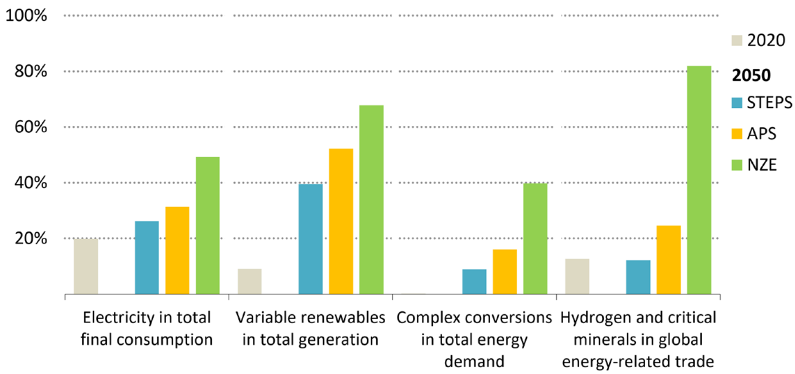

Figure 1 - Current and future indicators of energy systems (IEA, 2021a)

Naturally, the clean energy transition to an energy economy where electricity and renewable energy sources play a key role is also expected to significantly change the energy-related trade patterns, which have long been dominated by fossil fuels. Thus, as shown in Figure 1, the share in global energy-related trade of low-carbon hydrogen and critical minerals like lithium, an essential material to manufacture batteries, is expected to increase up 80% by 2050 (NZE). In this context, Peru has a big opportunity to become a key player in the future energy economy. This is true because Peru has both a huge potential to pro duce renewable energies and a long coastline with access to seawater, which represent the basic ingredients to generate large amounts of green hydrogen. Eventually, this produced hydrogen can be used not only for local consumption, but also for export to other countries. Similarly, the recent discovery of a vast deposit of lithium in Peru's southern region of Puno (NUNEZ-PALOMINO, 2020) also represents a big opportunity for the country to diversify and multiply its incomes from natural resources, and to become a lithium exporter country, such as Chile and Argentina. Of course, exporting lithium raw material is not enough. Local technology needs to be developed and expertise needs to be built up to produce lithium batteries, and to create more employment opportunities and increase the country's incomes. In this sense, cooperation agreements such as the one signed between PUCP and H2 Peru (EYNG, 2021) are welcome because they will allow the training of the high-level professionals who will make the expected clean energy transition a reality in the country.

Accordingly, in this work, accounting for a green hydrogen perspective, an overview of clean energy transition in Peru is provided. Thus, after this introduction, in Section 2 the current situation of renewable energies in Peru is highlighted, along with their historical evolution during the last two decades or so, and the prospects for these energy sources in the coming years. Next, in Section 3 the potential for renewable energy production in Peru is discussed, with especial emphasis on hydropower, wind, solar, and biomass. Section 4 focuses in turn on green hydrogen and its potential to contribute to the clean energy transition in Peru. A particular emphasis is put in this section on the production of green hydrogen and its applications in Peru and worldwide. Finally, some final remarks are summarized in Section 5.

2. RENEWABLE ENERGY IN PERU

In this section, the current situation of renewable energies in Peru is highlighted. This is complemented with the historical evolution of these environmentally friendly energy sources during the last two decades or so, and their prospects for the coming years.

2.1 Historical evolution

As a result of the first auction involving renewable energy resources (RER) carried out by the Peruvian Energy and Mining Investment Supervisory Agency (OSINERGMIN), non-conventional renewable sources (solar, wind, and biomass) started playing a role in the Peruvian energy mix around 2009 and 2010. At that time, the first photovoltaic plants were awarded, including Tacna Solar (20 MW), Majes Solar 20T (20 MW), Panamericana Solar (20 MW), and Grupo T Solar Global S.A. (20 MW). In addition to the referred solar projects, in this first auction, wind and biomass projects were also awarded. More specifically, hree wind power plants, (i) Talara (30 MW), (ii) Marcona (32 MW), and (iii) Cupisnique (80 MW), and two biomass ones, (i) Paramonga I Cogeneration Biomass Power Plant (23 MW) and (ii) Huaycoloro Biomass Power Plant (4.4 MW) were awarded (OSINERGMIN, 2019). The referred first auction covered 430 MW, representing 87% of the auctioned demand (OSINERGMIN, 2019). Notice that the entry into operation of the Huaycoloro power plant in 2011 represented the starting point of the use of RER in the Peruvian National Interconnected Electric System (SEIN) (BNE, 2019). Since the end of the first energy auction in 2010, until 2019, three additional auctions were held, which allowed increasing the presence of renewable generating plants in the SEIN. This occurred because several of the projects awarded in these four auctions progressively came into operation (OSINERGMIN, 2019).

Accordingly, Figure 2 highlights the historical evolution of both the installed capacity and the electric generation by source in Peru during this century. Accounting for the electric generation, specifically, it is noticed from this figure that since 2010 or so the share of non-conventional renewable sources in the Peruvian electricity matrix progressively increased. Nevertheless, it is also observed that the generation of electric energy using non-renewable sources-based power plants did so as well. This occurred due to the increase in electricity demand, which during the period under analysis grew at an average annual rate of 6% (MENDIOLA et al., 2012). To meet this additional demand, it was necessary to increase the electricity production in Peru. In particular, due to the availability of large amounts of natural gas from Camisea, in this period, thermoelectric power plants featured the highest average growth rate, 20%. Hydroelectric power plants in turn grew at an average rate of 1% only (MENDIOLA et al., 2012). In 2020, because of the pandemic caused by the Coronavirus, compared to the previous year, the electricity energy demand decreased by 29% (BID, 2022).

