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# On the green path of innovation – hydrogen from laser-assisted alkaline electrolysis

# Na zelenom putu inovacija – vodonik iz laserski potpomognute alkalne elektrolize

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**Abstract:** The dominant problem that needs to be solved today is the issue of energy sources and how to use them, which must be ecological and sustainable - in a word, green. As the best candidate for a global solution to this problem, hydrogen produced electrolytically stood out as a green fuel with no carbon footprint. However, for a hydrogen-based economy to have a realistic and sustainable perspective in the future, it largely depends on its efficient and economically viable production that would meet the market's needs. Special attention in this paper is devoted to the influence of laser radiation on the possibility of improving the process of alkaline electrolysis for obtaining hydrogen, as well as on increasing the amount of separated hydrogen when the electrolytic cell is directly irradiated with a laser beam during the electrolysis process itself. After the experiments, it was determined that the application of direct irradiation of the electrolyte with a green laser at 532 nm wavelength significantly increases the amount of hydrogen produced and reduces the voltage of the electrolytic process, which is directly related to the increase in the energy efficiency of the overall hydrogen production process.

**Keywords:** green economy, hydrogen, innovation, alkaline electrolysis, green laser.

**Sažetak:** Dominantan problem koji danas treba rešiti je pitanje energenata i načina njihove upotrebe koji moraju biti ekološki i održivi – jednom rečju zeleni. Kao najbolji kandidat za globalno rešenje ovog problema istakao se vodonik proizveden elektolitičkim putem, kao zeleno gorivo bez ugljeničnih otisaka. Da bi ekonomija zasnovana na vodoniku imala realnu i održivu perspektivu u budućnosti, u velikoj meri zavisi od njegove efikasne i ekonomski podobne proizvodnje koja bi zadovoljila potrebe tržišta. Posebna pažnja u ovom radu posvećena je uticaju laserskog zračenja na mogućnost poboljšanja procesa alkalne elektrolize za dobijanje vodonika, kao i na povećanje količine izdvojenog vodonika pri direktnom ozračivanju elektrolitičke ćelije laserskim snopom tokom samog procesa elektrolize. Nakon izvršenih eksperimenata utvrđeno je da se primenom direktnog ozračivanja elektrolita zelenim laserom talasne dužine 532 nm u značajnoj meri povećava količina proizvedenog vodonika i smanjuje napon elektrolitičkog procesa, što je u direktnoj vezi sa povećanjem energetske efikasnosti ukupnog procesa dobijanja vodonika.

**Ključne reči:** zelena ekonomija, vodonik, inovacije, alkalna elektroliza, zeleni laser.

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## INTRODUCTION

The green economy is a new concept of life that maintains a balance between economic growth and environmental protection. Aware that it is not easy to step into this new dimension, we are looking for the most elegant and safest ways to decarbonize the global economy to ensure a healthy and comfortable life in harmony with nature. The term and concept of “Green Economy” appeared for the first time in 1989 in a group of British economists from the London Center for Environmental Economics (Pearce et al., 1989). When the economic crisis hit in 2008, the green economy came to the fore, offering solutions to the global crisis and affirming sustainable development. The United Nations Environment Program (UNEP) then launched the Green Economy Initiative to gain political support for investments within its framework (Biely, 2014). Thus, the green economy has set goals that will contribute to the stable recovery of the global economy and are based on responsible management of resources and creating new, clean jobs. However, as this approach is very divergent and complex, its principles are not easy to put into practice. Hence, there is a need to implement laws related to green economic growth to overcome misunderstandings in environmental protection and reach sustainable development goals. Production of cleaner energy, Green innovations and Green trade are considered the most important determinants of green economic growth, contributing to economic prosperity and environmental sustainability.

Green innovations promote receptive, sustainable technologies that are “environmentally friendly”, cost less and are important for environmental protection. With the help of green innovations, it gets in the way of pollution because modern “smart machinery” is used, directly affecting economic growth. Green innovations can reduce greenhouse gas emissions, improve energy efficiency and protect the environment (Lorek & Spangenberg, 2014).

