# Optimizing Hydrogen Production through SOEC-PeLUIt40 Coupling: A Sustainable Approach to Clean Energy Generation

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**Abstract**

The urgent need for clean, sustainable energy solutions is crucial for tackling environmental concerns and securing energy resources. Hydrogen, a versatile and high-energy-density fuel, holds promise across multiple sectors. Yet, its widespread adoption relies on efficient, cost-effective production methods. In recent years, electrolysis has garnered significant attention as a sustainable means of hydrogen production. Solid Oxide Electrolysis Cell (SOEC) technology, operating at high temperatures, presents a promising avenue for enhanced efficiency and integration with high-temperature heat sources. One such source, the High-Temperature Gas-Cooled Reactor (HTGR), known for its safety and efficiency, offers potential for cogeneration applications. Indonesia is currently developing a small modular nuclear reactor named PeLUIt-40. This reactor is based on HTGR technology with a capacity of 40 MW. In addition to electricity generation, PeLUIt-40 can be coupled for hydrogen production in anticipation of achieving net zero emissions by the year 2060.This paper investigates the feasibility and capacity of hydrogen production through the coupling of SOEC technology with PeLUIt-40. Leveraging the high-temperature heat output of the reactor, this coupled system presents a synergistic approach to hydrogen production, maximizing energy efficiency while minimizing environmental impact. The Cycle Tempo computer code is employed to model and simulate the entire process. In a scenario where the PeLUIt-40 turbine bleed outlet temperature stands at 312.88°C, featuring a steam mass flow rate of 0.828 kg/s, a pressure level of 6.0 bar, and an enthalpy of 3088.85 kJ/kg, the outcome yields a hydrogen production rate of 215 kg/h, equivalent to 1.8 tons annually. In summary, this study presents an innovative approach to hydrogen production, utilizing waste heat from the PeLUIt-40 turbine. It demonstrates the viability of employing SOECs to transform surplus thermal energy into clean hydrogen, thus contributing to the advancement of environmentally friendly energy technologies.

## INTRODUCTION

The quest for clean and sustainable energy sources has never been more critical, as the world grapples with the challenges of climate change and environmental degradation[1]. Hydrogen, with its potential to serve as a clean and versatile energy carrier, has emerged as a promising solution to decarbonize various sectors, from transportation to industry [2], [3]. However, unlocking the full potential of hydrogen hinges on finding energy-efficient and eco-friendly methods of production. This article delves into an innovative approach to hydrogen production that capitalizes on the underutilized resource of waste heat, particularly from the PeLUIt-40 turbine. The integration of Solid Oxide Electrolyzer Cells (SOECs) in this process offers an exciting avenue for sustainable hydrogen generation [4]. This groundbreaking research not only addresses the need for clean energy solutions but also takes a significant step towards reducing greenhouse gas emissions.

The PeLUIt-40 reactor, a high-temperature system, emits substantial heat during its operations [5]. This residual thermal energy often considered a waste byproduct [6], can be harnessed to power SOECs, efficiently converting steam into both hydrogen and oxygen[7]. By doing so, this innovative approach minimizes the reliance on external energy sources for hydrogen production, thus promoting energy sustainability and reducing environmental impact. In this article, we explore the technical intricacies of integrating SOECs with the PeLUIt-40 reactor, with a specific emphasis on leveraging turbine bleed heat for the electrolysis process [8]. The research findings not only underscore the potential for efficient hydrogen production but also highlight the minimal environmental repercussions associated with this method, further supporting the transition to sustainable energy solutions. The study utilizes advanced simulation tools, such as the Cycle Tempo computer code, to model and assess the entire process, presenting a comprehensive analysis of this groundbreaking approach.

As we delve deeper into the details, we will uncover how this innovative system can yield significant hydrogen production rates, equivalent to multiple tons annually. Ultimately, this article sets the stage for a new era of clean and sustainable energy production, where waste heat becomes a valuable resource in our pursuit of a greener and more environmentally responsible future.