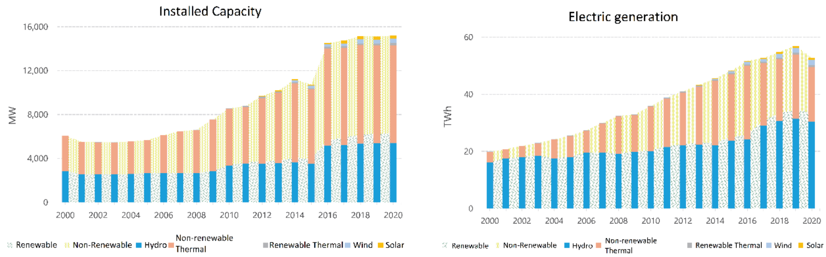

Figure 2 - Evolution of installed capacity (left) and electric generation (right) by source in Peru (adapted from OLADE, 2021)

2.2 Current situation

According to the International Energy Agency (IEA), the world energy matrix is currently based on fossil fuels. For instance, in 2019 the share of fossil fuels (oil, natural gas, and coal) in the world energy mix was 80.9%, followed by biofuels and waste with 9.4% (IEA, 2021). Comparatively, in Peru, in the same year, the share of fossil fuels in the Peruvian energy mix was 64.2% and of electric energy 20.5% (BNE, 2019). From the total amount of electric energy generated in Peru in 2019, 39.78% (22.644 TWh) came from non-renewable thermal and 55.2% (31.485 TWh) from hydropower (BNE, 2019). In 2020, in turn, as shown in Figure 3, the installed capacity and electric generation in Peru was 15.2 GW and 52.7 TWh, respectively. These values include all generation sources, renewable and non-renewable. Figure 3 highlights particularly that, although in percentage terms the installed capacity of non-renewable thermal is higher than the one associated with hydropower (58.57% vs 35.64%), when come to electricity production the share of hydropower (57.85%) is higher than that corresponding to non-renewable thermal (36.22%). Operating costs are one the main drivers for this outcome. Regarding renewable energy sources, in 2020 the share of wind, solar and renewable thermal was 5.79% in terms of installed capacity and 5.94% in terms of electric generation.

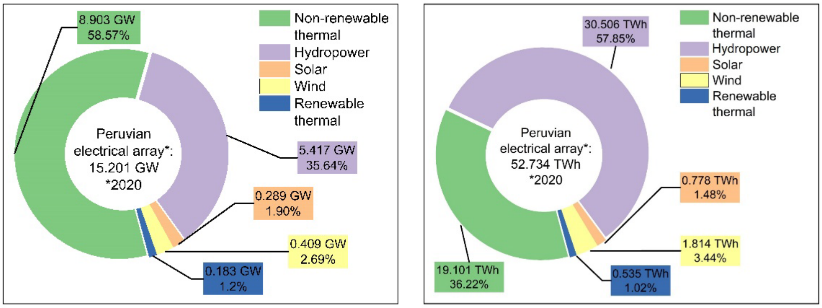

Figure 3 - 2020 installed capacity (left) and electric generation (right) in Peru (data taken from OLADE, 2021)

It is worth emphasizing here that Peru has not yet considered small-scale grid-connected or off-grid power generation systems. Notice here that microgeneration includes power generation systems featuring installed capacities of less than 200 kW, and medium distributed generation ones between 200 kW and 10 MW (OSINERGMIN, 2019). Indeed, even though the potential to develop this type of power generation ones between 200 kW and 10 MW (OSINERGMIN, 2019). Indeed, even though the potential to develop this type of power generation systems in Peru (especially those based on solar energy) is relatively large, there is no legal framework to promote and regulate them. However, in various regions of the country several projects (of the type mini solar on-grid, in particular) are being developed in an isolated manner. For instance, there are photovoltaic systems of 12 kWpand 14 kWp in bank offices in the neighborhoods of Lima (Metropolitan area) and Canto Grande, respectively, a 60 kWp photovoltaic system in a supermarket in Trujillo city, and a 40 kWp photovoltaic system in a cotton production company in the Ica region (NOVUM, 2021).

In addition to on-grid systems, the Peruvian Ministry of Energy and Mines (MINEM) has been developing mass electrification programs through the installation of off-grid photovoltaic systems in isolated communities (MINEM, 2021). For instance, the Mass Photovoltaic Program, under the responsibility of the MINEM General Directorate of Rural Electrification (DGER), aims to benefit 48 thousand rural homes in the regions of Amazonas, Ancash, Cajamarca, La Libertad, Lambayeque, Loreto, Piura, San Martin, and Tumbes (MINEM, 2021). At the same time, MINEM, through Electro Ucayali, a state-owned power generation and distribution company, and the private sector, in October 2020 commissioned the Atalaya solar power plant (500 kWp) located in the Ucayali region (MINEM, 2021). As emphasized above, the lack of a legal framework to regulate small and medium-scale solar panels-based power generation systems has been preventing Peru from developing them and taking advantage of the socio-economic benefits they represent. This highlights of course the need for the Peruvian government agencies in charge of promoting their implementation and regulation to take concrete measures in this regard.

Finally, as highlighted in Section 2.1, until 2019 four auctions based on RER were held in Peru. Consequently, by January 2022, 32 renewable power plants were in operation, representing an installed capacity of 881.3 MW (GESTIÓN, 2022). With these figures, in 2022 the share of renewable sources in the Peruvian electricity mix reached 5.5%. In addition, with the start-up of four new projects, it is estimated that this year the electricity production from wind and solar power plants will grow by 0.1% and 57.6%, respectively (GESTIÓN, 2022).

2.3 Forecast

To mitigate the impacts of climate change, the Peruvian Ministry of Environment (MINAM), through the Supreme Decree N° 003-2022 MINAM (DS N°003-2022 MINAM, 2022), has been promoting the use of renewable sources in the country. The goal is to reach a 20% share of non-conventional renewable sources in the Peruvian electricity matrix by 2030 (PERU ENERGIA, 2022). To achieve this goal, the governmental institutions involved are encouraged to take actions and to promote the use of RER. In the case of the Ministry of Economy and Finance (MEF), some of its responsibilities involves the evaluation of existing budgets to achieve compliance with the provisions of the Climate

Change Law N° 30754, articles 7 and 8. In the case of MINEM, this governmental institution should prioritize, within its competencies, the design of programs for the development of new technologies such as those based on green hydrogen, for example. With this initiative, green hydrogen will be a clean energy source to be included in the Peruvian electricity matrix in the medium and long terms (DS N°003-2022, 2022).