The green economy has another significant segment, the subject of our research, which is the economy based on green hydrogen or the hydrogen economy (Bockris, 1976).

The potential that hydrogen has to take over fossil fuel niches is fascinating. Fossil fuels are responsible for all kinds of pollution, from oil spills and ozone holes to climate change, which is increasingly evident (Mulder et al., 2019). The basis of the hydrogen economy is a system in which hydrogen is the energy carrier.

The main goal of the hydrogen economy is to obtain hydrogen from already available energy sources and to use it in transport, industry, and households. The hydrogen economy represents an elegant and long-term solution to the problems of environmental protection, depletion of natural resources, decarbonization, etc. The great advantages of the hydrogen economy are very attractive to legislators worldwide, who are working rapidly to improve and develop energy strategies that are necessary to transition from a fossil to a hydrogen world. The hydrogen economy is intensively researched, as evidenced by the existence of a large number of plans, reports, case studies and review papers. A large number of international organizations were founded to promote and educate legislators, industrialists and the general public, all with the aim of transitioning to the hydrogen age. (Mah et al., 2019; Parra et al., 2019; Dias et al., 2020).

Green hydrogen, obtained with the help of renewable energy sources, seems like a promising path to follow. The existing literature shows a consensus that green hydrogen has the power to decarbonize a wide range of industries, serve as a clean energy carrier from a renewable energy depot, and can be applied to all occasions (Oldenbroek et al., 2020; Badea et al., 2017).

However, the problems related to obtaining hydrogen are still extensive and do not allow it to come to the fore. In this paper, we will talk about green hydrogen obtained in alkaline electrolysis because it is environmentally friendly and fits into the green economy concept. Still, it requires more innovations to become dominant. In recent years, photolytic processes that use the energy of laser radiation to destroy water molecules have been studied and improved greatly (Perret et al., 2007; Bidin et al., 2014).

In order to examine the possibility of applying laser radiation in industrial alkaline electrolysis conditions, this research measured the amount of separated hydrogen during direct irradiation of the electrolyte solution with a laser beam of wavelength 532 nm at different current densities. 6M KOH was used as the electrolyte, and pure nickel electrodes (industry standard) were used for the cathode and anode.

## 1. MATERIALS AND METHODS

The effect of laser radiation on the amount of separated hydrogen was investigated by irradiating the electrolyte solution during the electrolytic process. The amount of separated hydrogen was measured without and with the use of a light source.

For the purposes of this experiment, a two-electrode glass cell was used, with a volume of 30 $cm^3$, with a sealed upper part containing the leads for the electrodes and the lead connected to the pressure gauge (U-tube). Nickel plates with a surface area of 2 $cm^2$ were used as the cathode and anode, which were previously prepared by mechanical and chemical treatment. The preparation procedure first involved polishing with 800 and 2000 grit polishing paper, followed by chemical treatment by immersing the electrodes in an aqueous solution of $HNO_3$, molar ratio 2:1, for 2 minutes and then washing with deionized water and ethanol. The electrolyte in this experiment was 6M KOH.

The continuous laser irradiation applied in the experiment was provided using a diode solid-state laser that emits light with a wavelength of 532 nm (green region of the visible spectrum), with a total output power of 750 mW.

Using potentiostat/galvanostat Reference 3000 (Gamry Instruments Inc.), chronopotentiometric measurements with current densities of 10, 25, 50, 100 $mAcm^{-2}$ were applied to the electrodes. The amount of separated hydrogen was measured with a manometer for 5 minutes. The same measurement procedure was repeated with the addition of a laser light source focused on the electrolyte area located in the cathode's immediate vicinity. The experiment was performed at standard laboratory conditions. A schematic view and a photo of the experiment are given in Figure 1.

