

TECHNO-ECONOMIC ASSESSMENT OF PV-PEM INTEGRATION FOR KURZEME COASTAL REGION

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Abstract. The study evaluates an integrated photoelectric and proton exchange membrane electrolyzer (PV-PEM) green hydrogen system consisting of a 10 megawatt (MW) solar PV plant and a 6 MW PEM electrolyzer located in Ventspils, Latvia. The PV plant is assumed to generate 10,000 MWh·year⁻¹, reflecting regional solar conditions and seasonal variability. After electrical losses and availability, the net electricity delivered to electrolysis is estimated at 9,400 MWh·year⁻¹. Using a PEM-specific electricity consumption of 54 kWh·kg⁻¹ H₂, annual hydrogen production reaches 174,000 kg·year⁻¹ (174 tH₂·year⁻¹) under PV-only operation. The PV-only case results in a low electrolyzer utilization of 18% capacity factor (1,600 h·year⁻¹), making capital expenditure (CAPEX) recovery the dominant cost driver. CAPEX for the hydrogen plant (electrolyzer with BoP compression and storage units) is estimated at EUR 8 million, with annual fixed OPEX EUR 0.36 million. The resulting Levelized Cost of Hydrogen (LCOH) is EUR 6.8 kg⁻¹ H₂, with CAPEX contributing approximately 69% (EUR 4.7·kg⁻¹) of total cost. A grid-integrated operating strategy increasing utilization to 50% capacity factor raises hydrogen output to 487 t H₂·year⁻¹ and reduces LCOH to EUR 4.6 kg⁻¹ H₂, assuming EUR 40·MWh⁻¹ electricity cost. The results show that improving electrolyzer utilization is the most effective pathway to reduce hydrogen cost in northern PV-based systems.

Keywords: electrolyzer utilization, hydrogen, techno-economic assessment.

Introduction

Green hydrogen is increasingly considered a key energy carrier for decarbonizing industry, transport, and seasonal energy storage [1-4]. In the European Union, hydrogen strategies and renewable integration targets are accelerating investments in electrolysis-based production pathways [5]. Latvia, despite being in Northern Europe, has a growing solar PV market supported by declining technology costs and policy-driven renewable energy expansion [6]. The coastal region of Kurzeme, including Ventspils, shows relatively favourable solar irradiation conditions for Latvia [7] and offers strategic advantages such as industrial activity and port infrastructure. However, solar electricity generation in Latvia remains highly seasonal, with big differences between summer and winter output [8]. This variability creates a technical and economic challenge for hydrogen production systems that require stable utilization to reduce unit costs. PEM electrolyzers are particularly suitable for renewable coupling because they can operate flexibly, ramp quickly, and handle partial-load operation better than many alternative electrolysis technologies [9-11].

The study evaluates the integration of PEM electrolyzer with a 10 MW PV plant located in Ventspils and defines a technically feasible configuration and provides an indicative estimate of installed electrolyzer capacity, hydrogen production, and economic indicators like CAPEX, operational expenditure (OPEX), and LCOH. The concept is developed for a PV-dominant electricity supply, acknowledging that Latvia's solar generation is strongly seasonal, with most energy produced between spring and early autumn. The Ventspils solar resource in the referenced assessment indicates an annual solar potential of approximately 900-1100 kWh·m⁻²·year⁻¹ [12], which is suitable for commercial PV deployment but implies relatively low annual full-load hours compared with southern Europe.

The study goal is to develop and evaluate the conceptual design and techno-economic model of a PEM electrolyzer integrated with a 10 MW solar PV plant in Ventspils, and to quantify installed capacity, hydrogen output, CAPEX, OPEX, and LCOH distribution under PV-only and improved operational strategies.

The study hypothesis is as follows: PEM electrolyzer sized below the PV peak capacity (6 MW for a 10 MW PV plant) can technically operate reliably under Ventspils solar conditions, but PV-only operation results in low annual utilization, making CAPEX the dominant driver of LCOH; therefore, improved utilization strategies (limited grid top-up or storage) are expected to significantly reduce LCOH.

The novelty of this study lies in the techno-economic assessment of the PV-PEM hydrogen production system under the climatic conditions of the Kurzeme coastal region in Latvia. Unlike many

studies focusing on high-irradiation regions, this study evaluates renewable hydrogen production in a Northern European environment characterized by strong solar seasonality. The study proposes a conceptual integration of a 10 MW solar PV plant with a 6 MW PEM electrolyzer and analyses the impact of two operational strategies: PV-only operation and PV combined with grid electricity, on hydrogen output and LCOH. The results highlight electrolyzer utilization as the key economic driver for hydrogen production systems in regions with moderate solar resources.