In terms of forecast, based on the reduction in greenhouse gas (GHG) emissions, the international consulting company Deloitte has made a projection (DELOITTE, 2021) for the Peruvian electric generation, including renewable energy sources, up to the year 2050. This projection includes two scenarios, (i) Increased Ambition and (ii) Green Development. The referred scenarios represent alternative horizons and involve, respectively, reductions in GHG emissions of 42% and 100% with respect to the amount of GHG emissions projected under the business-as-usual scenario. In the first scenario, mitigation measures and changes in the energy matrix, which maximize the potential in all sectors based on the unconditional national contributions proposed by the government, are accounted for. The second one, in turn, introduces mitigation policies and changes in the energy matrix focused at maximizing the benefits of decarbonization in a context of international support. Figure 4 summarizes the projections of electricity generation carried out accounting for both scenarios.

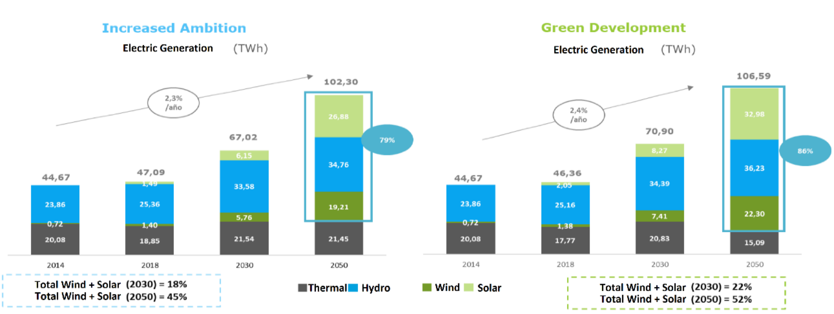

Figure 4 - Projected growth of electric generation in Peru until 2050 (adapted from DELOITTE, 2021)

As shown in Figure 4, both scenarios, Increased Ambition and Green Development, project annual electricity generation growth rates of about 2.3 to 2.4%. By 2050, thus, it is estimated that the share of renewable sources, including hydropower, in the Peruvian electricity mix will be 79% or more. In addition, both scenarios indicate that the use of non-renewable sources (thermal) to generate electricity increases until 2030 and then decreases by 2050. These decreases are of course larger in the Green Development scenario. Finally, notice that the second scenario (Green Development) aligns better with the goal that the Peruvian government has for 2030, which involves increasing the share of non-conventional renewable sources such as wind and solar in the Peruvian electricity matrix up to 20% (DELOITTE, 2021).

3. POTENTIAL FOR RENEWABLE ENERGY PRODUCTION IN PERU

This section discusses the potential for renewable energy production in Peru. Notice first that, according to the Peruvian Legislative Decree N° 1002, renewable energy resources (RER) include biomass, wind, solar, geothermal, tidal energy and mini-hydraulic (whose installed capacity does not exceed 20 MW) energy. Therefore, an especial emphasis is put in this section on (mini) hydropower, wind, solar, and biomass. Before going into detail about the different RER types, it is worth noticing here that in this section the term ‘installed power’ refers to the sum of the power capacities that can be delivered at each power plant under ideal conditions. Accordingly, Figure 5 shows the temporal evolution of the installed power of RER power plants in Peru during the period 2008-2018. Notice that during this period, the installed power of RER power plants grew at an annual rate of 9.34%, representing 7.9% of the total installed power in 2018 (OSINERGMIN, 2019).

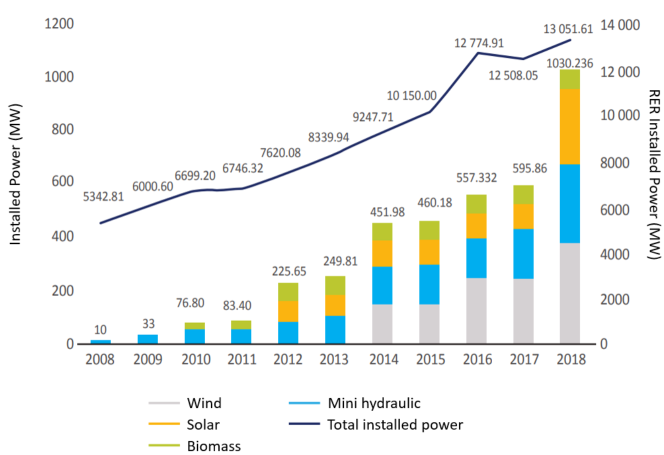

Figure 5 - Installed power evolution of RER power plants (OSINERGMIN, 2019)

3.1 Hydropower

The main energy resource in Peru is hydropower with a potential of 69,445 MW (MINEM, 2011). For this reason, Peru is considered a traditional hydroelectric country. Nevertheless, as indicated at the beginning of this third section, for renewable energy concepts, only mini-hydro power plants (installed capacity ≤ 20 MW) are accounted for. Accordingly, by 2018 a total of 25 of these mini hydroelectric plants were registered in the country, mainly located in Lima, Junín, and Cajamarca. For the referred year, the total installed power was of 298.86 MW and the electric production of 1,290.9 GWh (OSINERGMIN, 2019). The location and power capacity of the mini-hydropower plants in operation in the country by 2018 is shown in Figure 6.

Figure 6 - Location and power capacity of mini hydroelectric plants (OSINERGMIN, 2019)

According to the Hydrographic Map of Peru, the country has a total of 103 basins and 56 inter-basins belonging to three slopes, (i) Pacific, (ii) Atlantic, and (iii) Titicaca (Lake) (AUTORIDAD NACIONAL DEL AGUA, 2022). In 2011, the Peruvian Ministry of Energy and Mines (MINEM) commissioned Halcrow Group and OIST to elaborate the “Atlas of the hydroelectric potential of Peru”. The main objectives of this study were to evaluate the theoretical hydroelectric potential of Peru for a range of 1 to 100 MW and to promote private participation in energy generation. Thus, the referred study identified the 100 most promising hydroelectric projects, 65 of which have a technical potential of 20 MW or less. To further understand the study under discussion, it is important to define the term technical hydroelectric potential, which represents a technical-economic base measure of the resource’s potential. This concept includes the excluded technical potential and the usable one. The excluded technical potential accounts for the potential values that are within the Concession Areas for hydropower generation and the Protected Natural Areas of National Administration, Regional Administration and Buffer Zones. As previously mentioned, the usable hydroelectric potential is 69,445 MW, with the Atlantic slope accounting for most (87%) of the total (OSINERGMIN, 2019). The results of the referred study are summarized in Table 1.