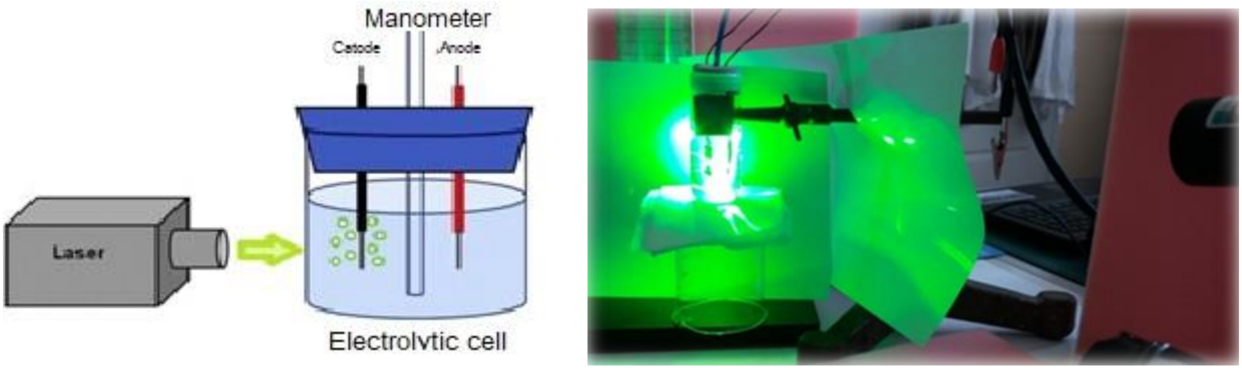


*Figure 1. Schematic representation and photo of the "green laser" experiment.*

## 2. RESULTS AND DISCUSSION

During the electrolysis process, the standard electrolyte solution (6M KOH) was exposed to continuous laser beam at 532 nm wavelength. The amount of separated hydrogen and the voltage change with time was measured at different current densities in conditions without and with laser action.

The change in the voltage response of the system for different applied current densities without and with laser irradiation is shown in Figure 2.

In the presented graphs it can be seen that there is a significant reduction in the electrolysis voltage at almost all current densities tested. At a current density of 50 $mAcm^{-2}$, the voltage of laser-assisted electrolysis is lower by as much as 220 mV. The obtained results show that laser radiation has a positive effect on the energy efficiency of the process of obtaining hydrogen by alkaline electrolysis.

In addition to the effect of laser radiation on the voltage response of the electrolytic system, its effect on the amount of separated hydrogen in a given period of time at different current densities was also monitored. The amount of separated hydrogen during the electrolytic process without and with the application of the "green laser" is shown in Table 1.

*Table 1. Quantities of separated hydrogen at different current densities without and with laser irradiation*

| **j / $mAcm^{-2}$** | **Amount of separated $H_2$ without laser / mol** | **Amount of separated $H_2$ with laser / mol** | **Δ $H_2$ / mol** |
|---|---|---|---|
| 10 | $2{,}3\cdot10^{-5}$ | $2{,}7\cdot10^{-5}$ | **$0{,}4\cdot10^{-5}$** |
| 25 | $6{,}4\cdot10^{-5}$ | $7{,}4\cdot10^{-5}$ | **$1{,}0\cdot10^{-5}$** |
| 50 | $13{,}4\cdot10^{-5}$ | $14{,}8\cdot10^{-5}$ | **$1{,}4\cdot10^{-5}$** |
| 100 | $27{,}6\cdot10^{-5}$ | $30{,}1\cdot10^{-5}$ | **$2{,}5\cdot10^{-5}$** |

