ARMENIAN NATIONAL PLATFORM
EASTERN PARTNERSHIP CIVIL SOCIETY FORUM

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THE POSSIBILITIES OF PRODUCTION OF HYDROGEN, ESPECIALLY "GREEN" HYDROGEN IN ARMENIA

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Annotation

The research is dedicated to the collection, updating and assessment of prospects for hydrogen, especially green hydrogen production, its potential, economic, environmental benefits, as well as state of the art of renewable energy sources (RES) in Armenia. The progress in development of PV plants in Armenia, the characteristics of the world's leading solar PV panels, the capacity factors/efficiencies of power plants operating from RES in Armenia in 2022 were studied and appropriate data are presented. The total capacity of PV plants in 2022 was 408.1MW, of which 196.9 MW of industrial scales PV plants.

The international experience in the area of green hydrogen production was studied, including in the CIS countries and EU, where it is considered as one of the prospective options to reduce dependence on gas and oil imported from Russia and other fossil fuel rich countries and to reduce emissions of greenhouse gases and harmful gases. In 2021, the hydrogen demand in the world was 94 million tons. Less than 5% of total hydrogen production is produced using renewable and low-carbon energy sources (so called “green” hydrogen) through electrolysis. By now there no operational electrolysers of industrial scales in Armenia. The research will be useful to experts, teachers and students involved in study and work in that area.

The author expresses his deep gratitude to all those who provided me with professional, advisory and organizational help during this research work at its various stages.

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Հեղինակ՝ Արտաշես Սարգսյան, ֆ.մ.գ.թ.

Արտաշես Սարգսյան «Հայաստանում ջրածնի, հատկապես «կանաչ» ջրածնի արտադրության հնարավորությունները», Երևան, 2023թ. - 24էջ:

Հետազոտությունը նվիրված է Հայաստանում ջրածնի, հատկապես «կանաչ» ջրածնի արտադրության ներուժի, տնտեսական, բնապահպանական օգուտների, ինչպես նաև վերականգնվող էներգիայի աղբյուրների (ՎԷԱ) վերաբերյալ տվյալների հավաքագրման, արդիականացման և հեռանկարների գնահատման: Ուսումնասիրվել է Հայաստանում ՖՎ էլեկտրակայանների առաջընթացը, աշխարհի առաջատար արեվային ՖՎ վահանակների բնութագրերը, Հայաստանում ՎԷԱ-ներից գործող էլեկտրակայանների արդյունավետությունը 2022թ. համար «ավանդական» էլեկտրակայանների հետ համեմատ:

Ուսումնասիրվել է արտասահմանյան փորձը կանաչ ջրածնի արտադրության ոլորտում, այդ թվում ԵՄ-ում, ԱլԳ երկրներում, որտեղ այն դիտարկվում է որպես Ռուսաստանից և այլ երկրներից ներմուծվող գազից ու նավթից կախվածությունը նվազեցնելու և ջերմոցային ու վնասակար գազերի արտանետումները կրճատելու հեռանկարային տարբերակներից մեկը և հակիրճ ներկայացվել է հետազոտությունում: 2021թ. ջրածնի պահանջարկը աշխարհում կազմել է 94 միլիոն տոննա: Ջրածնի ընդհանուր արտադրության 5%-ից պակաս արտադրվում է օգտագործելով վերականգնվող և ցածր ածխածնային էներգիայի աղբյուրները՝ էլեկտրոլիզի միջոցով (կանաչ ջրածին): Հետազոտությունը օգտակար կլինի ոլորտի փորձագետներին, դասախոսներին ու ուսանողներին:

Հեղինակը իր խորին երախտագիտությունն է հայտնում բոլոր նրանց, ովքեր տարբեր փուլերում ինձ տրամադրել են մասնագիտական, խորհրդատվական և կազմակերպչական օգնություն:

Այս հրապարակումը պատրաստվել է Եվրոպական Միության ֆինանսական աջակցությամբ: Բովանդակության համար պատասխանատվություն է կրում բացառապես հեղինակը, և պարտադիր չէ, որ այն արտահայտի Եվրոպական Միության տեսակետները

ՀԵՏԱԶՈՏՈՒԹՅՈՒՆԸ ԿԱՏԱՐՎԵԼ Է ԱՐԵՎԵԼՅԱՆ ԳՈՐԾԸՆԿԵՐՈՒԹՅԱՆ ՔԱՂԱՔԱՑԻԱԿԱՆ ՀԱՍԱՐԱԿՈՒԹՅԱՆ ՖՈՐՈՒՄԻ ՀԱՅԱՍՏԱՆԻ ԱԶԳԱՅԻՆ ՊԼԱՏՖՈՐՄԻ ՔԱՐՏՈՒՂԱՐՈՒԹՅԱՆ ԵՆԹԱԴՐԱՄԱՇՆՈՐՀԱՅԻՆ ՀԵՏԱԶՈՏԱԿԱՆ ԾՐԱԳՐԵՐԻ ՇՐՋԱՆԱԿՆԵՐՈՒՄ

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CONTENTS

List of abbreviations

EaP	Eastern Partnership (EaP)
TPP	Thermal Power Plant
AANP	Armenian Nuclear Power Plant
HPP	Hydro Power Plant
Small HPP	Small Hydro Power Plant
Wind PP	Wind Power Plant
RES	Renewable Energy Resources
ENA	Electricity Network of Armenia
CC	Combined Cycle
CCGT	Combined Cycle Gas Turbine
PSRC	Public Services Regulatory Commission
SDG	UN Sustainable Development Goals
CCSU	Carbon Capture, Utilization And Storage
EE	Energy Efficiency
RA	Republic of Armenia
US AID	United States AID for International Development
VVER	Water-Water Energy Reactor
VAT	Value Added Tax
WB	World Bank
MJ	Mega Joule (10^6 J)
MW	Mega Watt (10^6 W)
PV	Photovoltaic
IRENA	International Renewable Energy Agency
UNFCCC	United Nations Framework Convention on Climate Change-
NREL	National Renewable Energy Laboratory

Exchange rates (as of October 2023)

1 USD = 405 AMD (Armenian dram)
1 Euro = 425 AMD

1. INTRODUCTION

This researh is devoted to assessment of perspectives of hydrogen production, especially green hydrogen production potential, economical and environmental benefits, as well as renewable energy resources (RES) in Armenia through data collection, update and prospects evaluation.