Table 1 - Technical hydraulic potential of Peru (MINEM, 2011)

Slope	Total (MW)	Excluded (MW)	Usable (MW)
Pacific	11402	2671	8731
Atlantic	86971	26345	60627
Titicaca	87	0	87
Total	98460	29016	69445

3.2 Wind

By 2018, Peru had five wind farms, (i) Marcona, (ii) Wayra I, and (iii) Tres Hermanas in Ica, (iv) Cupisnique in La Libertad, and (v) Talara in Piura, with a total installed power of 375.46 MW (OSINERGMIN, 2019). From these wind power plants, Wayra I is the largest one in the country, featuring a total power of 132.3 MW. According to its specifications, this power plant will generate a total of 600 GWh per year, which is equivalent to the annual consumption of almost half a million Peruvian homes, and will prevent the emission of almost 288,000 tonnes of CO2 into the atmosphere per year (ENEL, 2022a).

As shown in Figure 7, the greatest wind potential is found in the coastal regions of Peru, which at an average height of a wind turbine of 100 m feature an average wind speed between 6 and 12 m/s. In the highlands, the wind speed is between 6 and 9 m/s, where Cajamarca is the most outstanding region, having a wind potential similar to that associated with the coastal regions. As for the jungle, its potential is much lower than that characterizing the other two regions.

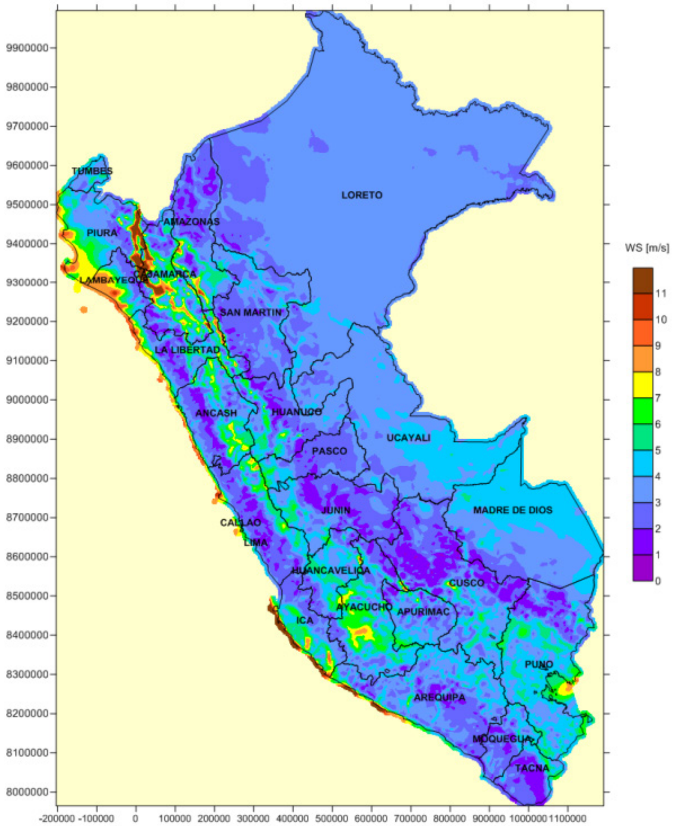

Figure 7 - Map of the average annual wind speed at 100 m height (MINEM, 2016a)

To estimate the wind potential of Peru, the Wind Atlas of Peru divides it into three categories, (i) the total wind potential, (ii) the usable wind potential, and (iii) the excluded wind potential. For the total wind potential, preferential areas were identified. This was done to allow carrying out in future detailed on-site research focused on the installation of wind turbines. For the identification of the referred areas, the following considerations were made (MINEM, 2016a),

- Moderate to excellent power density ($P/A>300\ W/m^2$) at 100 m,
- Favourable wind frequency distribution,
- Land slope less than or equal to 20%,
- Proximity to passable access roads,
- Proximity to towns, existing medium and high voltage lines, and power substations,
- Existing wind farms, and.
- Local altitude less than 3500 meters high.

The usable wind potential in turn fulfils the above conditions and is found outside inadequate areas, such as archaeological zones, national parks, natural reserves, and recreational areas. Finally, the excluded wind potential is that which, although it fulfils the conditions of the total wind potential, is located in an unsuitable area and it is impossible to tap into it. Table 2 shows the details of the wind potential of Peru.

Table 2 - Wind power potential of Peru (MINEM, 2016a)

Region	Usable (MW)	Excluded (MW)	Total (MW)
Amazonas	129	288	417
Ancash	708	108	816
Arequipa	1020	156	1176
Cajamarca	891	282	1173
Ica	2280	3015	5295
La Libertad	921	264	1185
Lambayeque	7017	2097	9114
Lima	429	189	618
Piura	7098	1503	8601
Total	20493	7902	28395

3.3 Solar

Without accounting for hydropower, solar energy is the second largest RER in Peru with a potential of 25,000 MW. Peru currently has seven solar photovoltaic plants, located on the south of the country, in the regions of Arequipa (2), Moquegua (4) and Tacna (1) (OSINERGMIN, 2019). The largest solar power plant in the country is Rubí, from

Enel Green Power Peru (ENEL, 2022b), with an installed capacity of 144.48 MW. In 2018, this power plant registered an annual production of 424.2 GWh. According to Enel, the Rubí plant can generate 440 GWh per year, equivalent to the consumption of 350,000 Peruvian homes, thus avoiding the annual release of more than 209000 tonnes of CO2 (ENEL, 2022b).

One of the drawbacks of RER is their intermittence. In the case of solar energy, it relates to the decrease in solar radiation in the months of June and July (winter), which occurs due to the presence of cloudiness in the coastal regions of the country and the reduction of daylight hours per day. This aspect is highlighted Figure 8, which compares the energy production in several solar power plants during typical summer and winter months. In the case of the Rubí plant, for instance, during winter, peak energy production decreases by about 35% (Figure 8).

