

# Metal Magnesium Fuel Cycle to Make Indonesia a Leading Renewable Energy Country

Shigeaki Uchida  
School of Materials Science and  
Engineering  
Henan University of Science and  
Technology  
Luoyang, China  
uchidashigeaki@haust.edu.cn

Dangqin Yin  
School of Materials Science and  
Engineering  
Henan University of Science and  
Technology  
Luoyang, China

Chao Han  
School of Materials Science and  
Engineering  
Henan University of Science and  
Technology  
Luoyang, China  
hanchao\_0531@126.com

Mujahidin Didin  
School of Electrical Engineering  
Institute Teknologi Bandung  
Bandung, Indonesia  
33220305@std.stei.itb.ac.id

Rachmawati  
School of Electrical Engineering  
Institute Teknologi Bandung  
Bandung, Indonesia  
rachmaw@itb.ac.id

Tomomasa Ohkubo  
School of Mechanical Engineering  
Tokyo University of Technology  
Hachi-oji, Japan  
ookubotmms@stf.teu.ac.jp

Mitsuharu Uemoto  
School of Engineering  
Kobe University  
Kobe, Japan

Keke Zhang  
School of Materials Science and  
Engineering  
Henan University of Science and  
Technology  
Luoyang, China  
zhkeke@haust.edu.cn

Ning Ma  
School of Materials Science and  
Engineering  
Henan University of Science and  
Technology  
Luoyang, China

Zhonghao Heng  
School of Mechanical Engineering  
Qinghai University  
Xining, China  
hengzhonghao@hotmail.com

Denov Bryan  
School of Electrical Engineering  
Institute Teknologi Bandung  
Bandung, Indonesia  
bryandenov@gmail.com

Rismana Eriawan  
RO Life Sciences and Environment  
National Research and Innovation  
Agency,  
South Tangerang, Indonesia  
ppid@brin.go.id

Mitsuo Nakai  
Faculty of Engineering  
Fukui University of Technology  
Fukui, Japan  
mitsuo-nakai@fukui-ut.ac.jp

Shoma Ohara  
School of Mechanical Engineering  
Tokyo University of Technology  
Hachi-oji, Japan

Xiao Xiao  
School of Materials Science and  
Engineering  
Henan University of Science and  
Technology  
Luoyang, China  
xiaoxiaonov@163.com

Meng Zhang  
School of Materials Science and  
Engineering  
Henan University of Science and  
Technology  
Luoyang, China  
zmmse@haust.edu.cn

Suwarno  
School of Electrical Engineering  
Institute Teknologi Bandung  
Bandung, Indonesia  
suwarno@stei.itb.ac.id

Rachmilda Tri Desmana  
School of Electrical Engineering  
Institute Teknologi Bandung  
Bandung, Indonesia  
trides@gmail.com

Zaeni Arpan  
School of Electrical Engineering  
Institute Teknologi Bandung  
Bandung, Indonesia  
arpanzaeni@gmail.com

Kazunori Shibata  
Institute of Laser Engineering  
Osaka University  
Suita, Japan  
shibata.kazunori.ile@osaka-u.ac.jp

Zen-ichiro Kawasaki  
Appointed Researcher  
Institute for Laser Technology  
Suita, Japan  
thunderstorm1949@gmail.com

**Abstract**—The reduction in greenhouse gas emissions necessary to achieve the Paris Agreement's goal of minimizing climate change is not only significantly behind schedule, but it is also clear that the targets submitted by each country are insufficient. Indonesia has achieved remarkable economic development, but resolving the dilemma between economic growth and environmental conservation remains a major challenge. To address the issue of the variability of renewable energy, fundamental transformation is necessary, and we

propose a social system that reuses magnesium as a “renewable fuel.” The concept of renewable fuel eliminates the variability and uneven distribution of renewable energies, reduces the burden on existing transmission and distribution networks, and contributes to the mainstreaming of renewable energy as a core energy source. This concept is particularly suited to Indonesia's energy supply, given its archipelagic geography, and enables the country to achieve both economic development and environmental conservation.