## The PeLUIt-40 and SOEC Integration

### Overview of the PeLUIt-40

PeLUIt represents a concept for a combined electricity and steam-heat generation system intended for application across diverse industries. The electrical power output per unit of commercial PeLUIt ranges from 10MWe to 100MWe, aligning with the infrastructure conditions prevailing in Indonesia [5], [9]. PeLUIt is designed based on advanced-generation nuclear reactor technology, incorporating a high level of safety. National development necessitates a substantial supply of electricity and industrial steam heat. Indonesia stands to serve as a market and is contingent upon the capabilities of foreign energy industries. Collaboration between research institutions and the national industry is imperative to cultivate domestic capabilities. PeLUIt constitutes a national innovation product aimed at fostering energy independence for the national industrial sector, with the expectation of ensuring a dependable supply of electricity and industrial steam heat [10].

The main components of the PeLUIt-40 reactor consist of fuel, coolant fluid, reflector, control rod components, etc. [11], all of which are contained within the Reactor Pressure Vessel (RPV). The primary region where nuclear (fission) reactions occur is referred to as the reactor core. The reactor is designed with a geometry of 197 cm in height, 180 cm in diameter, and employs spherical fuel elements with a diameter of 6 cm. The design parameters and main components of PeLUIt-40 are illustrated in Figure 1[5], [9]. The reactor is designed to utilize helium gas as the coolant fluid [12]. Helium gas is selected as the coolant working fluid in the reactor due to several considerations, including its classification as a noble gas, non-corrosive properties, and inertness at high temperatures [13].

|  |  |  |
| --- | --- | --- |
| **Parameter**  | **Value**  | Main component of RPV |
| Reactor core | 40 MWt |
| Diameter of active core | 180 cm  |
| Height of active core | 197 cm |
| Thickness of side reflector | 100 cm |
| Thickness of top reflector | 130 cm |
| Void thickness | 40 cm |
| Thickness of bottom reflector | 243 cm |
| Uranium enrichment | 17% |
| Beginning uranium loading | 5 g/pebble |
| Number of fuel recirculation | 5 passes |
| Pebble balls diameter | 6 cm |
| Diameter of fuel kernel | 500 µm |
| Density of fuel kernel | 10.4 g/cm3 |
| TRISO layers | Buffer/I-PyC/SiC/O-PyC |
| Thickness | 90/40/35/40 µm |
| Density | 1.05/1.9/3.18/1.9 g/cm3 |
| Graphite reflector density | 1.75 g/cm3 |

*FIG. 1. The design parameters and main components of PeLUIt-40 within the Reactor Pressure Vessel (RPV)* [5]

### Introduction to Solid Oxide Electrolyzer Cells (SOECs)

Solid Oxide Electrolyzer Cells (SOECs) represent electrochemical devices employed for the electrolytic generation of hydrogen gas (H2) from water (H2O). The fundamental principle governing SOECs lies in the process of electrolysis, wherein water molecules are disassembled into their constituent elements, hydrogen, and oxygen, through the application of an electrical current [14]. SOECs, to facilitate this intricate electrochemical transformation, operate under elevated temperatures, typically within the range of 500 to 900° C. This elevated temperature regime is indispensable as it ensures that the solid-state ceramic materials comprising the SOEC are conducive to ionic charge transport, specifically permitting the migration of oxygen ions (O2-) and protons (H+). SOECs are thoughtfully engineered with solid electrolytes, which manifest a robust ionic conductivity, particularly at these elevated temperatures. This unique property expedites the swift movement of oxygen ions within the confines of the cell. The structural composition of SOECs encompasses two crucial electrodes—an anode and a cathode—that are demarcated by the solid electrolyte [15]. At the anode, oxygen ions are liberated by the electrolyte and conjoin with electrons to yield oxygen gas (O2) through an oxidation reaction:

Anode Reaction: O2- (emanating from the electrolyte) >>> O2 + 2e-. Meanwhile, at the cathode, water molecules undergo cleavage into protons (H+) and oxygen ions, facilitated by the provision of an electrical current:

Cathode Reaction: H2O + 2e- >>> H2 + O2- (originating from the electrolyte).