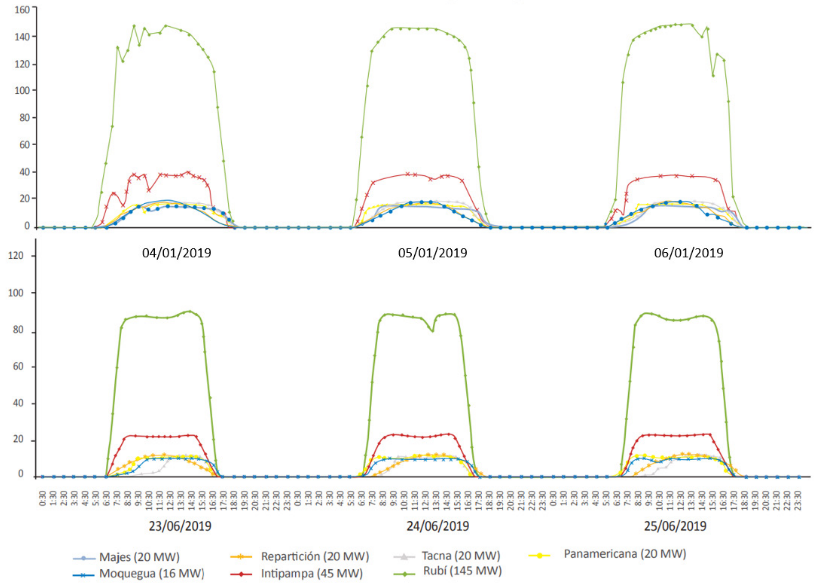

Figure 8 - Energy production [MW] in solar power plants during summer (January) (top) and winter (June) (bottom) (OSINERGMIN, 2019)

Despite the referred intermittency, Peru has an excellent availability of solar energy. This is due to fact that Peru is located in a privileged area, near the equatorial line, where, contrarily to what happens in countries such as the Nordic ones, solar radiation is relatively uniform (TAMAYO, 2011). Notice that, depending on the form that solar radiation reaches our planet, it can be classified into three types, (i) direct radiation (reaching the earth's surface without altering its direction), (ii) diffuse radiation (reaching the earth's surface after being affected by some elements or particles present in the earth's atmosphere), and (iii) reflected radiation (reflected by the earth's surface itself). Global horizontal radiation is in turn the sum of direct and diffuse radiation. Figure 9 shows both the direct (left) and global horizontal (center) radiation that characterize Peru. From this figure, it is observed that the regions of Arequipa, Moquegua, and Tacna (southern regions of Peru) feature the highest levels of direct and global horizontal radiation. Particularly, direct radiation is in the range of 7.5 to 8.5 kWh/m^2, whereas global horizontal radiation is in the interval of 6.8 to 7 kWh/m^2. Figure 9 also shows the photovoltaic energy potential (right), expressed in kWh/kWp, where Wp (Watt peak) represents the theoretical power output of a photovoltaic system under standard test conditions (STC),

- Temperature of 25°C,
- Irradiance of 1000 W/m^2 , and
- Air mass (AM) of 1.5.

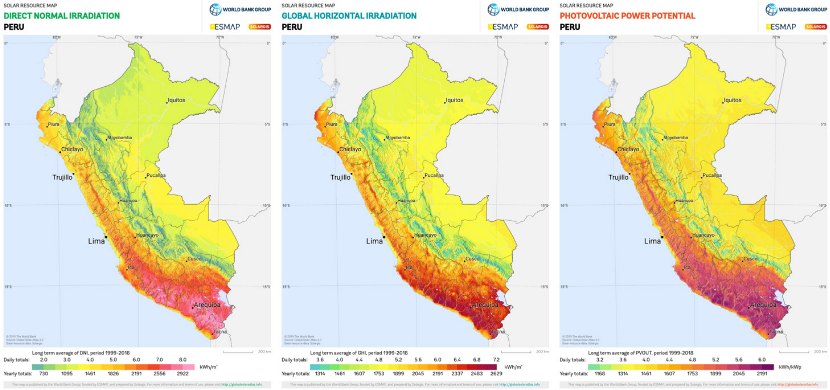

Figure 9 - Maps of direct radiation (left), global radiation (center), and photovoltaic power potential (right) (THE WORLD BANK GROUP, 2022)

3.4 Biomass

The term "biomass" refers to a wide range of organic matter that originates from the photosynthesis processes of plants. Through these processes, plants with chlorophyll take advantage of the sun's energy to convert both carbon dioxide and water into high-energy organic matter (OSINERGMIN, 2019). Figure 10 shows the main sources of biomass used to obtain energy.

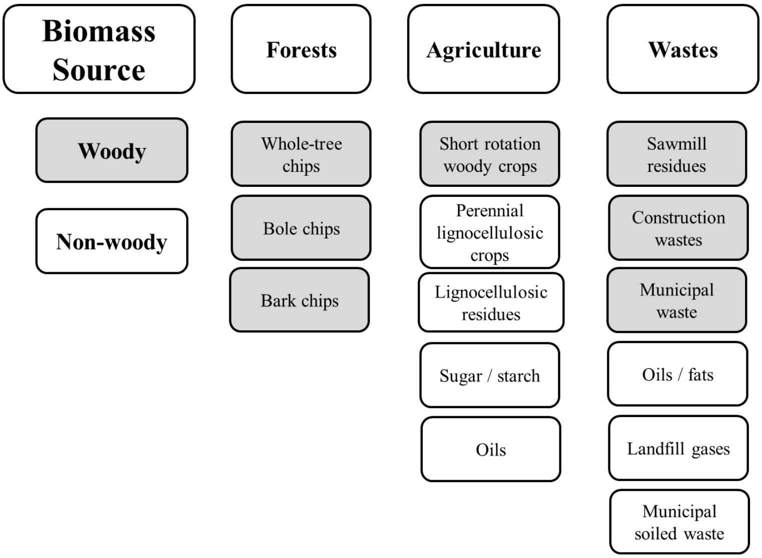

Figure 10 - Biomass sources (DAHIYA, 2020)

Peru currently has five biomass plants, (i) Paramonga, (ii) Huaycoloro, (iii) La Gringa V, and (iv) Doña Catalina, located in Lima, and (v) Maple Ethanol in Piura. In 2018, with respect to the total installed capacity, the Maple Ethanol and Paramonga biomass power plants featured the largest share with 52.9% (37.5 MW) and 32.4% (23 MW), respectively (OSINERGMIN, 2019). Peru, being an agro-industrial country, has an untapped biomass energy potential that is not currently utilized. For instance, in a previous study carried out on the availability of agricultural residues (MITIGATION MOMENTUM, 2015; OSINERGMIN, 2019), it has been determined that 13 types of crops generate enough residues (about 31 million tonnes) to produce electricity. In this sense, Figure 11 shows the distribution of biomass-related primary energy resources by type of waste. Finally, it is worth noticing that the energy potential of biomass in Peru has not been fully assessed. Indeed, what is currently available in the country comes from research carried out on behalf of private companies seeking to meet their electrical or thermal demand associated with their operations.