*Keywords—Renewable fuel, Renewable energy, Solar pumped laser, Autoreduction of metal oxide*

## I. INTRODUCTION

The frequency and intensity of climate change phenomena are increasing. Despite the conclusion of the Paris Agreement, global carbon emissions reached a record high of 57.1 GtCO<sub>2</sub>e in 2023. Furthermore, when combining the emission reduction targets (NDCs: Nationally Determined Contributions) set by each country by 2020, it is impossible to achieve the Paris Agreement's target of limiting global warming to 1.5 degrees Celsius. An additional 57% reduction beyond the projected reduction by 2035 is necessary[1]. This reality is challenging for both developed countries, where reductions are already underway, and developing countries, which face a dilemma between future economic development and emissions reduction. In particular, G20 countries account for 77% of global greenhouse gas emissions, 85% of GDP, 75% of trade, and 66% of the global population [2], making them key players in CO<sub>2</sub> reduction efforts. In particular, countries with large populations and rapid economic development, such as China, India, Indonesia, Mexico, Saudi Arabia, South Korea, and Turkey, remain heavily dependent on coal and have not yet reached their emissions peak. Fundamental measures are particularly necessary to steer these countries toward emissions reduction. This paper proposes a new cycle of renewable energy that is suitable for Indonesia's natural environment and resources, as well as the challenges facing the country.

## II. INDONESIA'S CURRENT SITUATION TOWARD THE PARIS AGREEMENT GOAL

Indonesia's CO<sub>2</sub> emissions are sourced from forest use (decrease) at 30% [3], the energy sector at 40%, and industrial processes (cement, nickel smelting) at 15%[4]. In particular, forest loss is caused by illegal slash-and-burn practices aimed at expanding palm oil plantations. In response, the government's NDC targets a 31.9% reduction from the 2030 business-as-usual scenario (BAU) level (without international assistance) and a 43.2% reduction (with international assistance such as JEPT (Just Energy Transition Partnership)[5]. To achieve these targets, policies such as carbon pricing, emissions trading systems, forest conservation and REDD+ (Reducing Emissions from Deforestation and forest Degradation forest) conservation funding, blue carbon (mangroves, seaweed) cultivation, and battery industry (nickel) development are being implemented. However, the scale of the society and industrial structure heavily reliant on the world's largest coal resources is significant, and the combination of population growth and economic development is making emission reductions increasingly challenging. The Climate Action Tracker, which evaluates each country's NDCs and progress toward achieving the Paris Agreement goals, has deemed many countries' efforts to be "insufficient," and Indonesia is no exception[6]. To address this and not only achieve NDC targets but also effectively contribute to the Paris Agreement goals, a fundamental transformation of the energy industry structure, including coal phase-out, is necessary. Specifically, this involves fully transitioning the energy sector, which accounts for 40% of Indonesia's CO<sub>2</sub> emissions, to renewable energy. This sector currently generates 300 TWh of energy, and considering economic growth rates, it is projected to reach up to 800 TWh by 2050[7].

The above actions for the future must be taken with Indonesia's various current challenges in mind. The biggest challenge is the excessive population concentration in urban areas such as Java Island and the economic disparity between these areas and other regions (rural areas and remote islands). The population is almost evenly divided between remote islands and rural areas, making this a significant issue in terms of scale. The resolution of these challenges is greatly influenced by the country's energy issues. Despite being rich in natural resources, only a portion of them (coal) are currently being utilized, and the transition to solar power is the key action. On the other hand, the country consists of approximately 17,000 islands, and the population density in rural areas is only a few dozen people per square kilometer (compared to over 1,000 people per square kilometer in urban areas like Java Island). Therefore, rural areas lack developed power grids and rely on individual diesel-powered generators. This situation is conducive to the transition of the energy system. The so-called "Leap Frog Strategy", which saw mobile phone networks bypass fixed-line telephones in Africa, can be applied here. Additionally, the plan to relocate the capital to Nusantara, East Kalimantan aims to create a 100% renewable energy city, and practical renewable fuel technology development can be proposed to achieve the goal.