The Green hydrogen production's international experience was studied and briefly presented in the research, including in the EU, in EaP countries, where it is considered as one of the prospective options for reducing the dependence on imported gas from Russia and other countries and reducing the emissions of greenhouse and harmful gases.

In 2021, hydrogen demand in the world was 94 mln tons [1]. Currently, natural gas is the primary feedstock for hydrogen production (almost 80% of global hydrogen production), followed by coal. Hydrogen produced from natural gas and coal is called "grey" and "black" hydrogen, respectively.

Less than 5% of total hydrogen production is produced using renewable and low-carbon energy sources through electrolysis. Hydrogen produced in such a way is called "green" hydrogen [2]. The EU has announced a target of 10 million tons of green hydrogen imports per year by 2030 [3].

According to the strategic plan approved by the Armenian government in 2021, until 2030 it is envisaged to install solar PV plants with a total capacity of 1000 MW, which will provide 15% of the total electricity production.

Part of volumes of electricity generated by PV plants can be also used for powering electrolysers. HPPs, both existing and planned, can also represent significant potential for powering electrolysers. The potential (unutilized) of large and medium power hydropower plants partly designed previously is about 300 MW. Wind power plants in Armenia are underdeveloped, while the economically justified potential is 500-600 MW according to various estimates. Electricity to be produced from them can also be used by electrolysers.

2. HYDROGEN PRODUCTION POLICY ABROAD AND IN ARMENIA

The Sustainable Energy Committee of the UN Economic Commission for Europe has developed guidelines on green hydrogen production under the title "Hydrogen as an innovative solution to carbon neutrality" (United Nations, ECE/ENERGY/2020/8 Economic and Social Council, Geneva, 25-27 November 2020 Economic Commission for Europe, Committee on Sustainable Energy, Hydrogen – an innovative solution to carbon neutrality) [4]. As noted in that document, in 2015 the United Nations General Assembly (UNGA) set an ambitious 2030 development agenda [5] as expressed in the UN Sustainable Development Goals (SDGs). Among the 17 interrelated SDGs are, for example, SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 13 (climate action).

The 2016 Paris Agreement, signed under the United Nations Framework Convention on Climate Change (UNFCCC), committed signatories to keeping the rise in global average temperatures below 2°C above pre-industrial levels and continuing efforts to limit that increase to 1.5°C. As of 2020, 194 countries, including Armenia and the EU, have signed the Paris Agreement.

A large number of measures [4] have been proposed, including supporting the deployment of grid-connected electrolysers, ideally powered by renewable or low-carbon electricity, promoting the large-scale construction of renewable electricity installations integrated with hydrogen production plants, supporting both within the UNECE region, and abroad to projects aimed at importing renewable energy from the most economically justifiable and competitive locations with wind, solar and biomass energy resources.

Bearing in mind that the solution to achieving a carbon-neutral energy system must be found within the "gas-renewable energy-energy efficiency" triangle, the group of experts recognizes the key role of the gas industry in transitioning to a hydrogen economy through energy system integration. In the European "Green Deal" document, the European Commission recognized the important role of RES and hydrogen in the neutralization of carbon emissions [4].

RESs are used in the process of green hydrogen production, therefore, the works of updating the data on the current state of RESs in Armenia and the future development tendencies/trends were carried out and the prospects of green hydrogen production were evaluated.

It is quite an innovative problem, which has not yet been considered within the framework of the EaP CSF. At the same time, there is a lot of information about the achievements and great prospects of hydrogen production in the world, especially in the EU area and in China.

According to preliminary internet searches, there have been implemented some researches on hydrogen production potential in EaP countries, but the proportion of these researches is very small compared to other countries.

In 2023, The Ministry of Economy of the RA has spread information that now the ministry is discussing with Germany the possibility of establishing a joint production of green hydrogen ("Sputnik Armenia"). In 2022, the organizations of Armenia and France signed a cooperation agreement on the construction of the first industrial demonstration of green hydrogen production.

As of today, there are no built and operating hydrogen production plants in Armenia. Certain research works are carried out under the auspices of the RA National Academy of Sciences, Yerevan State University (YSU), the American University of Armenia (AUA), the Renewable Energy Department of the RA Ministry of Territorial Administration and Infrastructure, the "Energy Strategic Center" of the RA Energy Research Institute.

3. HYDROGEN PRODUCTION, STORAGE, AND TRANSPORTATION

In 2021, technology overview on hydrogen production was developed by UNECE [2]. This work presents the possibilities of hydrogen production from natural gas, coal, renewable energy sources, biomass, nuclear power plants. The technologies of hydrogen storage and transportation are also described, and the problems of hydrogen use in energy, transportation, industrial, population and commercial sectors are presented. In Annex 1 the picture of the Hydrogen Value Chain is presented.

Today, the use of electricity from coal, nuclear power plants and wind turbines for the production of pure hydrogen with "Carbon Capture, Utilization and Storage" (CCSU - Carbon Capture, Utilization And Storage) technologies is 2-3 times more expensive than traditional hydrogen production technologies from natural gas and other hydrocarbons.

Fig. 1. 250kW electrolyser, Linden, Germany

The 250kW electrolyser shown in Figure 1 is part of a pilot complex where nine project partners are investigating how hydrogen can be safely and reliably transported and stored in pipelines. An electrolyzer installed in a container can produce up to 170 kg of hydrogen per day. One day's production of hydrogen by 250kW electrolyser would theoretically be enough for a fuel cell powered vehicle to travel about 17,000 km.

