# Thermal and Electrical Coupling to Electrolysis Plants

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**Abstract:**
Close coupling of nuclear and electrolysis plants requires modifications of the power transmission station to take advantage of the low-cost, clean electricity produced by nuclear plants. In addition, high-temperature electrolysis can reduce the cost of electrolysis when the steam produced by nuclear plants is used to heat and produce steam for electrolysis. RELAP and HYSYS models provided the basis for preliminary hydrogen production studies. This work supports a conceptual architectural engineering design of the thermal energy delivery systems. Understanding the thermal and electrical interfaces is essential for PRAs and ensuring the safety of plant operations and protection and stability of the power systems and reactor core.

## 1. INTRODUCTION

Increasing penetration of variable wind and solar renewable energy generation are placing greater pressure on nuclear power plants to engage in flexible power operations (FPO). In addition, nuclear power plants (NPPs) are challenged to compete with natural gas (NG) combined-cycle power plants in wholesale electricity markets due to the historically low cost of natural gas. Flexible and hybrid operations present opportunities for NPPs to increase revenues while also meeting electric grid generating demands. A particularly promising option is to couple nuclear power plants to high efficiency solid oxide electrolysis cell (SOEC) technology hydrogen production. Coupling an NPP to a flexible hydrogen production plant has multiple advantages. The hydrogen market is rapidly growing in the United States and in other countries. Hydrogen is gaining recognition as an important energy carrier for energy storage and production of steel, fertilizers, and synthetic fuels. It is needed to refine petroleum crude and for direct use in fuel cells for electricity generation and for use in small and heavy-duty transportation vehicles. As markets for clean hydrogen develop, water-splitting electrolysis processes powered by clean energy from LWRs provide a tremendous opportunity to reduce air pollution and other emissions, as well as provide NPPs with additional revenue sources [1]. SOEC systems are particularly advantageous because they can use low-pressure steam at approximately 250 °F to increase efficiency and reduce hydrogen production costs.

A hybrid system provides an offtake for energy produced by an NPP when the price offered for committing electricity to the grid is lower than the cost of producing this electricity. The co-located hydrogen plant benefits by obtaining electrical power, steam, or thermal energy directly from the NPP at a cost that is lower than can be purchased from the grid at either the electricity transmission-customer level or the electricity distribution-customer level. At minimum, this integration requires a tightly coupled connection to the power-generation operations of the nuclear plant. The NPP hybrid plant may then apportion energy between the electricity grid and the hydrogen plant to optimize the revenue of the integrated energy system, depending on specific day-ahead electricity-grid capacity commitments and reserve capacity agreement requirements. For this market arrangement to work, the hydrogen plant receives electricity without paying grid service fees (i.e., it is considered as house load for the nuclear plant). This mode of energy sharing may require approval of governing utility commissions, depending on whether the hybrid operations can affect grid supply and pricing, and in consideration of provisions for grid-capacity payments that may apply to a hybrid system.

The thermal energy requirement of the hydrogen plant is less than 30% of the electrical energy requirement, such that even under conditions of maximum hydrogen production, the majority of the power from the nuclear reactor still flows to the power turbine system to generate electricity. Within this paradigm, flexible operation of the nuclear plant entails adjusting the relative dispatch of electricity between the grid and the hydrogen production plant and adjusting the relatively smaller amount of thermal energy to the power turbine system of the nuclear plant and the hydrogen production plant while maintaining the reactor power approximately constant at its rated power. This paper focuses on pressurized water reactors (PWRs). A similar study for boiling water reactors (BWRs) will be the topic of future work.

The remainder of this report is organized as follows. Section 2 summarizes the SOEC technology. Section 3 describes the options that are being explored for thermal coupling between PWRs and SOEC plants. Section 4 briefly introduces the electrical coupling options, and Section 5 offers conclusions of the work.