## III. BREAKING AWAY FROM THE CURRENT TRAJECTORY

A plan is in place to shut down 5 GW (10% of existing capacity) of coal-fired power plants using JETP (Just Energy Transition Partnership) funds (20 billion dollars), but it is delayed due to concerns about job losses and private sector risk aversion. Additionally, while renewable energy will replace coal-fired power, the need to build thermal (natural gas) power plants to compensate for renewable-energy fluctuations raises concerns about the "double investment problem" experienced by developed countries. To overcome these challenges and achieve a transition away from coal dependence while establishing renewable energy as the backbone of the energy system, new technological systems are required in addition to the current power grid-based renewable energy transmission system.

Hydrogen, ammonia, and even batteries, which store renewable energies as a material, can be referred to as "renewable fuels." However, due to limitations in stability and resource availability, they cannot serve as the backbone of the energy system. In the future, as Indonesia achieves economic growth and becomes an energy-demanding nation on par with developed countries, a fuel material capable of storing and distributing approximately 800 TWh of energy will be required. The mainstreaming of renewable energy literally requires a "mountain's worth" of fuel material (a few billions of tons of fuel).

We propose the use of magnesium (Mg) as a fuel material that can meet this massive material requirement while being relatively stable and easy to handle. Mg is abundantly present in seawater. Assuming a uniform distribution of Mg concentration in seawater, an estimated 1,800 trillion tons of Mg exists. Mg has been traditionally produced from seawater (using established technologies), and extraction techniques are available. If extraction is performed using renewable energy sources such as solar power, it can become a renewable fuel. The energy stored in Mg is stable and poses no environmental concerns. Since Mg can be transported across borders, it can be strategically produced as an energy export material, and has far greater economic viability than biomass,

carbon pricing, etc. Indonesia is surrounded by sea on all sides and has significant potential for renewable energy resources, with solar energy estimated at 3,200 GW [8]. This potential is sufficient to support Indonesia's economic development, and the key to realizing it lies in renewable fuels.

#### IV. MAGNESIUM-BASED RENEWABLE FUEL CYCLE SYSTEM

The overview of the Mg-based renewable fuel system is shown in Fig. 1. Mg extracted from seawater is circulated as a fuel material. Although it is called fuel, it is not simply burned; after energy extraction, it is recovered and regenerated as fuel. The ease of recovering MgO compared to carbon is another advantage of Mg fuel. The energy sources driving extraction and regeneration are renewable energies. We are developing the system by dividing it into three elemental technologies: (1) Mg extraction from seawater, (2) energy conversion from Mg, and (3) regeneration of Mg fuel. Below, we introduce an overview of each elemental technology.

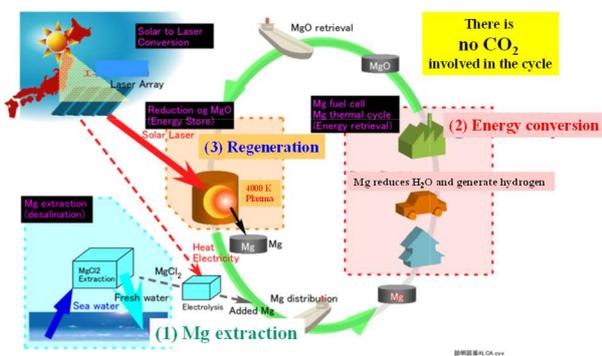


Fig. 1. Magnesium renewable fuel closed-loop energy system

##### A. Extraction

The extraction technology consists of three sub-element technologies: (1-1) salt precipitation using seawater evaporation, (1-2) molten salt electrolysis, and (1-3) power generation and heat storage technology using Concentrated Solar Power (CSP). The concept is shown in Fig. 2.