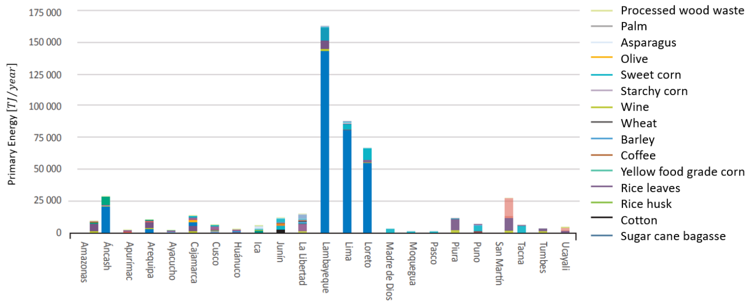

Figure 11 - Distribution of biomass-related primary energy resources (MITIGATION MOMENTUM, 2015)

3.5 Other renewable energy sources

Other renewable energy resources in Peru include geothermal energy, which is related to the energy contained in the Earth's core. Since Peru is located in the Pacific Ring of Fire, near the subduction zone of the Nazca plate, below the South American plate, the country has a relatively high potential for geothermal energy (MINEM, 2012). Peru is indeed the country with the largest geothermal energy potential in South America. This potential, which compares to those characterizing countries, such as Italy and New Zealand, is mainly available in the south of the country. Several studies carried out on the subject since the 1970s confirm this aspect (TAMAYO, 2011). For instance, Figure 12 shows the number of active volcanoes per country vs the geothermal energy potential.

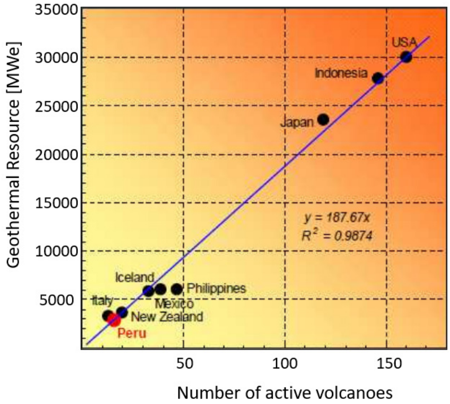

Figure 12 - Number of active volcanoes vs. Geothermal resources (TAMAYO, 2011)

In 2012, West Japan Engineering Consultants, Inc., hired by the Japan International Cooperation Agency (JICA) as part of the Technical Cooperation with the Peruvian Ministry of Energy and Mines (MINEM), developed the work “The master plan for development of geothermal energy in Peru” (MINEM, 2012). The main goal of this work was to establish the basis for the development of geothermal energy in Peru with focus on the production of both electricity and heat. The referred study concluded that Peru has abundant geothermal resources, representing a total potential of 2,860 MW. More specifically, the goal is to develop 1,000 MW of geothermal power by the year 2030 (MINEM, 2012). In this context, in 2010 the geothermal map of Peru was also updated (VARGAS and CRUZ, 2010), which allowed the identification of several hot and mineral water springs throughout the country (Figure 13). In short, the potential to produce renewable energy in Peru is relatively large. So, this potential should be utilized to fostering the clean energy transition in the country.

Figure 13 - Map of the geothermal potential in Peru (MINEM, 2016b)

4. GREEN HYDROGEN

Several green hydrogen related issues are discussed in this section. More specifically, the main hydrogen features in terms of physical properties and other characteristic parameters are initially highlighted. This is followed by a discussion of the role that hydrogen can play in energy transition. Finally, emphasis is placed on green hydrogen in the Peruvian context.

4.1 Hydrogen features

According to the Royal Society of Chemistry (RSC, 2022), hydrogen is the most abundant and lightest element in the universe. As such, it is found in the sun and most of the stars, and on planets like Earth, where largest amounts are present in form of water. From the three naturally occurring isotopes of hydrogen, 1H (protium), 2H (deuterium), and 3H (tritium), the most abundant one is 1H (99.9885%). At typical ambient conditions (20°C and 1 atm), the most stable allotropic form of hydrogen is the diatomic (molecular) hydrogen (H2). And, since the fusion point of hydrogen is 13.99 K (-259.16°C) and its boiling point 20.271 K (-252.879°C) (HAYNES et al., 2014), at these conditions, hydrogen is in gaseous state. Therefore, in the Earth's atmosphere hydrogen is present as a gas, but in very small quantities (less than 1 ppm). Even though hydrogen gas is not available in large amounts in natural environment, it can be found in various molecules such as water, sugars, hydrocarbons, and proteins. In these molecules, the corresponding bond enthalpies (bond related energy) vary. For instance, the bond enthalpies characterizing H2, NH3 (ammonia), CH4 (methane), and H2O (water) are equal to 435.9, 390.8, 415.5, and 462.8 kJ/mol, respectively (RSC, 2022). This means that referred forms of hydrogen contain bond energy that can be extracted and used in the applications of interest (OLIVEIRA, 2022).

Regarding other characteristic parameters of molecular hydrogen, it is worth noticing that it features a critical point of 32.938 K (-240.212°C) and 1285.8 kPa (12.69 atm), and a triple one of 13.80 K (-259.3467°C) and 7.041 kPa (0.069 atm) (HAYNES et al., 2014). In addition, at 25°C and 1 atm, its ratio of specific heats is equal to 1.405 and its density equal to 0.08264 kg/m3. This last density value is, respectively, about 860 and 1050 times less than those values associated with its liquid (70.99 kg/m3) and solid (86.71 kg/m3) states (SANKIR and SANKIR, 2017). In terms of energy content, hydrogen features a gross heat of combustion, which is a parameter typically 5% to 10% higher than the net heat of combustion (where water remains in the gas state), of about 141.8 MJ/kg. Notice that this value is almost three times the one associated with methane (55.5 MJ/kg), the main constituent of natural gas (HAYNES et al., 2014). Therefore, for each kilogram of hydrogen that is oxidized (in a heat engine or fuel cell, for instance), 141.8 MJ of energy is released. Besides, since the enthalpy of vaporization of water is about 2.258 MJ/kg (HAYNES et al., 2014), it means that the oxidation of 1 kg of hydrogen produces about 63 times the amount of energy that can be obtained from condensing (using a steam turbine, for instance) 1 kg of water (OLIVEIRA, 2022). In short, the energy content per unit mass of hydrogen is relatively large.