## 2. SOEC TECHNOLOGY OVERVIEW

High temperature electrolysis (HTE) systems utilize solid oxide SOEC technology to electrochemically split steam molecules into hydrogen and oxygen by applying an external voltage potential across the cell. Importantly, rSOC systems have 20-25% higher system efficiencies in both electrolysis and fuel cell operating modes compared to conventional low temperature electrolysis technologies and are also expected to have lower costs, in part because they use low-cost thermal energy to decrease electricity consumption.

Oxygen ions can only conduct through the electrolyte at high temperature, which is why SOEC cells operate at temperatures of 700°C and hotter. A direct current electric potential applied to the SOEC stacks drive the electrons from the anode to the cathode and facilitates oxygen ion transport through the crystalline solid oxide electrolyte (which functions as a membrane with selective permeability to separate oxygen ions from hydrogen ions and steam). Increasing the electric potential increases the electric current flow and hydrogen production but results in greater Joule heating (exothermic operation above thermal neutral voltage) and losses within the cell. It is favorable to operate the electrolysis cell near the thermal neutral potential, which is defined as the potential at which the electrical energy supplied to the system is equal to the energy content of the generated hydrogen. Endothermic operation of the system will occur if the cells are operated below the thermal neutral potential, and in that case, additional heat must be provided to the cell to maintain operation at constant temperature.

Fig. 1 shows a simplified process flow diagram of the SOEC system process, which operates at temperatures between 700-850°C. System efficiency is maximized by using heat exchangers to cool the hot product gases while preheating the incoming steam from approximately 150°C to the operating temperature. During standard online operating conditions, saturated steam is supplied at approximately 150°C by heat from the CSP plant and a pressure of 4-5 bar. A reducing atmosphere is necessary at the hydrogen electrode to preserve the integrity of the electrode materials, and for this purpose, a small amount of product hydrogen is recycled to the hydrogen electrode inlet so that the incoming steam has an $H_2$ concentration of 5-10%. Power, or current demand, is regulated by the AC/DC power converter through a current command from a low-level programmable logic controller (PLC). Product hydrogen goes through a condenser unit to both cool the gas to < 40 ℃ and to remove the saturated steam content to < 7%. Oxygen is produced on the air electrode side. Air is fed to the air electrode as a sweep gas to maintain a product oxygen concentration of < 40% $O_2$ to avoid an excessively enriched oxygen atmosphere. The inlet air is sent to the air electrode heat recuperator that uses the air electrode product exhaust to preheat the inlet air from 25℃ to ~750-800℃. The trim heaters are used primarily during startup to raise the temperature reagent gases and SOEC stacks to operating temperatures, although they may also be used when the SOEC stacks are operated at or near the endothermic regime to provide additional heat to the stack hot box.