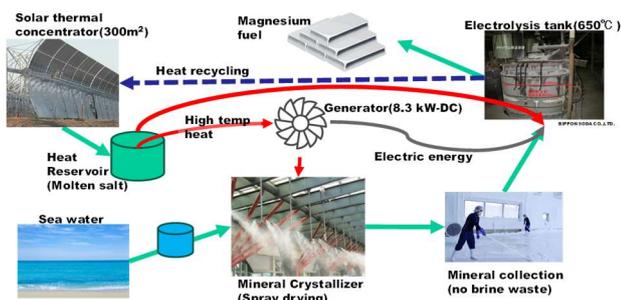


Fig. 2 Seawater Mg extraction system driven by solar power

In the precipitation technology, a spray drying method is employed to generate solid salt. This method involves spraying heated (concentrated) seawater to enhance drying efficiency, resulting in a higher Mg salt production rate. Molten salt electrolysis has been practicalized in several ways (such as the Norsk Hydro method or Dow Chemical Method), but development challenges include selective extraction of Mg from a mixture of Mg, Na, and K molten salts, avoiding the risk of Na precipitation, and improving the durability of electrolysis electrodes. (1-3) CSP has developed significantly

in the US and southwestern Europe, but in recent years, China has taken the lead in terms of installed capacity. Technologically, it is in commercial phase, but the development of plant technology that can stably supply the different thermal conditions required for (1-1) and (1-2) 24 hours a day is still a challenge [9], [10].

##### B. Conversion

Mg energy conversion can take various forms, such as electrode materials for primary (air) batteries (direct power generation), combustion with air (heat generation), and hydrogen generation (water reduction). Among these, hydrogen generation will have great contribution to the recent spread of hydrogen energy technology. Mg efficiently generates hydrogen by reducing water molecules. Especially when the reaction temperature is set above 700°C, it can achieve device power density equivalent to conventional internal combustion engines, making it suitable for high-output applications. On the other hand, hydrogen, which is a gas, needs to overcome restrictions on volume and pressure during transport, and technological development is generally focused on reducing volume (increasing pressure). For this reason, hydrogen infrastructure such as supply stations is costly and always carries the risk of accidents. In this way, if Mg is considered as a hydrogen transport medium, it contributes to the safety of distribution, convenience and diversity of energy conversion (hydrogen combustion). Hydrogen generation technology requires the development of continuous stable operation equipment for commercialization, but this can be achieved through joint research between industry and academia.

##### C. Regeneration

The regeneration of Mg fuel is the reduction of MgO. Industrially, the mainstream method is the Pidgeon method, which uses coal as a reducing agent and generates large amounts of CO<sub>2</sub>. This will be converted into a new technology that uses renewable energy and does not depend on CO<sub>2</sub> emissions. Metal oxides are automatically reduced to metals when heated to high temperatures, but generally the temperature required is several thousand degrees Celsius, and in the case of MgO, it is around 4000 Kelvin. In order to maintain this temperature, a large amount of dissociation heat and radiation loss must be supplied, and the amount required is around 10<sup>9</sup> W/m<sup>2</sup> (or 10<sup>5</sup> W/cm<sup>2</sup>, in the conventional laser engineering discipline). For example, even if sunlight is concentrated, the power density is limited to 10<sup>7</sup> W/m<sup>2</sup> due to the size of the sun image, so it is not possible to obtain the required amount. Therefore, we are developing a method to convert sunlight into laser light that can increase the power density and reduce MgO directly. Generally, using laser light makes it easy to achieve temperatures exceeding 10,000 Kelvin, which is the temperature at which substances ionize. The advantages of using lasers include high energy efficiency because only the target material (MgO) is heated, and no refractory material container is required to trap heat (although a container to control oxygen is necessary).

Figure 3 shows the limit value of the reduction energy efficiency (laser to Mg fuel) calculated from the standard formation free energy of Mg and MgO. The regeneration energy efficiency of Mg fuel, calculated from the chemical potential of the material, is 56%. Industrially, the goal is to achieve the aforementioned efficiency by suppressing

radiation losses from MgO heated to 4,000 Kelvin and losses due to the re-combination of Mg with oxygen after reduction.