Water electrolysis and fuel cell technology play a major role in hydrogen production and utilization cycles. The minimum specific heat of hydrogen combustion is 119.96 MJ/kg (33.32kW*h), the maximum specific heat of combustion is 141.88MJ/kg (39.41kW*h), the density is 0.08375 kg/m³, the boiling point - 252.9^{0}C at 1 atm pressure. Note that the specific heat of combustion of gasoline is 46 MJ/kg. According to the 2020 IRENA report, the cost of a 1MW electrolyzer is in $400,000-$870,000 range.

There are several fuel cell technologies that differ slightly in implementation, but at a basic level they all work the same way, taking in hydrogen and oxygen, then combining them to produce electricity, with only water and heat as byproducts. The most common technology uses a proton exchange membrane (PEM). The hydrogen is delivered to the anode of the fuel cell, where it is split into protons and electrons under the influence of a catalyst (usually a platinum-type metal). Protons pass through the PEM while electrons flow through the circuit, powering whatever electrical load you have connected before recombining with protons and oxygen on the cathode side of the fuel cell to form water. The electrolyzer is very similar, but works in the opposite direction. An electric current is applied to water, splitting it into hydrogen and oxygen. Any fuel cell can, in principle, work backwards as an electrolyser, but they are generally not optimized for bi-directional operation, so-called "renewable fuel cells".

According to 2009 report of the NREL (US organization) [15], the available data for hydrogen conversion from energy carriers are as following:
hydrogen production from coal: 7.6 kg coal/kg hydrogen,
from natural gas: 4.5 nm3 gas/kg hydrogen,
from NPP and HPP: 58, 8 kWh/kg of hydrogen.

1 kg of hydrogen requires an average of 11.34 L or 3 gallons of water (1 gallon is about 3.78 L), 1 kg of hydrogen can replace 4.35 kg or 1.58 gallons of gasoline.

4. "GREEN" HYDROGEN

Green hydrogen production by electrolysis involves generating electricity from a renewable energy source and using it to produce oxygen and hydrogen gas from water as the primary element.

Hydrogen produced by electrolysis form RES is a 100% sustainable source of energy as it does not emit any harmful/greenhouse gas during the production process and does not cause any environmental pollution.

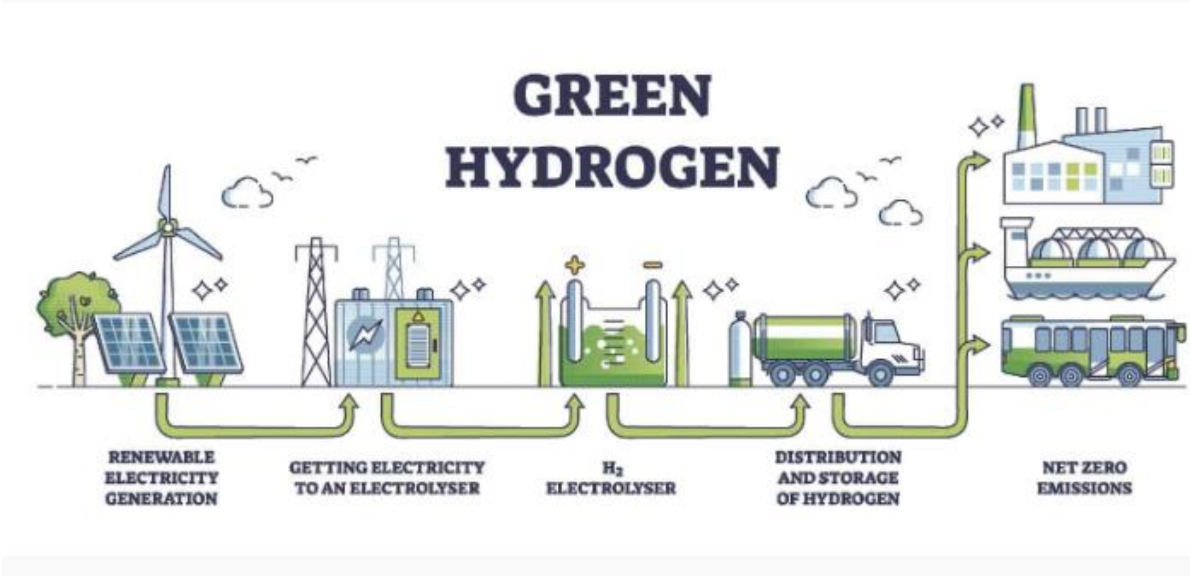

Fig. 2. Green hydrogen – production transportation, and storage (Source` https://currentaffairs.adda247.com/issues-with-green-hydrogen/)

According to a recent study [3], the levelized cost of green hydrogen production in Armenia using newly built PV plants in 2025 for preferential interest rates (about 2%) will be 3.4 USD/kg, making it competitive in the international arena. At commercial rates (about 10%), production costs increase significantly and will be about 6.1 USD/kg). According to the recommendations of that expert group, in order to economically justify the production of hydrogen, such possible options as the reuse of the copper smelter (t. Alaverdi), the organization of fertilizer and ammonia production, joining the regional hydrogen production and transport programs were considered.

Fig. 3. Advanced highly efficient electrolysers for green hydrogen production by BloomEnergy company, USA (The estimated price is around 1.3 mln USD/MW)

Fig. 4. 5.78 MW solar PV station near v.Tsapatagh, Armenia

5. ADVANCEMENT IN SOLAR PV ELECTRICITY USE IN ARMENIA

Armenia highly prioritizes the development of renewable energy resources, though main achievements have been fixed in the utilization of small hydropower plants and solar energy use. Over last five years Republic of Armenia (RA) has significantly advanced in solar PV stations installations and use. Natural climatic conditions for solar energy use are favorable in Armenia. Annual average value of sunshine hours is 2500 hours. Average annual flow of solar radiation on horizontal surface is 1720 kWh/m^2. For comparing purposes [16], in Central Europe this average value is 1000kWh/m^2, particularly, in Poland, Czech Republic, and Slovakia 950-1050kWh/m^2, in Hungary – 1200 kWh/m^2, in Bulgaria – 2000 kWh/m^2. The Government of Armenia (GoA) is planning to reach 1 000 MW of solar PV capacities and to provide through them at least 15% of total electricity generation by 2030. This target is expected to reach through the government support with introducing feed-in tariffs, by attracting foreign investments, etc. Notably that world prices on PV solar have sharply fallen during last ten years and continue to fall at rate 2.3%/year (see Fig 1). 46% cells efficiency is achieved in certain laboratory tests, though commercial cells have efficiencies 19-21%. Perovskite solar cells are currently of large interest due to their cost/effectiveness features. With that the latest events related with COVID-19 pandemic will creates definite risks that should be taken into account.