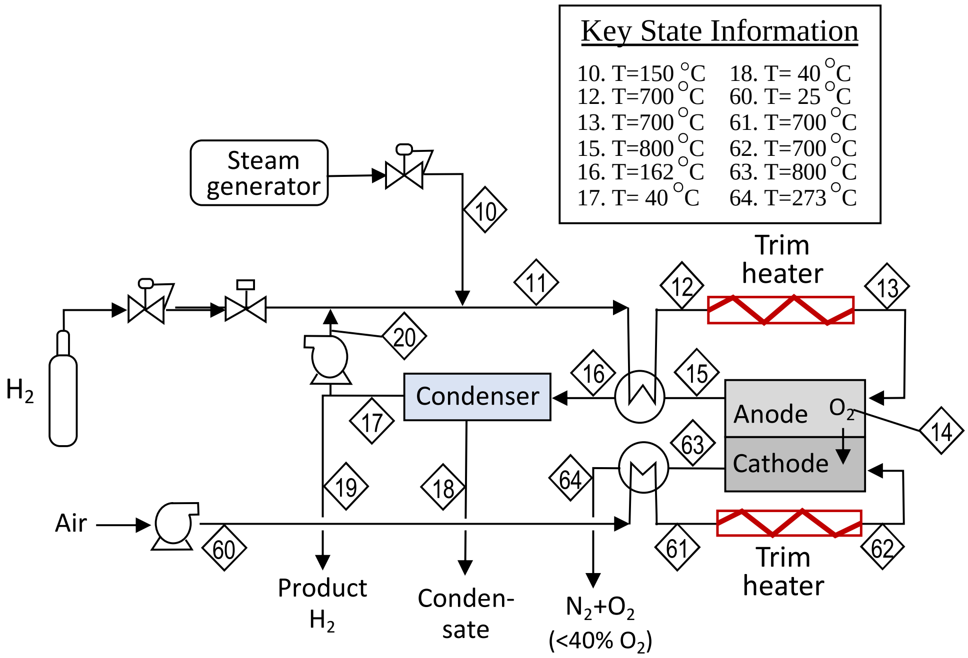


**Figure 1:** High level process flow diagram (PFD)

## 3. PWR/SOEC THERMAL POWER COUPLING

Figure 2 contains a simplified diagram of thermal power coupling options that are being explored. In both options, steam from the PWR is used to boil demineralized or deonized water into steam to send to the hydrogen plant in a once-through steam line. Condensate in the unfired boiler is returned to the condenser. For the first option, heat in the unfired boiler is provided by steam extracted from the main steam line, while for the second option, the extraction steam comes from the crossover piping between the high-pressure turbine and the moisture separator reheater (MSR). Simulations of the performance of the integrated system for the first option have been performed using a high-fidelity, full-scope simulator and using a reduced-order model as described in [2] and [3]. RELAP and HYSYS models have also been used to for preliminary hydrogen production studies [4]. Figure 3 shows predicted decreases in turbine power output for extracting approximately 15% and 50% of the steam from the main steam line for Option 1 as predicted by the two models. Two different versions of the reduced order (RO) model were employed. In one version, all of the pressure drops in the plant lines and components were assumed to be linear (RO-linear) and in the other (RO-nonlinear), non-linearities were introduced into the pressure drops to better replicate the mass flows that were predicted by the high-fidelity, full-scope simulator (Hancock, et. al). As expected, the power output from the turbine system decreases as steam flow to the hydrogen plant increases. Interestingly, the RO models predict more power loss from the turbine at 15% steam extraction compared to the high-fidelity simulator, but that trend is reversed at 50% steam extraction for which the RO models predict less power loss from the turbine compared to the high-fidelity simulator. The discrepancies between all simulations are less than 7% of the full turbine power output, and it is clear that extracting steam from the main steam line has the potential to derate the performance of the PWR. For example, extracting 50% of the steam from the main steam line causes the turbine power to decrease more than 65%. Extracting such high levels of steam causes the turbine system to operate far below its design condition, which results in loss of performance. It is expected that performance of the PWR could be improved significantly by injecting the heated condensate from the unfired boiler into the feedwater heater train rather than to the PWR condenser.

Assuming the steam sent to the hydrogen plant can be used with 95% efficiency, the efficiency of the integrated PWR/SOEC system can be estimated and is shown in Fig. 4. For 15% thermal power extraction, the total power output of the PWR increased from 968 MWe to 773 MWe plus 468 MWth

(1241 MWe+th), resulting in an overall thermal efficiency of 41.9% Similarly, the combined power output of the nuclear plant during 50% thermal power extraction also increased, yielding an overall thermal efficiency of 60.1%, even though the net electrical output decreased to 30% of the full power output when 50% of the steam was extracted. Figure 4 also shows that for 50% thermal power dispatch, the power dissipated by the condenser decreased from close to 2,000 MWth to 1,100 MWth, indicating a substantially diminished impact on the environment in terms of heating of the cooling water reservoir.