The generated protons (H+) at the cathode's side of the SOEC migrate through the solid electrolyte towards the anode's side. Here, they reunite with electrons to form hydrogen gas (H2). To power this electrolytic process, an external electrical power source is connected to the SOEC. This external source supplies the requisite energy for water molecule dissociation and supports the transit of ions within the cell. The resultant hydrogen gas, produced at the anode side, is amenable to collection and deployment across diverse applications. These may encompass clean energy production, fueling of hydrogen-powered vehicles, utilization within industrial processes, or integration into energy storage systems. SOECs proffer an efficacious and environmentally responsible route to hydrogen production, owing to their reliance on electrical energy sources, typically derived from renewable origins. Significantly, this approach obviates the need for fossil fuel combustion, thereby yielding minimal greenhouse gas emissions. Hence, SOECs assume a pivotal role in the ongoing transition toward sustainable energy solutions and the broader adoption of hydrogen as a green and versatile energy carrier.

### Rationale for integrating SOECs with turbine heat.

The rationale for integrating SOECs with turbine heat (Figure 2) lies in the efficient utilization of excess thermal energy to produce clean hydrogen. Turbine systems, like the PeLUIt-40, generate significant heat during their operation. By harnessing this heat to power SOECs, the system highly becomes energy efficient. It maximizes the use of thermal energy, minimizing losses and improving the overall energy conversion efficiency. SOECs are a clean technology that enables the production of hydrogen from water without generating greenhouse gas emissions. By using excess heat to drive this process, the resulting hydrogen is considered "green" since it's produced using renewable or waste energy sources, rather than relying on traditional methods that may involve fossil fuels.



*FIG. 2. PeLUIt-40 cogeneration scheme*

The integration of SOECs with heat systems enhances the overall energy infrastructure. It transforms excess heat, which might otherwise be wasted, into a valuable energy carrier, hydrogen. This green hydrogen can then be stored, transported, and used in various sectors, including power generation, transportation, and industry. SOECs can be deployed in various locations, including those with excess waste heat sources. This decentralization of hydrogen production allows for distributed and efficient energy production, reducing the need for centralized hydrogen production facilities and associated transportation costs. The produced hydrogen can serve as an energy storage medium, helping to balance the grid and store excess energy during periods of low demand. This can be particularly valuable in renewable energy systems, where energy generation is intermittent. By utilizing waste heat for hydrogen production, the overall carbon footprint of the energy system can be reduced. This contributes to sustainability goals and helps mitigate climate change by reducing the release of greenhouse gases.

The rationale for integrating SOECs with turbine waste heat is to enhance energy efficiency, reduce environmental impact, and utilize excess thermal energy to produce clean and versatile hydrogen. This integration aligns with the goals of transitioning to sustainable and low-carbon energy systems, making it a promising approach in the broader context of clean energy advancement.

## RESULT AND DISCUSSION

The cogeneration system of PeLUIt-40, combined with hydrogen production using the SOEC method, was modelled and simulated using Cycle Tempo software. In this study, we explored two heat extraction scenarios to supply the SOEC plant. The first scenario involves Peluit-40 cogenerating with the SOEC plant using medium pressure (MP) steam. MP steam is the hot steam output from the first turbine, extracted at a temperature of 284°C and a pressure of 4.2 bar, within the same fluid flow as the steam for the direct water heater or deaerator, as shown in Figure 3. The hot steam produced from the MP turbine output will exchange heat with the SOEC feedwater, which is demineralized water. The MP steam transfers heat to the demineralized water until it reaches saturated conditions (145°C, 4.2 bar) to utilize latent heat. Under these conditions, the net electricity production of Peluit-40 will be assessed to determine its feasibility for supplying electricity to the SOEC plant.



*FIG. 3. The Cycle-Tempo model of PeLUIt-40 for hydrogen production using medium pressure (MP) steam turbine*

In the second scenario (Figure 4), the cogeneration system for hydrogen production utilizes high-pressure (HP) steam, extracted from the fluid flow of the crossover pipe at 520°C and 60 bar. This hot steam is then directed to the demineralized feedwater for heat exchange, resulting in hot steam that serves as feed for the SOEC. The HP steam undergoes heat exchange until it reaches a saturated condition at 275°C and 60 bar, benefiting from latent heat. Subsequently, the net electricity production is assessed to ensure it remains sufficient to power the SOEC plant.