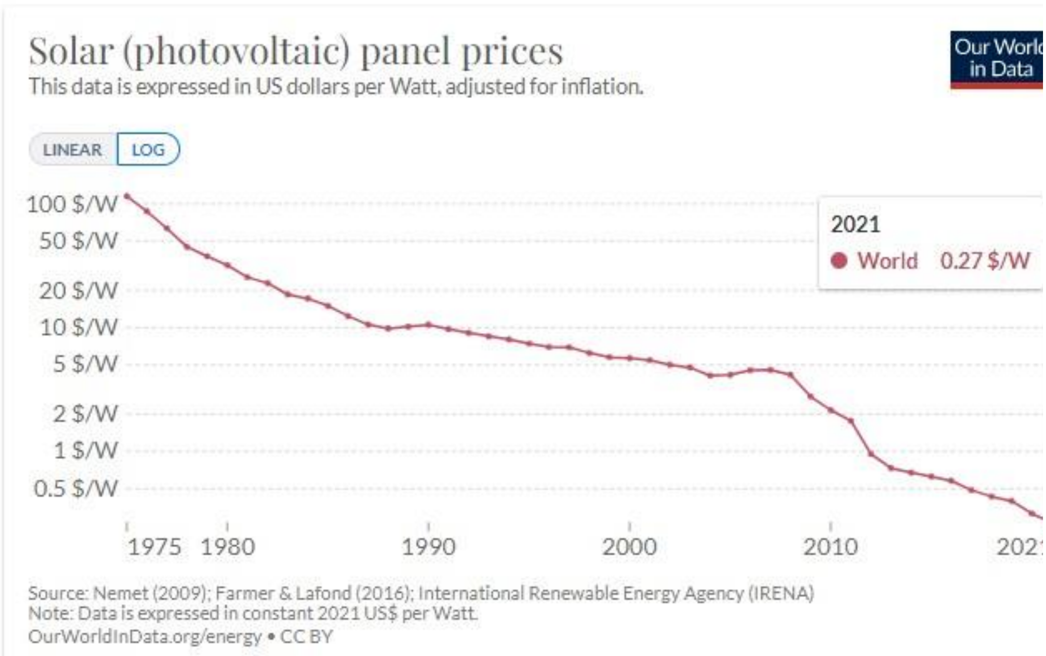

Fig. 5. Solar photovoltaic panel prices (Source` Our World in Data)

Country's average energy demand is more than 3 Mtoe. 27% of energy demand in 2020 is covered with domestic energy production mostly from nuclear and hydro resources [10]. Armenia practically lacks proven fossil fuels resources of industrial scales (in the past it used limited quantity of coal and peat for heating purposes[3]) and imports natural gas and oil products mainly from the Russian Federation. Natural gas (over 80% in 2020) is imported from Russia via pipeline through Georgia. Natural gas is imported also from Iran on the basis of barter agreement - natural gas in exchange of exported electricity. All Thermal Power Plants operate on natural gas.

In 2021, Government of Armenia (GoA) approved the RA Energy Sector Development Strategic Programme to 2040 and the Action Plan to Ensure Implementation of the RA Energy Sector Development Strategic Programme, based least-cost strategies to develop the entire energy system and the measures necessary to implement this strategy. In 2022, the GoA approved the Programme on Energy Saving and Renewable Energy for 2022-2030, the Action Plan Ensuring Implementation of the First Phase (2022-2024) of the Programme. The government has approved the plan to increase renewables to 66% of the power generation mix by 2036.

Armenia adopted the Law on Energy in 2001: it includes provisions for market rules and ownership structure. The law on Energy Saving and Renewable Energy (2004) defines the policy principles for renewables and energy savings. It also defines small HPP as a station with capacity less than 10MW, after law's amendment (in 2011) – less than 30 MW. The Government of Armenia has obliged to purchase all the electricity from RES, including small hydro during 15 years from the start of operation. The Public Services Regulatory Commission's (PSRC) has introduced feed-in tariffs on electricity from RES within that period.

Further, we present some figures and diagrams to illustrate the progress in solar PV applications in Armenia up to the end of 2022. In 2022, amount electricity generated and delivered from all types of power stations was 8618.8 mln. kWh, the final electricity consumption - 6404.7 mln. kWh [4]. Share of renewable electricity in final electricity consumption was 33.1% including large and medium-sized hydro power stations (with capacity more than 30MW) and 16.8% without taking into account only small hydro, solar PV, and wind.

For 2022, shares of electricity generation by different types of power stations in total volumes of electricity generation are presented on the Fig. 1. On the Fig. 2 shares of electricity generation by different types of renewable energy sources (RES - small hydro with capacities less than 30MW, solar photovoltaic, wind) in total electricity generation are presented. There are no operating geothermal power plants in Armenia. The only Lusakert biogas-based power plant is not in operation for several years.