To take full advantage of the referred energy content, hydrogen must be produced first and then transported and stored appropriately at the point of use. Notice however that these hydrogen transport and storage processes, which are directly related to each other, depend on the type and scale of the specific application accounted for (DELL et al., 2014). For transporting and distributing large amounts of hydrogen in gaseous state, as it happens when doing so in the case of natural gas, the use of pipelines seems to be the most obvious choice. For non-stationary applications such as automotive or aircraft related ones, in turn, this choice is not so obvious anymore. In this sort of applications, depending on the hydrogen storage conditions, in terms of temperature and pressure, the size, volume, and weight of the containers used for hydrogen storage purposes can vary considerably. Of course, both options involving the storage in gaseous and liquid states are feasible. Nevertheless, since the temperatures at which hydrogen is in liquid state are significantly low (between 15 and 30 K, approximately), the amount of energy required to liquefy hydrogen is relatively large (about 30% of the energy value of the hydrogen itself) (DELL et al., 2014). Therefore, there are several technical challenges that need to be overcome first before having a widespread use of hydrogen as a fuel.

4.2 Hydrogen and clean energy transition

According to the IEA (IEA, 2021b), in 2019, about 80% of the total energy consumed in the world (606 EJ) came from fossil fuels. Of this amount, about two-thirds was used in the transport and industry sectors (IEA, 2021c). This means that the amount of energy currently coming from fossil fuels, which is used to cover our daily needs, is huge. This also emphasizes the size of the climate change problem that needs to be faced. The big issue associated with fossil fuels is that their use release greenhouse gases such CO_2 that directly impact on climate change. Indeed, it has been scientifically proven that the increase in greenhouse gas emissions is responsible for long-term climate change. More specifically, the increase of CO2 in the Earth's atmosphere causes global warming, which in turn affects precipitation, glaciers,weather patterns, tropical cyclone activity, and severe storms (WEATHERHEAD, 2021). In this context, increasing the share of renewable energy sources, including green hydrogen, in the world energy mix is crucial.

Since hydrogen is not freely available in natural environment, but in combination with other elements such as oxygen (water) and carbon (fossil fuels), energy needs to be spent to extract hydrogen from these sources. Accordingly, similar to electricity, hydrogen is also a secondary form (vector or carrier) of energy that is used for storing and transporting energy (DELL et al., 2014). Unlike electricity, however, hydrogen can be both a fuel and an electricity storage, which makes hydrogen and electricity complementary and interconvertible (DELL et al., 2014). Therefore, in a decarbonized energy mix, hydrogen has the potential to become an important energy vector. For instance, using electricity coming from renewable energy sources and electrolytic processes, green hydrogen can be produced, transported, and stored for final usage. This low-carbon hydrogen can be utilized next (i) to produce electricity, using fuel cells or hydrogen-fired gas turbines, (ii) for green mobility, in cars, heavy duty and mining trucks, and in propulsion related applications, (iii) in the industry, to produce cement and steel in the cement and metallurgical industries, for instance, and (iv) in the production of synthetic fuels (COLLINS, 2022).

In this context, the share in the energy mix of fuels with very low emissions intensity, such green hydrogen, is expected to increase in the following years. For instance, Figure 14 shows, for the same long-term scenarios discussed in Figure 1, a forecast of low-carbon hydrogen supply and demand by 2030 (IEA, 2021a). From this figure it is noticed that, according to the NZE, about 18.5 EJ of low-carbon hydrogen will be produced by 2030, half of which will come from water electrolysis processes. Figure 14 also highlights that the transformation and industry sectors will be the largest consumers of the produced low-carbon hydrogen. It is worth noticing that this 18.5 EJ represents about 3% of the total energy consumed in the world (606 EJ) in 2019 (IEA, 2021b). To have a better idea of the amount of energy that this 18.5 EJ represents in practice, let’s take as reference the Itaipu (hydroelectric) power plant (ITAIPU BINACIONAL, 2022a), the second largest power station in the world. This power plant, with an installed capacity of 14 GW, featured a record annual production of 0.37 EJ in 2016 (IHA, 2022b). Therefore, 18.5 EJ of low-carbon hydrogen is equivalent to about 50 (18.5/0.37) Itaipu power plants (OLIVEIRA, 2022). That is, to produce the referred amount of 18.5 EJ, 50 hydrogen production plants, with a power production capacity equal to the Itaipu power plant, will need to be constructed and operated by 2030. This highlights the magnitude of the effort that needs to be carried out to make things happen.

Of course, major investments in research, development, and innovation will be required to lower the hydrogen production costs and to make these supply and demand predictions true. If this does not happen, as the STEPS and APS emphasize, the use of low-carbon hydrogen and hydrogen-based fuels by 2030 will see only a small increase. Naturally, due to the availability of resources, hydrogen production related costs are expected to vary from country to country. In a hydrogen-based economy, therefore, some countries will be hydrogen importers, and some will be exporters. In this scenario, Peru has a large potential to become a hydrogen exporter country. This aspect will be further explored in the following section.