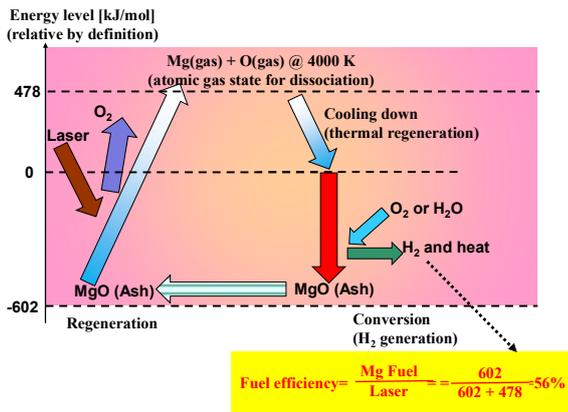


Fig. 3 Energy efficiency of laser regeneration (MgO reduction)

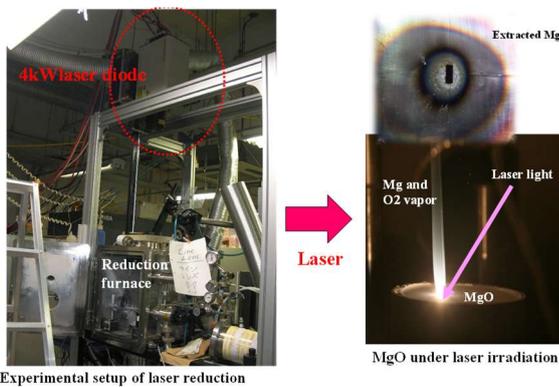


Fig. 4 4-kW laser diode system used to demonstrate the principle of MgO laser reduction.



Fig. 5 Prototype of solar-pumped MOPA laser system installed on a tandem sun light tracker.

The sub-element technologies are (3-1) automatic reduction of MgO using laser light and (3-2) solar-pumped lasers. The regeneration efficiency of Mg fuel in practice is determined by the energy efficiency of these sub-technologies, so research is being conducted to improve the efficiency of

each. The principle of automatic reduction has been demonstrated by experiments using semiconductor lasers (laser diode) as shown in Fig. 4 [11]. A 4-kW laser diode system was used to demonstrate the principle of laser reduction of MgO. MgO was heated to 4000 Kelvin and reduced without using any reducing agents. The reduction efficiency was in the order of a few percent, which is thought to be due to recombination (reoxidation) during the cooling process of dissociated Mg and oxygen atoms. Theoretical research on the methods to suppress reoxidation for improving reduction efficiency is currently underway.

Development research on solar-pumped lasers has a history equivalent to that of laser technology itself [12]. In previous research and development, the devices employed for converting sunlight into laser light have been the oscillator type. Energy efficiency is determined under the light conversion conditions in the laser crystal known as small-signal gain. To improve the efficiency, we are developing an amplifier-type laser device, called MOPA type (Master Oscillator Power Amplifier), that achieves saturated amplification gain. It is a standard technology used in the configuration of high-power laser systems, but there are few examples of it in the solar-pumped laser research. Development is underway for a laser device that connects a series of multi-stage amplifiers with laser light while tracking changes in the incident angle of the solar light. A prototype device was developed during the solar pumped laser demonstration campaign conducted by the team of Tokyo Institute of Technology (Fig. 5)[13]. A similar system is expected to be implemented for future development.

The above-mentioned elemental technologies have been developed and researched individually to date, and the degree of progress toward practical application varies, ranging from basic research conducted in laboratories to development research for practical application. Rather than waiting for all technological elements to be ready before the system becomes operational, it is entirely possible for the extraction and conversion technologies to be practicalized and commercialized first. In this case, MgO from combustion residues would accumulate in society, but the environmental impact would be minimal. MgO is a highly stable substance and can be utilized in landfills or other industrial products such as cement aggregates and sand with minimal environmental impact.

Our research group has an intension to establish a research and development base for extraction and conversion technologies in Indonesia and aim for their commercialization. In particular, extraction technology involves plant technology development accompanied by sub-element technology development, necessitating the establishment of a collaborative framework among national research institutes, universities, and industry.