Both scenarios presented utilize modelling data as shown in Table 1. The PeLUIt -40 has a thermal power output of 40 MW, with approximately 13.5 MWe convertible to electrical power, assuming a thermal efficiency of 30% for the HTGR [16]. In general, a single SOEC module is assumed to require 2100.7 kWe of electrical energy, distributed as follows: 1732.2 kWe for the stack, 56.8 kWe for the heater, and 311.8 kWe for auxiliary equipment.



*FIG. 4. The Cycle-Tempo model of PeLUIt-40 for hydrogen production using high pressure steam.*

TABLE 1. COMPONENT SPECIFICATION OF SOEC-PELUIT40 COGENERATION

|  |  |  |
| --- | --- | --- |
| Component | Energy (kW) | Explanation |
| Reactor (PeLUIt-40) | 40.000,00 |  |  |
| Thermal energy |  | 40.000,00 | Thermal output of PeLUIt-40 |
| Electrical generation | 13.539,4 |  |  |
| Electricity generation (gross) |   | 13.539,4 | Total electrical generation |
| He Circulator | 1.584,44 |  |  |
| HP Feed Water Pump | 172,06 |  |  |
| Condensate Pump | 8,43 |  |  |
| Cooling water pump | 174,99 |  |  |
| Internal electrical consumption |  | 1.939,92 |  |
| Electricity generation (net) |  | 11.599,53 |  |
| Evaporator | 1.005,3 |  |  |
| Steam output |  | 1.005,26 | Thermal steam need for H2 plant |
| Electrical consumption for H2 plant |  | to be calculated | Electrical need for H2 plant |
| Remaining electrical generation |  | to be calculated |  |

The simulation results for the first scenario are presented in Table 2, while those for the second scenario are presented in Table 3. Both scenarios yield nearly the same amount of hydrogen production, but they differ in the amount of residual electricity generated. Based on the observation of the Q (heat) versus T (temperature) diagram for the evaporator component, which generates steam for SOEC feed, in the cogeneration scenario at the MP steam PeLUIt point, a pinch/cross temperature phenomenon is noted between the hot fluid (steam from PeLUIt) and the cold fluid (demineralized water). This occurs because the saturated temperature of the hot fluid is lower than that of the cold fluid. To avoid this cross-temperature issue, steam extraction must be performed at a higher-pressure point (greater than 4.2 bar).

TABLE 2. Simulation results of hydrogen production using the SOEC method BY USING MEDIUM PRESSURE (MP) STEAM OF PeLUIt-40

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Number of SOEC modul | Electricity consumption need for SOEC (MWe) | MP-turbine mass flow rate output PeLUIt-40 (kg/s) | Hydrogen production capacity (kg/h) | The remaining electricity that can still be generated (MWe) |
| 1 | 2.11 | 0.141 | 43 | 9.61 |
| 2 | 4.22 | 0.282 | 86 | 7.44 |
| 3 | 6.34 | 0.423 | 129 | 5.26 |
| 4 | 8.45 | 0.564 | 172 | 3.09 |
| 5 | 10.56 | 0.706 | 215 | 0.91 |

By integrating the solid oxide electrolysis cell (SOEC) method and heat extraction from both the HP and MP steam flow before and after first turbine, several alternative hydrogen production scenarios are devised. Heat extraction at the hot steam flow outlet after the high-pressure turbine enhances the efficiency of heat utilization more optimally compared to extraction at other flow points. Thermodynamically, heat extraction at the outlet of the high-pressure turbine does not compromise the stability of electricity generation. This system scenario is capable of flexible hydrogen production with a predetermined number of SOEC modules. The minimum hydrogen production expected is 43 kg per hour, equivalent to 394.200 tons annually with one SOEC module, and at least 215 kg per hour, equivalent to 1883.400 tons annually with five SOEC modules.