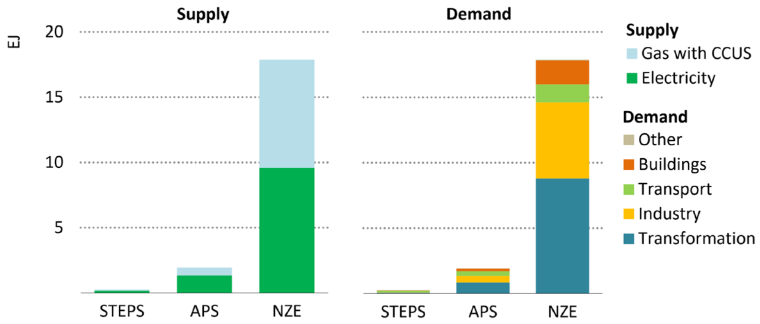

Figure 14 - Forecast of low-carbon hydrogen supply and demand by 2030 (IEA, 2021a)

4.3 Green hydrogen in Peru

Until a couple of years ago, almost nobody talked about green hydrogen in Peru. Indeed, two of the first initiatives on the subject date back to January 2021, that is when a R&D green hydrogen-related project was launched (ANDINA, 2021; FPCE, 2022), and February 2021, that is when the Peruvian Hydrogen Association (H2 Perú) was officially created (H2 PERÚ, 2022a). The main goal of the referred R&D project (ANDINA, 2021; FPCE, 2022) is to design, build and test an electrolytic hydrogen production plant using solar radiation as energy source to produce clean energy. In particular, different advanced photovoltaic, electrolyzer, and control related technologies are being accounted for in this R&D project (LUCAS and CELIS, 2022; ANTONIOU et al., 2022; MAS et al., 2022). H2 Perú in turn has recently (February 2022) submitted a bill to the Peruvian authorities (legislative and executive branches) (H2 PERÚ, 2022b), which proposes the design and implementation of a green hydrogen national strategy promoting innovation, development, production, and export of green hydrogen as an energy vector, fuel or as an input to industrial processes. More recently (July 2022), Mmex Resources Corporation, an American company focused on the development, financing, construction, and operation of clean fuel infrastructure projects powered by renewable energy, announced that it will develop the first green hydrogen project in Peru (MMEX RESOURCES CORPORATION, 2022). This green hydrogen production plant is expected to produce up to 55 tonnes per day of hydrogen, using 160 MWe of renewable energy. To facilitate exports of green hydrogen and other related products to Asia and the west coast of United States, the referred plant will be located on the southern coast of Peru, near the Pacific Ocean. Of course, the Peru's mining industry relying on the use of heavy extraction and transportation equipment is also a target market for this project.

According to H2 Perú (H2 PERÚ, 2022c), the northern and southern regions of Peru have the largest potential for green hydrogen production. This is thanks to the availability of renewable energy resources in such regions (mostly wind energy in the northern and solar energy in the southern). In addition, due to their energy footprint and the type of activities performed there, the central and southern regions of Peru are the main potential consumption centers of green hydrogen. Indeed, from all Peruvian departments, Lima is the largest consumer of energy in Peru, with 38% of the total (H2 PERÚ, 2022c). Mining and manufacturing are, in turn, the main activities that make southern Peru the region with the largest potential for industrial use of green hydrogen. In this sense, first estimates of green hydrogen demand in Peru indicate amounts of 30,000 t/year by 2030, and 350,000 t/year by 2050 (H2 PERÚ, 2022d). Notice that between 20 and 30% of these amounts are associated with the mining industry.

Producing green hydrogen for domestic consumption only will not be enough to effectively transition to a hydrogen-based economy in Peru. There are so many reasons to believe so, including political, economic, and social ones. Therefore, other drivers are needed to achieve a fast transition to an energy economy in which hydrogen is a key player. One of these drivers could be the green hydrogen export. As previously indicated, Peru has a large potential to become a hydrogen exporter country. This is true because Peru has both a huge potential to produce renewable energies (about 115 GW if hydropower, solar, and wind are summed up – OSINERGMIN, 2019) and a long coastline with access to seawater. Therefore, the green hydrogen produced in Peru can be used not only for domestic consumption, but also for export to other countries. Asian countries and the west coast of United States can be some of the destinations for this green hydrogen. Finally, notice that Peru has also a large offshore wind potential (ESMAP, 2020). Therefore, the electric energy generated by Peruvian offshore wind farms can be either transported to land to produce green hydrogen there or used directly offshore to do the same. Detailed assessments are needed of course to determine the most feasible option to be implemented in practice.

5. FINAL REMARKS

An overview of the clean energy transition in Peru, from the perspective of green hydrogen, was provided in this work. Accordingly, the current situation of renewable energies in Peru was initially highlighted, along with their historical evolution and prospects. Next, the potential for renewable energy production in Peru was discussed, with especial emphasis on hydropower, wind, solar, and biomass. Finally, green hydrogen and its potential to contribute to the clean energy transition in Peru was addressed. In the discussions carried in this this work, it has been highlighted that most of the increase in energy demand (annual growth rate ~ 7%) that occurred in Peru during the last two decades was covered by fossil fuels, natural gas more specifically. This means that CO2 emissions associated with energy generation in Peru increased significantly during the last twenty years. Notice however that, since 2010 or so, the share of non-conventional renewable sources in the Peruvian energy mix progressively increased as well. For instance, in 2018, this share was about 7.2%. Although the non-conventional renewable sources related share is still small, it represents a progress because back in 2008 this share was 0%.

It has been emphasized here as well that the potential to produce renewable energy in Peru is relatively large. For instance, for hydropower, solar, and wind, this potential represents about 70, 25, and 20 GW, respectively. Nevertheless, only about 7.1, 1.1, and 1.8% of this potential, respectively, is currently being tapped. Therefore, there is a big room to keep increasing the share of non-conventional renewable energies in the Peruvian energy mix. It should be noticed here that the tomorrow's energy economy is expected to be very different from the one currently in place. In particular, because of the ongoing global decarbonizing process, human society is expected to increasingly meet its energy needs with electricity. Thus, around 40% of primary energy is expected to be converted at least twice before reaching end-users. In other words, energy is expected to travel through batteries, electroly zers, and fuel cells undergoing conversions from electricity to heat or fuels, and back again. In this sense, low- or zero-carbon (green) hydrogen is expected to be key to providing flexibility to the energy system and helping manage the imbalances between variable energy supply and demand. In this context, Peru has a big opportunity to become a key player in the future energy economy. This comes from the fact that Peru has both a huge potential to produce renewable energies and aong coastline with access to seawater, which represent the basic ingredients to generate large amounts of green hydrogen. Eventually, the green hydrogen produced in the country can be used not only for local consumption, but also for export to other countries. Asian countries and the west coast of United States can be some of the destinations for this green hydrogen.

6. ACKNOWLEDGMENTS

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