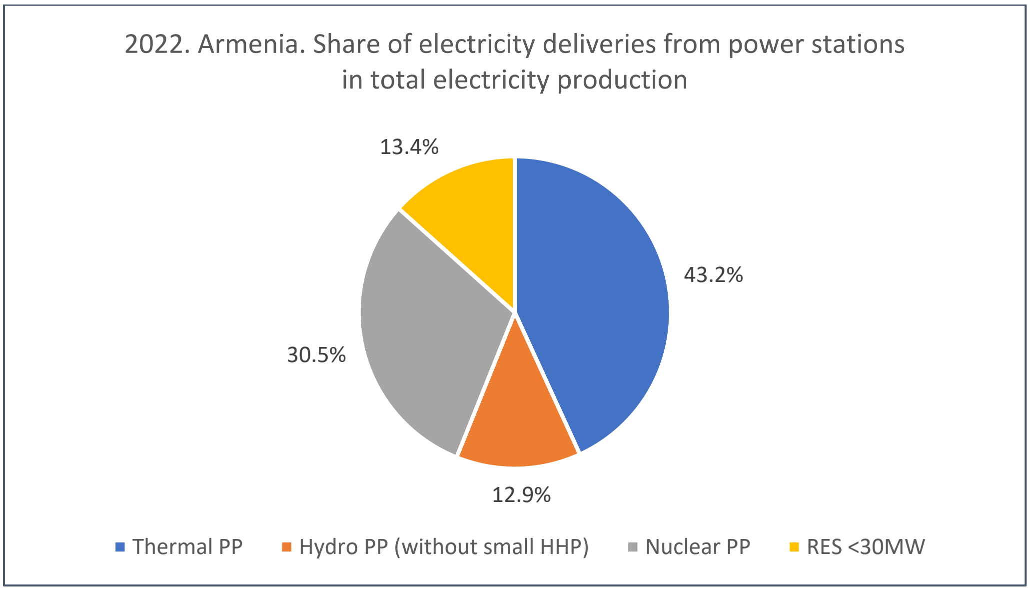

Fig. 6. 2022. Armenia. Share of electricity deliveries from power stations in total electricity production

As can be seen from the Fig. 7, solar photovoltaic stations stand on the second place after small hydro regarding the electricity generation shares in total electricity production. Share for both Solar PV industrial and PV autonomous producers totals 4.2%. The PV stations' generated electricity share in country's final electricity consumption is higher and totals 5.27% (see Fig. 8).

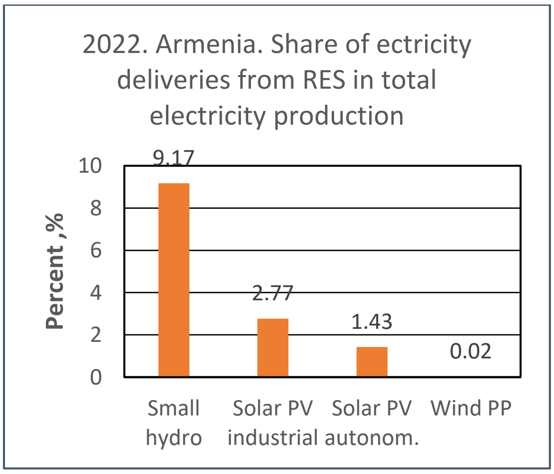

Fig. 7. 2022. Armenia. Share of electricity deliveries from RES in total electricity production Diagram 2

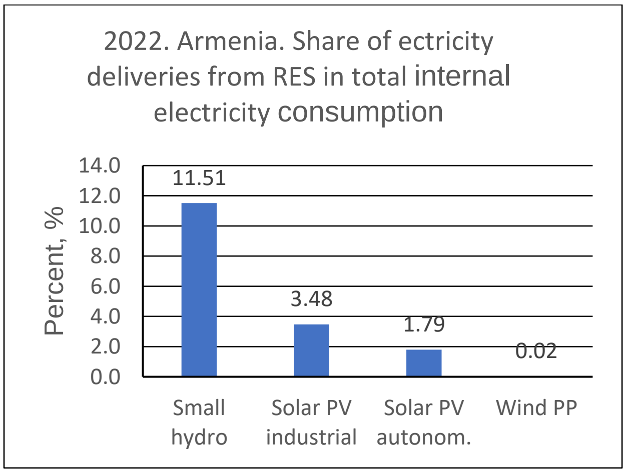

Fig. Diagram 8. 2022. Armenia. Share of electricity deliveries from RES in total internal electricity consumption

According to data received from Electricity Network of Armenia (ENA), the installed capacity of PV industrial stations + PV autonomous producers in 2020 – 101.6MW, in 2021 – 220.9MW, in 2022 – 408.1MW. For comparing purposes, in 2018 there were 9 Industry-scale PV stations with total capacity of 7.02 MW and 784 PV autonomous generators with total capacity of 16.15MW, so totally installed PV capacity was 25.17 MW (see Fig. 9).

What mechanisms are used for autonomous PV providers. There is no license required to operate PV station with capacity less than 500kW for legal person and with capacity less than 150 kW for individuals.