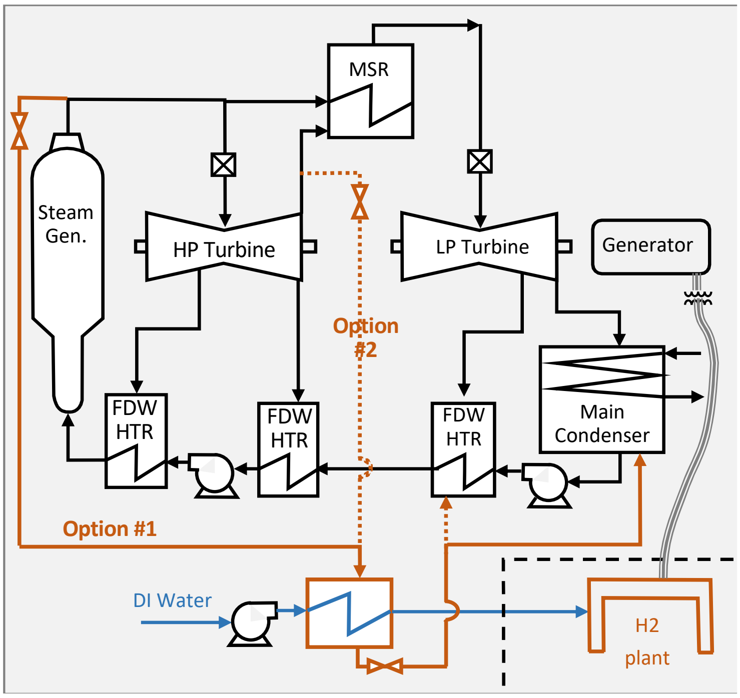


**Figure 2:** Simplified diagram of PWR/SOEC plant thermal power coupling options

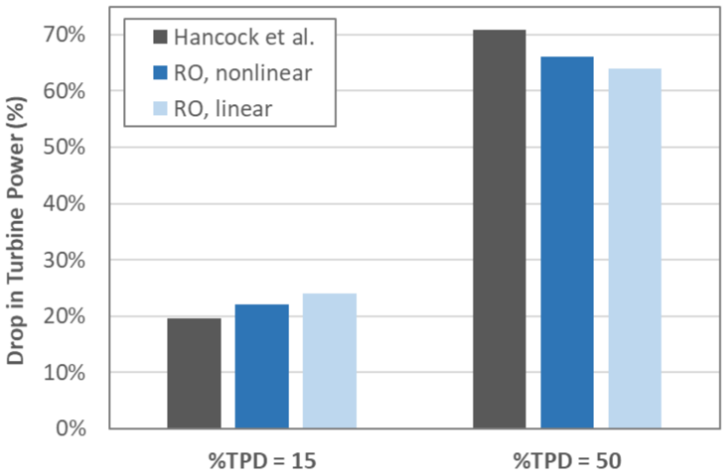


**Figure 3:** Predicted drop in turbine power output for 15% and 50% TPD according to a full-scope TPD-GPWR simulator (Hancock et al) and two versions of the RO-TPD-PWR simulator.

## 3. PWR/SOEC ELECTRIC POWER COUPLING

Similar to the thermal power coupling simulations, two different levels of electric power coupling are considered. The first option considers a hydrogen plant that is sufficiently small that it can be treated as a house load for the PWR. The hydrogen plant requires a combination of AC and DC power. Approximately 90% of the total power requirement is needed as DC power at a voltage of 200-800 VDC, so the electric power from the PWR generator needs to be stepped down and converted to DC.

Approximately 10% of the total power required by the hydrogen plant is needed as AC power to operate pumps and blowers and electric topping heaters. Figure 5 shows a single-line diagram of the PWR-hydrogen plant electrical connection in which the hydrogen plant is treated as a house load. A concern in this design is that in the event the hydrogen plant must be quickly isolated from the PWR, the power to the hydrogen plant would be diverted to the Generator Step-Up (GSU) transformer, which could actuate protective relays and potentially trip the main generator of the PWR. To avoid this unallowable event, the power being dispatched to the hydrogen plant must be very low relative to the total generator capability. It is required that a single unit auxiliary transformer (UAT) be able to support all auxiliary loads in the PWR, which for a GW plant are in the range of 65-70 MVA. The hydrogen plant could be powered from another UAT of similar size without unduly increasing risk to the PWR. In that case, the electric power available to the hydrogen plant would be 65-70 MVA or approximately 60 MWe.