TABLE 3. Simulation results of hydrogen production using the SOEC method BY USING HIGH PRESSURE (hP) STEAM OF PeLUIt-40

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Number of SOEC modul | Electricity consumption need for SOEC (MWe) | HP-turbine mass flow rate output PeLUIt-40 (kg/s) | Hydrogen production capacity (kg/h) | The remaining electricity that can still be generated (MWe) |
| 1 | 1.80 | 0.141 | 43 | 8.64 |
| 2 | 3.60 | 0.282 | 86 | 6.73 |
| 3 | 5.40 | 0.423 | 129 | 4.82 |
| 4 | 7.20 | 0.564 | 172 | 2.91 |
| 5 | 9.00 | 0.706 | 215 | 1.00 |

Nuclear cogeneration emerges as a pivotal component in the shift towards a sustainable energy paradigm, heralding a multitude of advantages that underscore its significance in this transition. Nuclear cogeneration distinguishes itself through its marked reduction in greenhouse gas emissions compared to conventional power plants, thereby aligning with global imperatives aimed at combating climate change. Furthermore, the comparatively smaller land footprint required by nuclear cogeneration vis-à-vis other power generation technologies underscores its efficiency in land utilization, thereby mitigating environmental impact. The inherent characteristics of nuclear cogeneration, including its substantial capacity and capability to serve as a baseload power source, engender a reliable and consistent energy supply, thereby contributing significantly to grid stability and bolstering energy security. The proven track record of nuclear cogeneration, demonstrated by the operation of 79 reactors worldwide accumulating approximately 750 cumulative years of operation, instills confidence in its reliability and safety, further bolstering its appeal.

A compelling aspect of nuclear cogeneration lies in its competitive pricing, rendering it economically viable and attractive for investment. This affordability augments its accessibility and feasibility as a sustainable energy solution, thereby amplifying its potential impact. Furthermore, nuclear cogeneration holds promise in supporting clean energy initiatives and facilitating the attainment of net zero emissions targets.

By harnessing nuclear energy for hydrogen production, as delineated in Presidential Regulation of the Republic of Indonesia No. 63/2022, nuclear cogeneration can gradually supplant natural gas for non-electricity uses, thereby contributing significantly to decarbonization endeavors. In summation, nuclear cogeneration emerges as a formidable contender in the quest for a sustainable energy landscape, offering an array of advantages encompassing low emissions, efficient land utilization, reliability, proven technology, competitive pricing, and facilitation of clean energy objectives.

## CONCLUSSION

The research explores an innovative approach to hydrogen production by utilizing waste heat from the PeLUIt-40 high-temperature gas-cooled nuclear reactor. By integrating Solid Oxide Electrolyzer Cells (SOECs) with this reactor, the study demonstrates the potential for efficient, emission-free hydrogen production. Two scenarios are examined: one where PeLUIt-40 provides both electricity and steam, and another where it only provides steam while electricity is sourced from the national grid. Both scenarios show significant promise in terms of cost reduction and sustainability. The research underscores the potential of using waste heat for hydrogen production, achieving high efficiency and minimal environmental impact, thus supporting the transition to sustainable energy solutions. This study's findings contribute to preparing for Net-Zero Emissions (NZE) and advancing green hydrogen production. Heat extraction at the hot steam flow outlet after the high-pressure turbine enhances the efficiency of heat utilization more optimally compared to extraction at other flow points. Thermodynamically, heat extraction at the outlet of the high-pressure turbine does not compromise the stability of electricity generation. This system scenario is capable of flexible hydrogen production with a predetermined number of SOEC modules. The minimum hydrogen production expected is 43 kg per hour, equivalent to 394.200 tons annually with one SOEC module, and at least 215 kg per hour, equivalent to 1883.400 tons annually with five SOEC modules.

ACKNOWLEDGEMENTS

The authors extend their gratitude to the HITN-2024 Program Budget of the Nuclear Energy Research Organization (ORTN)-BRIN for supporting this study. We hope that this research will contribute to the development of the PeLUIt-40 design in Indonesia and lead to its eventual design licensing by Bapeten.

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