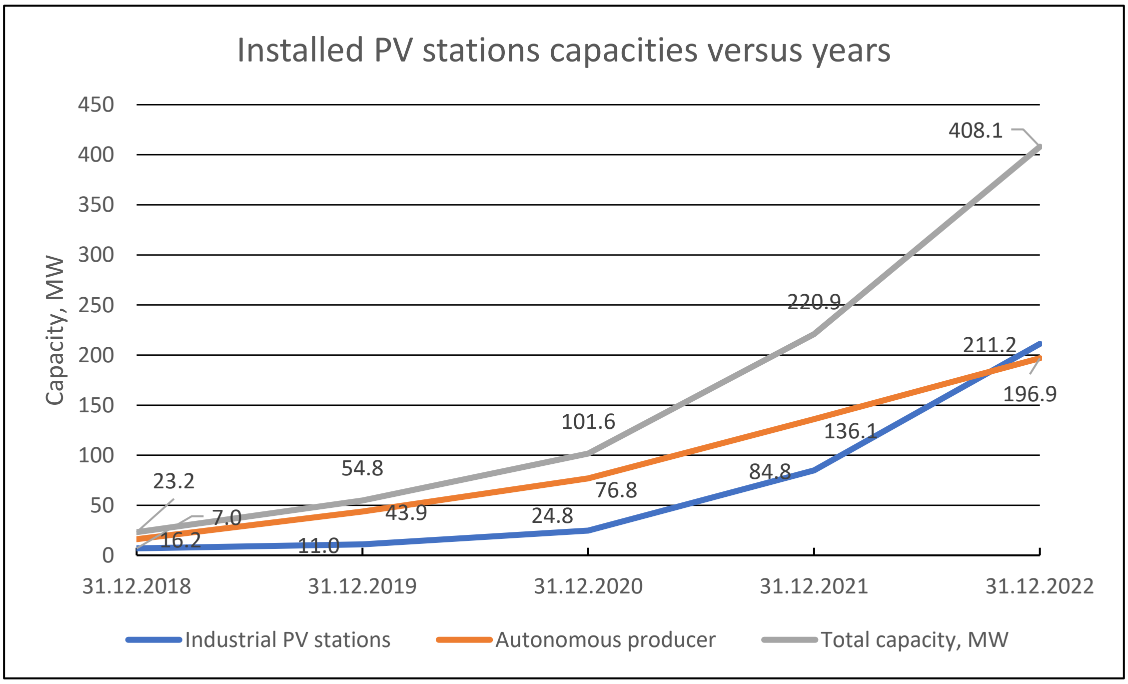

Fig. 9. Installed PV stations capacities versus years

In case of autonomous PV provider Net metering mechanisms has been used while PV station supply electricity to ENA. For this purpose, the reverse multi-tariff electronic meter is installed in accordance with state regulations. Excess electrical energy above the needs is sold to ENA. If the amount of electricity provided by the autonomous energy producer is positive as a result of the annual calculation, the autonomous energy producer shall be reimbursed at the rate of 50% of the tariff set by the Commission (around 24 AMD/kWh without VAT, 1 Euro is around 417 AMD, 2023) according to Armenian regulations established through Public Services Regulatory Commission.

Currently three local organizations have capacities to manufacture solar PV panels from solar cells, but solar PV cells are completely imported from abroad. Though there exist capacities to establish locally manufacturing of solar invertors and charge regulators, but practically all the them are imported from abroad.

6. WORLD ADVANCED SOLAR PV PANELS

The latest achievements of the top manufacturers in the field of high-efficiency (up to 23.6%) commercial Photovoltaic (PV) panels produced in industrial volumes as of June 2023 are briefly described. (see Table 1). The following is based on material presented in [11]. Key features include silicon type (monocrystalline, polycrystalline silicon wafers), wafer structure, junction technologies (homogeneous/heterogeneous), and layer/surface passivation method and materials.

Some models of solar panels of the companies mentioned in Table 1 (Longi Solar, Jinco Solar, Recom, Risen Energy, Canadian Solar, etc.) have been also used in Armenia, including bifacial panels, in which both the front and back surfaces convert light. electricity. In last two years we have seen a dramatic increase in companies producing more efficient solar PV panels with high-efficiency (above 22%) based on new technology N-type HJT, TOPcon and IBC (Interdigitated Back-contact) cells.

Table 1. World Advanced Solar PV Panels

	Manufacturer company	Type of panel/cells technology	Panel capacity*	Efficiency, %	Country
1	Aiko Solar	Black Hole series, N-type ABC, Back contact	460W	23,6	China
2	Recom Tech	Black Tiger/TOPcon Back-contact	460W	23,0	France
3	Longi Solar	Hi-Mo Scientist/HPBC	450W	23,0	China
4	SunPower	Maxeon 6/ N-type IBC	440W	22,8	USA
5	Canadian Solar	Hi Hero/N-type HJT	445W	22,8	Canada
6	Jinco Solar	Tiger NeoN/N-type TOPcon	440W	22,5	China
7	Risen Energy	Hyper-ion/N-type TOPCon	440W	22,5	China
8	REC	Alpha-Pure R N-type HJT	430W	22,3	Singapore
9	SPIC	Andromeda 2.0, N-type IBC	440W	22,3	China
10	Q cells	Q.Tron-G1+/(MBB) half-cut N-type TOPCon	400W	22,3	Զsouth Korea

*Panels with 54-66 cells (108-HC, 120-HC or 132-HC) and 96/104 cells format: Commercial panels length more than 2 meters are not included: The standard size of 60 cells panels are 1mx1.65m.

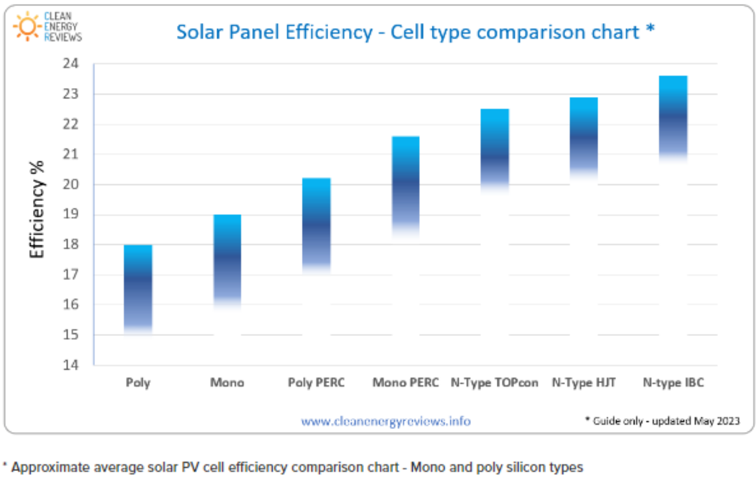

Fig. 10. Comparison diagram of the average efficiency of solar PV cells. – Mono (Mono) and Poly (Poly) Crystalline Silica Types (from Cleaner Energy Reviews). From left to right: polycrystalline cells, monocrystalline cells, polycrystalline PERC cells, monocrystalline PERC cells, N-type TOPCon, N-type HJT, N-type IBC cells. Source: Clear Energy Reviews, 2023

Abbreviations:

HJT - Heterojunction Cells, **TOPCon - Tunnel Oxide Passivated Contact, Gapless Cells, PERC - Passivated Emitter and Rear Contact Cells**, **Multi Busbar** – Multi ribbon and micro-wire busbars, **Split Cells** - half-cut and 1/3 cut cells, **Shingled Cells, IBC-Interdigitated Back Contact, PERT** - Passivated Emitter Rear Totally Diffused-cells, **PERL** - passivated emitter with rear locally diffused cells:

7. BRIEF ANALYSIS OF ELECTRICITY GENERATING PLANTS FROM RENEWABLE ENERGY SOURCES IN ARMENIA AS OF 2022.

As of December 31, 2022, electricity from RES was produced at the following power plants. There were 189 small HPPs (each with capacity less than 30 MW) with a total capacity of 389 MW, 61 solar photovoltaic (PV) plants with a total capacity of 211.9 MW, 10,282 stand-alone PV plants with a total capacity of 196.9 MW, wind power plant with installed capacity of 2.64 MW. The Lusakert Biogas Plant with an installed capacity of 0.85 MW and an estimated annual output of 7 million kWh has been inactive for several years. Geothermal power plants have not been built in the republic.

To characterize the productivity of different types of power plants, together with capacity factor (CF) the annual average production of electricity per MW capacity were calculated. For 2022 calculated values for solar are with certain approximations. The values of some indicators with some approximations based on actual data are given in Table 2. The data on generated electricity are taken from PSRC. The data on the capacities of solar plants and other RES are taken from the ENA and the PSRC.

For most of the solar PV plants in Armenia, the solar panels are not equipped with sun tracking devices. In solar PV plants that use one axis solar trackers with motors, the electrical energy production can be increased by about 30%. For two-axis solar PV plants in which the solar panels are oriented in a way to be perpendicular to the solar radiation (the sun moves from east to west and north to south and vice versa) electrical energy production can be increased by up to 40%.
So, for example, the solar photovoltaic station with a sun-tracking system built on the shore of Lake Sevan in Tsapatagh (see Fig. 4) has a capacity of 5.78 MW, and the average annual production of electricity is 12.3 million kWh or about 2.13 million kWh/MW (based on the data provided by the owner company).

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Table 2. 2022 data on annual electricity production per 1 MW and capacity factors values for different power plants types in Armenia

Type of power plant (complex of power plants)	**Data on annual electricity production per 1 MW (mln. kWh/MW)**	**Capacity Factor (CF), %**	**Notes**
Contour Global Hydro Cascade CJSC (former Vorotan cascade of HPPs)	1.81	20.7	Total installed capacity of HPPs - 404 MW
Small HPPs	2.03	23,2	189 small HPPS with total capacity of 389 MW
Solar PV stations	1.61	18,3	Average capacity per year ((211,2+84,8) /2) MW
Autonomous solar PV stations	0.62	7,1 (not taking into account own consumption)	196,9MW [1] by the end of year
Wind Power Plants (WPP)	0.64	7,3	2,64 MW [2]
	1.29	14,7	With available capacity of 1.32MW
Armenian Nuclear Power Plant (ANPP)	6.83	78	In case of 385 MW of ANPP capacity
«Yerevan Thermal Power Plant» CJSC (steam gas cycle power unit)	7.06	80,6	For TPP capacity of 242 MW
Lusakert biogas plant (start of operation - 2008)	3.21 (2009-2011) (power plant has not operated in last several years)	36.6	0,85 MW plant's Installed capacity of MW and 7 mln. kWh of planned annual average electricity production. In reality 2.73 mln kWh in 2009-2011 ((2.7+2.9+2.6)/3=2.73 mln kWh)

[1]Data for electricity for plants own consumption are not taken into account

[2] Total capacity of WPPs in the balace is indicated as 4.2MW, but according to expert estimates and site visits only Lori-1 wind power plant supplu electtricity network with electricity with available capacity of 2.64 MW (half of installed capacity).

CONCLUSION AND RECOMMENDATIONS

1. Approved in 2021 by the Government of Armenia the strategic plan envisages that by 2030 solar PV plants with a total capacity of 1000 MW will be installed, which will provide at least 15% of the total electricity production in the country. Their use may also be promising for producing "green" hydrogen fueled by electrolysers.

2. The main challenge of green hydrogen production is the high cost of production. The production of green hydrogen is 2-3 times more expensive than the production of hydrogen using any fossil fuel.

3. There is a lack of awareness and understanding of green hydrogen among the general public.

4. HPPs, both existing and planned, represent a significant potential for the production of "Green" hydrogen in Armenia. The potential (unused) of planned large and medium power hydropower plants is about 300MW, including Meghri HPP, Shnokh HPP, Loriberd HPP and other HPPs.

5. Wind power plants in Armenia are underdeveloped, while the economically justified potential is 500-600MW according to various estimates. If necessary financial investments are available, the Wind PPs to be built in Armenia can also be used for the production of "green" hydrogen.

6. The electricity produced in NPPs for the production of hydrogen ("yellow" hydrogen) for domestic consumption will serve the purposes of improving energy security. The same applies to the production of hydrogen ("grey" hydrogen [2]) for electricity produced from thermal power plants. From the point of view of exports abroad, the cost and demand of this type of hydrogen will make them uncompetitive. But it will occupy its certain place in the domestic market of Armenia.