#### SUMMARY

Progress in reducing greenhouse gases to halt global warming, as promised in the Paris Agreement, is significantly behind schedule. This presents a dilemma for countries seeking economic development, and is a particularly pressing issue for Indonesia. The solution to this challenge lies not in extending existing approaches but in a game-changing transformation. Indonesia, with its young and large population and abundant natural environment and resources, is in a favorable position to initiate this transformation. An

energy circulating system using magnesium as a fuel material is a technology that addresses the intermittency of renewable energies and fundamentally supports sustainable development. The technological foundation is taking shape, and this transformation can be achieved through international technical cooperation.

#### ACKNOWLEDGMENT

Part of this research (on the Chinese side) is supported by the Henan Province Specially Appointed Researcher Employment Contract.

#### REFERENCES

- [1] U. N. Environment, "Emissions Gap Report 2024 | UNEP - UN Environment Programme." Accessed: Jun. 16, 2025. [Online]. Available: <https://www.unep.org/resources/emissions-gap-report-2024>
- [2] "Government at a Glance 2025," OECD. Accessed: Jun. 26, 2025. [Online]. Available: [https://www.oecd.org/en/publications/government-at-a-glance-2025\\_0efd0bcd-en.html](https://www.oecd.org/en/publications/government-at-a-glance-2025_0efd0bcd-en.html)
- [3] Vizzuality, "Indonesia Deforestation Rates & Statistics | GFW." Accessed: Jun. 27, 2025. [Online]. Available: <https://www.globalforestwatch.org/dashboards/country/IDN?category=undefined>
- [4] H. Ritchie, M. Roser, and P. Rosado, "CO<sub>2</sub> and Greenhouse Gas Emissions," Our World in Data, May 2020, Accessed: Jun. 26, 2025. [Online]. Available: <https://ourworldindata.org/co2/country/indonesia>
- [5] Indonesia, "Enhanced Nationally Determined Contribution Republic of Indonesia," 2022.
- [6] "Indonesia NDC Assessment." Accessed: Jun. 26, 2025. [Online]. Available: <https://climateactiontracker.org/countries/indonesia/targets/>
- [7] "PLN Annual Report 2023," Annual Report, 2023. [Online]. Available: <https://www.pln Nusantara Power.co.id/investor/annual-report>
- [8] "Indonesia Energy Transition Outlook." Accessed: Jun. 26, 2025. [Online]. Available: <https://www.irena.org/Publications/2022/Oct/Indonesia-Energy-Transition-Outlook>
- [9] A. H. Alami et al., "Concentrating solar power (CSP) technologies: Status and analysis," *International Journal of Thermofluids*, vol. 18, p. 100340, May 2023, doi: 10.1016/j.ijft.2023.100340.
- [10] R. Meyer, M. Schlecht, and K. Chhatbar, "Solar resources for concentrating solar power (CSP) systems," in *Concentrating Solar Power Technology*, Elsevier, 2012, pp. 68-e2. doi: 10.1533/9780857096173.1.68.
- [11] M. S. Mohamed et al., "Laser Induced Magnesium Oxide Reduction for Renewable Energy Cycle with Solar Power," *The Review of Laser Engineering*, vol. 36, no. APLS, pp. 1199–1202, Jan. 2008, doi: 10.2184/lsej.36.1199.
- [12] D. Liang, J. Almeida, C. Vistas, B. Tibúrcio, and D. Garcia, *Solar-Pumped Lasers: With Examples of Numerical Analysis of Solid-State Lasers*. in *Green Energy and Technology*. Cham: Springer International Publishing, 2023. doi: 10.1007/978-3-031-24785-9.
- [13] S. Uchida et al., "Experimental Study of Solar Pumped Laser for Magnesium-Hydrogen Energy Cycle," in *AIP Conference Proceedings* 830, ISBEP, AIP, 2006, pp. 439–446. doi: 10.1063/1.2203286.