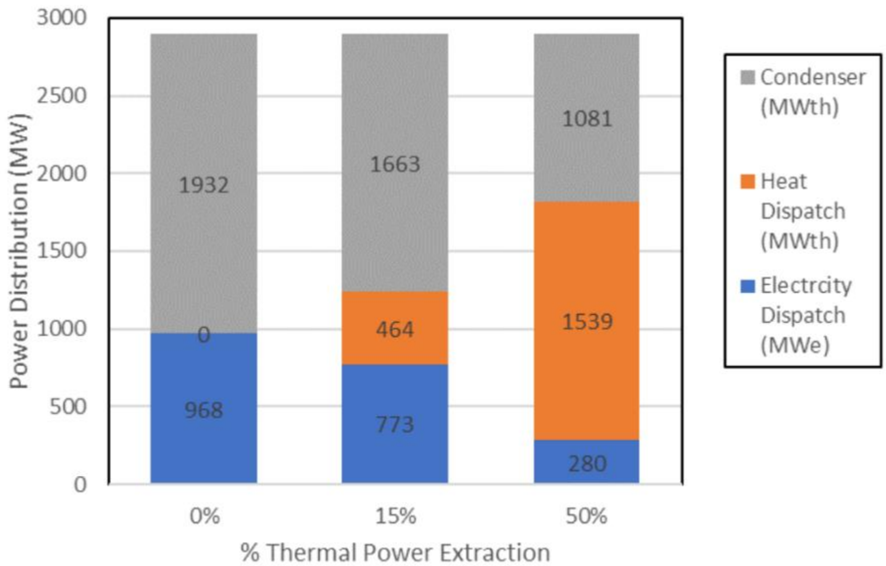


**Figure 4:** Summary of thermal power destination for pure electric power dispatch (0%) thermal power dispatch, and mixed-mode operations with 15% and 50% thermal power dispatch

The second electric coupling option follows a standard industrial facility connection to a power plant in which the power connection is made on the high voltage side of the GSU. Transmission cables at switchyard voltage would carry power to the hydrogen plant approximately 1 km from the PWR. For large quantities of hydrogen production, the hydrogen plant must be located some distance (0.5-1.0 km) from the PWR to protect the PWR from potential hydrogen deflagration events. A sudden loss-of-load at the hydrogen plant would be similar to any nearby loss of load, and the impact to the generator would follow normal "generator load rejection" protection schemes and would be evaluated accordingly. As an example, General Electric (GE) generators have load rejection relaying that will trip the main generator on a 40% mismatch between reactor power and generator output. A notable issue for this case is the "Point of Interconnection" or POI that demarcates the equipment owned by the nuclear utility and the grid operator. There is interest to tap off the power line to the hydrogen plant after the GSU but before the POI, if possible, so that power can be supplied to the hydrogen plant without being subject to grid fees. This may be possible for plants in which the POI is at the first disconnect switch after the GSU going to the switchyard; however, it will likely not be possible for plants in which the POI is right at the connection to the HV bushing.