LITERATURE AND SOURCES

1. Global hydrogen review 2022, International Energy Agency (IEA).
2. Technology Brief, Hydrogen, UNECE, 51p., 2021.
3. Assessment of green hydrogen potential in Armenia, the German Economic Team, 2023.
4. Hydrogen – an innovative solution to carbon neutrality. 2020 Economic Commission for Europe, Committee on Sustainable Energy, https://unece.org/fileadmin/DAM/energy/se/pdfs/CSE/comm29_Nov.20/ECE_ENERGY_2020_8_Hydorgen_final.pdf.
5. Transforming our world: the 2030 Agenda for Sustainable Development. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf.
6. The European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
7. https://www.equilibar.com/blog/applications/hydrogen-energy-update-q-a-with-alan-black/
8. https://news.energysage.com.
9. Public Services Regulatory Commission of Armenia- https://www.psrc.am:
10. https://www.iea.org/reports/armenia-energy-profile/overview.
11. Cleaner Energy Reviews, Monthly newsletter, 2023.
12. Artashes Sargsyan. Advancement In Solar PV Installations In Armenia, Noyan Tapan Highlights, #31(1434), 2023, pp.8-9. PDF(Eng), www.nt.am.
13. Electricity Network of Armenia. – www.ena.am
14. Ministry of Territorial Administration and Infrastructure of Armenia - https://www.mtad.am.
15. Hydrogen Resource Assessment. Hydrogen Potential from Coal, Natural Gas, Nuclear, and Hydro Power Anelia Milbrandt and Margaret Mann, NREL, 2009.
16. Sargsyan A. Assessment of Renewable Energy Potential in Armenia (2017 Update).Yerevan, Lusabats Publishing House, 2017-29p.
17. NGO Ecoteam web site – http://ecoteam-armenia.org

Appendix 1. Hydrogen Value Chain

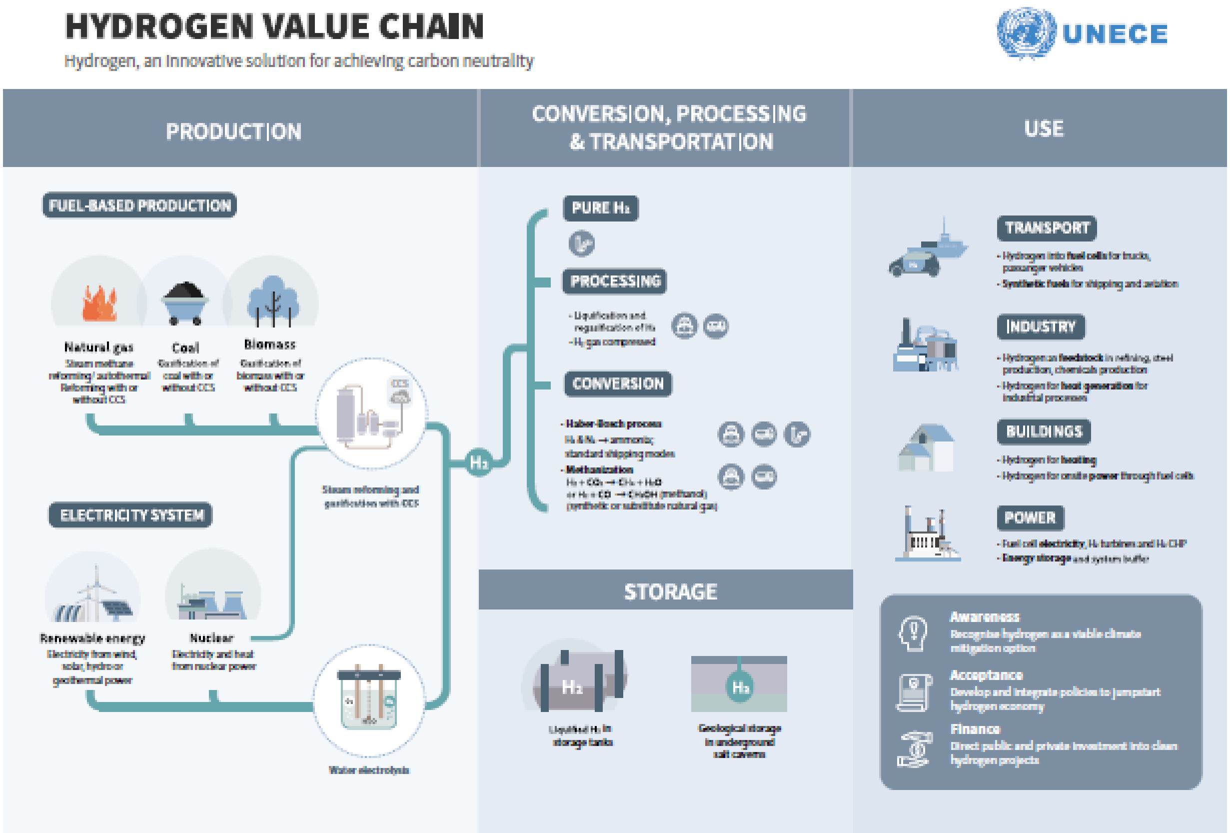
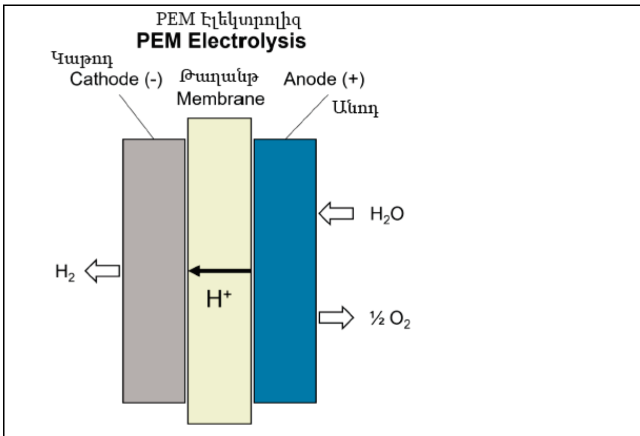


Fig. 11. Hydrogen Value Chain

Appendix 2. PEM electrolyser operation principles



In PEM electrolyser, chemical reactions occur at the anode and cathode to produce hydrogen during the electrolysis of water.

$H_2O \rightarrow H^+ + \frac{1}{2} O_2 + 2e^-$ Անոդ

$2H^+ + 2e^- \rightarrow H_2$ Կաթոդ

$H_2O \rightarrow H_2 + \frac{1}{2} O_2$ Ընդհանուր ռեակցիա

Fig. 12. PEM lectrolyser operation principles

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