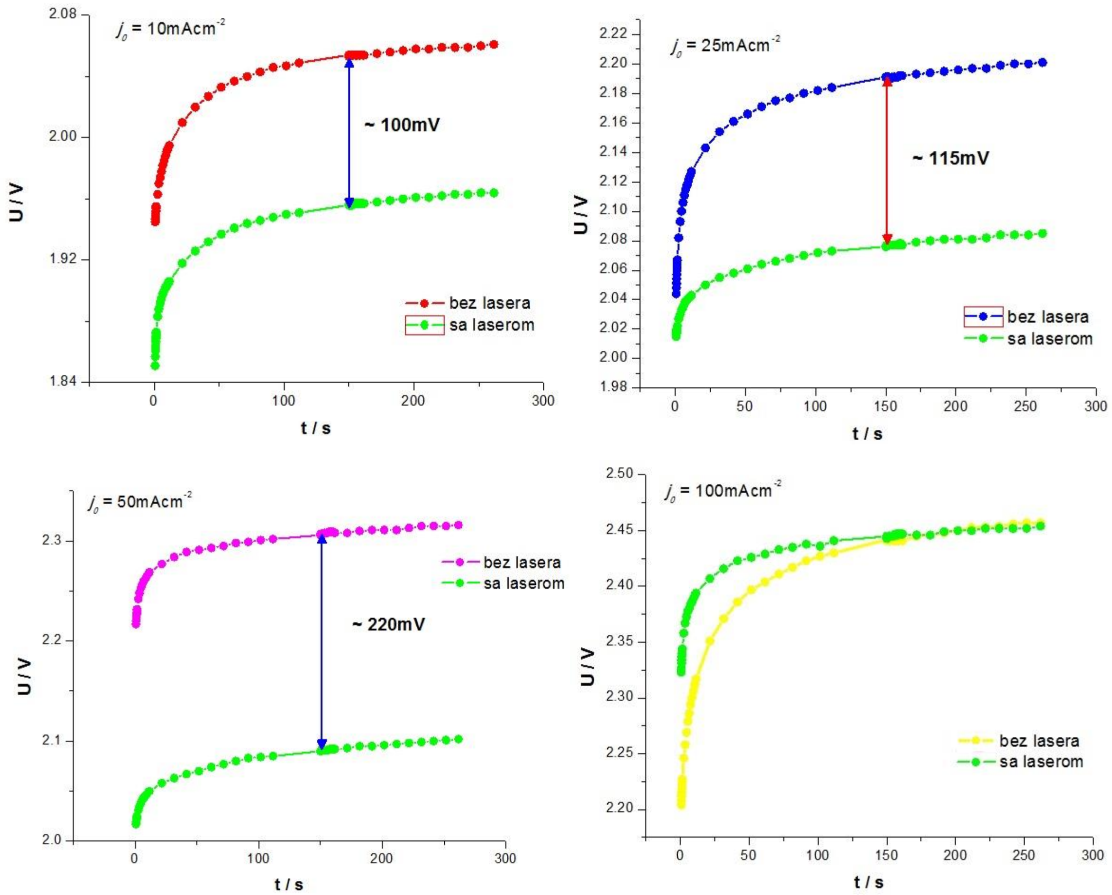


*Figure 2. Voltage change with time in the electrolytic process, without and with the application of laser radiation*

Based on the obtained results, there is a noticeable increase in the separated amount of hydrogen during laser irradiation of the electrolytic system at the same current densities. It can be seen that with an increase in the applied current density, $\Delta H_2$ also increases, i.e. the difference in the amount of hydrogen obtained between laser-assisted and classical electrolysis.

The phenomenon of increased hydrogen release in the presence of laser radiation with a wavelength of 532 nm, i.e. of green laser radiation, can be explained through the concept of electrical susceptibility or through the dielectric constant of water (Bidin et al., 2014). Both physical quantities relate to the polarization of water by an electric field. Dielectric constant and electrical susceptibility describe the ability of the medium itself to polarize under the influence of the field and thereby increase or decrease the total electric field. Green laser radiation is transparent to water, i.e. water does not absorb it, the frequencies of visible light are much higher than the vibrational frequencies of water molecules, which indicates that in this case the energy of laser radiation is not responsible for breaking hydrogen bonds. However, the high transparency for green laser radiation gives the possibility to fully utilize the total intensity of the laser radiation to create an additional electric field that will support the electrolytic process. This additional electric field helps in the transfer of charges during electrolysis and thereby promotes the production of hydrogen.