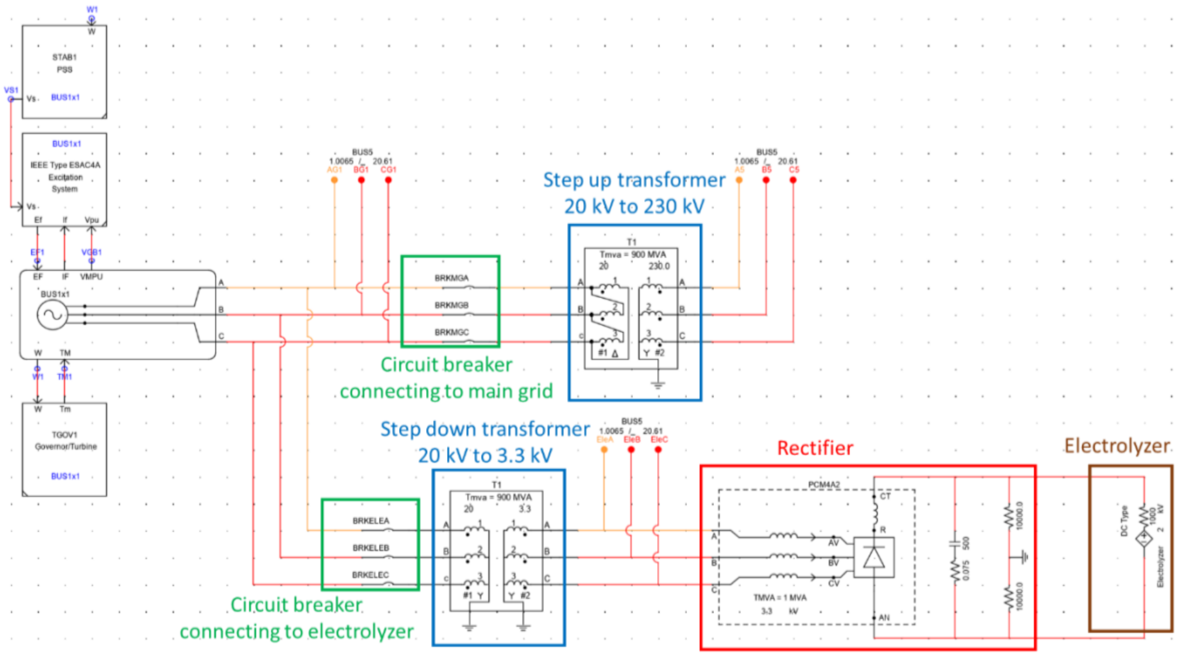


**Figure 5:** Single-line diagram of PWR-Hydrogen plant electric power connection for a demonstration-scale hydrogen production plant that is less than approximately 60 MWe.

## 4. CONCLUSION

There are multiple options that are being explored to thermally and electrically couple nuclear plants to industrial hydrogen production plants. This paper briefly summarized work at INL seeking to couple currently operating pressurized water reactors (PWRs) in the U.S. with solid oxide electrolysis cell (SOEC) high temperature hydrogen production plants. Extracting high levels of steam to support hydrogen production causes the turbine system to operate below its design condition, which results in loss of PWR performance; however, much more of the nuclear heat can be used effectively and the cooling load of the condenser decreases dramatically. For 50% thermal power dispatch, the power dissipated by the condenser decreases from close to 2,000 MWth to 1,100 MWth. Options for electrically connecting the PWR to the hydrogen plant have also been considered. Hydrogen plants as large as 60 MW could possibly be connected as auxiliary loads to the PWR. Larger hydrogen plants must be connected to the PWR using a standard industrial facility connection to a power plant in which the power connection is made on the high voltage side of the Generator Step-Up (GSU) transformer.

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### References

[1] R. D. Boardman, J. S. Kim, S. Hancock, H. Hu, K. Frick, D. Wendt, A. Elgowainy, R. Weber (2019). "*Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest*", Idaho National Laboratory report INL/LTD-19-53294, (Mar. 2019).
[2] S. Hancock, T. Westover, "*Simulation of 15% and 50% Thermal Power Dispatch to an Industrial Facility Using a Flexible Generic Full-Scope Pressurized Water Reactor Plant Simulator*", energies, 15, pp. 1151-1-15. https://doi.org/10.3390/en15031151. (2022).
[3] T. Westover, M. Casteel, Y. Luo, F. Gallego-Dias, R. Lew, B. Poudel, S. Hancock, "*Validation of a Reduced-Order PWR Power Dispatch Simulator*", Idaho National Laboratory report INL/LTD-21-64481, (Sept. 2021).

[4] T. L. Westover, S. Hancock, A. Shigrekar. "*Monitoring and Control Systems Technical Guidance for LWR Thermal Energy Delivery*", I Idaho National Laboratory external report NL/EXT-20-57577, (Feb. 2020).