## CONCLUSION

The results of testing the effect of green laser radiation on the amount of separated hydrogen, by irradiating a standard electrolyte solution (6M KOH) during the electrolytic process itself, show a significant reduction in the electrolysis voltage in cases of laser irradiation of the electrolytic cell at all tested current densities. The voltage of laser-assisted electrolysis, in the case of an applied current density of 50 mAcm$^{-2}$, is even 220 mV lower than the voltage of classical electrolysis. Regarding the amount of separated hydrogen, there is a noticeable increase during laser irradiation of the electrolytic system at all current densities tested. It is observed that with the increase in the applied current density, the difference in the amount of hydrogen obtained between laser-assisted and classical electrolysis also increases.

Considering the promising results in the case of laser-assisted electrolysis, further work on this issue will go in the direction of researching the mechanism that enables increased hydrogen production, as well as testing the long-term stability of such systems under different operating conditions.

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REFERENCES

[1] Badea, G., Naghiu, G. S., Giurca, I., Aşchilean, I., & Megyesi, E. (2017). Hydrogen Production Using Solar Energy - Technical Analysis. *Energy Procedia*, 112, 418-425. https://doi.org/10.1016/j.egypro.2017.03.1097

[2] Bidin, N., Razak, S. N. A, Azni, S. R., Nguroho, W., Mohsin, A. K., Abdullah, M., Krishnan, G., & Bakhtiar, H. (2014). Effect of green laser irradiation on hydrogen production. *Laser Physics Letters*, 11(6), 066001. https://doi.org/10.1088/1612-2011/11/6/066001

[3] Biely, K. (2014). The United Nations Environment Programme's Green Economy initiative: shifting the concept with the financial crisis of 2008. *LUCID* - Early Career Researchers Conference held at: Lund, Sweeden, 16 p.

[4] Bockris, J. (1976). *Energy: The Solar-Hydrogen Alternative*. Architectural Press.

[5] Dias, V., Pochet, M., Contino, F., & Jeanmart, H. (2020). Energy and Economic Costs of Chemical Storage. *Frontiers in Mechanical Engineering*, 6:21. https://doi.org/10.3389/fmech.2020.00021

[6] Lorek, S., & Spangenberg, J. (2014). Sustainable consumption within a sustainable economy - Beyond green growth and green economies. *Journal of Cleaner Production*, 63, 33-44. https://doi.org/10.1016/j.jclepro.2013.08.045

[7] Mah, A. X. Y., Ho, W. S., Bong, C. P. C., Hassim, M. H., Liew, P. Y., Asli, U. A., Kamaruddin, M. J., & Chemmangattuvalappil, N. G. (2019). Review of hydrogen economy in Malaysia and its way forward. *International Journal of Hydrogen Energy*, 44(12), 5661-5675. https://doi.org/10.1016/j.ijhydene.2019.01.077

[8] Mulder, M., Perey, P., & Moraga, J. L. (2019). *Outlook for a Dutch hydrogen market* (Issue 5). https://www.rug.nl/ceer/blog/ceer_policypaper_5_web.pdf

[9] Oldenbroek, V., Smink, G., Salet, T., & van Wijk, A. J. M. (2020). Fuel cell electric vehicle as a power plant: Techno-economic scenario analysis of a renewable integrated transportation and energy system for smart cities in two climates. *Applied Sciences* (Switzerland), 10(1), 143, 1-54. https://doi.org/10.3390/app10010143

[10] Parra, D., Valverde, L., Pino, F. J., & Patel, M. K. (2019). A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. *Renewable and Sustainable Energy Reviews*, 101, 279-294. https://doi.org/10.1016/j.rser.2018.11.010

[11] Pearce, D. W., Markandya, A., Barbier, E. B., (1989). *Blueprint for a Green Economy*. Earthscan, London.

[12] Perret, R., Weimer, A., & Roth, K. (2007). *Development of Solar-Powered Thermochemical Production of Hydrogen from Water*, excerpt from 2007 DOE Hydrogen Program Annual Progress Report. DOE Hydrogen Program FY Annual Progress Report.