Limitations of the study stem from a simplified annual energy balance approach and do not capture hourly variability of PV generation and electrolyzer operation. The analysis assumes constant system performance and does not consider dynamic efficiency changes or degradation effects of PEM electrolyzers over time. Economic results rely on assumed values for CAPEX, OPEX, and electricity prices, which may vary depending on market conditions. The model does not include sensitivity analysis for key parameters, limiting the assessment of uncertainty. Two operational scenarios are evaluated, without considering alternative system configurations such as hybrid PV-wind or storage integration. Grid constraints, infrastructure availability, and regulatory factors are not included in the analysis along with environmental impacts or lifecycle emissions. Therefore, the results should be interpreted as indicative and require further validation through detailed modelling and real-world data.

The study is based on a conceptual techno-economic model using annual energy balance assumptions rather than detailed hourly simulations of PV generation and electrolyzer operation. Two operational strategies were evaluated, while other configurations, such as battery storage or hybrid renewable systems, were not considered. Infrastructure, regulatory aspects, and detailed electrolyzer degradation effects were also outside the scope of this study. These factors will be addressed in future studies through more detailed system modelling, expanded scenario analysis, and consideration of market and infrastructure conditions to improve the accuracy and practical relevance of the techno-economic assessment.

Materials and methods

This study applies a conceptual techno-economic methodology trend to the evaluation of a PV-PEM hydrogen production system consisting of a 10 MW solar PV plant and a 6 MW PEM electrolyzer located in Ventspils, Latvia. The assessment begins by defining the local solar resource and selecting a mid-case annual PV generation of approximately 10,000 MWh·year⁻¹ based on regional irradiation and yield conditions. A clear system boundary is then established, covering PV generation, electrical conversion and protection, PEM electrolysis, hydrogen drying and conditioning, compression, buffer storage, and final delivery or export. PEM electrolysis is chosen due to its operational flexibility and suitability for variable renewable electricity supply [13; 14]. The electrolyzer capacity is sized to match the PV production profile, and a 6 MW unit is selected as a practical compromise between capturing available solar electricity and avoiding excessive oversizing that would reduce annual utilization.

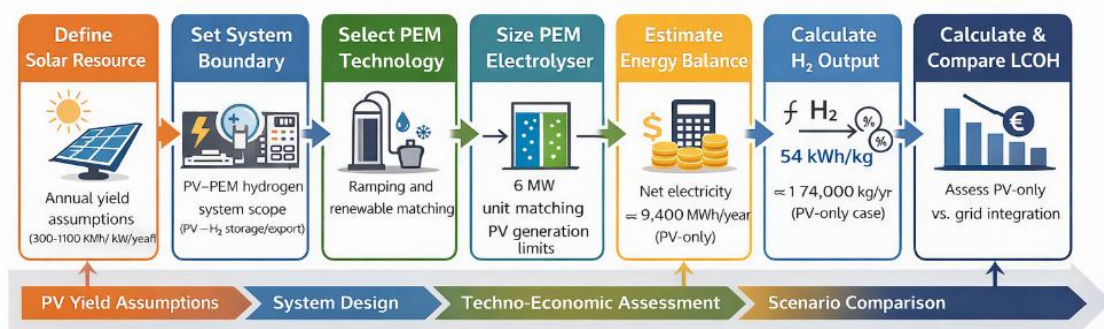


Fig. 1. Research design of the study

The techno-economic model was implemented as a deterministic annual energy-balance calculation. The modelling procedure consists of four sequential steps: (1) estimation of annual PV electricity generation based on installed capacity and representative regional yield; (2) calculation of net electricity delivered to the PEM electrolyzer after electrical losses and availability factors; (3) estimation of hydrogen production using the specific electricity consumption of the PEM electrolyzer; (4) calculation of economic indicators, including annualized CAPEX, OPEX, and LCOH.

An annual energy balance is developed to estimate net electricity delivered to the electrolyser after accounting for internal electrical losses and equipment availability, resulting in approximately 9,400 MWh·year⁻¹ available for electrolysis under PV-only operation. Electrolyser utilization is quantified through capacity factor calculations, showing low PV-only utilization of around 18% due to the strong seasonal nature of solar generation in Latvia. CAPEX is estimated to use a component-based breakdown that includes the electrolyzer package, balance-of-plant systems, compression, and storage, resulting in an installed hydrogen plant CAPEX of approximately EUR 8 million.

OPEX is estimated on an annual basis and includes fixed maintenance and service costs, site overheads, water treatment consumables, and a stack replacement reserve, leading to an OPEX level of approximately 0.36 million EUR·year⁻¹ for PV-only operation. LCOH is then calculated by annualizing CAPEX using a 20-year project lifetime and an 8% discount rate (CRF \approx 0.102) and dividing the total annualized cost by annual hydrogen production. Then two operational scenarios are compared: a PV-only case without grid integration and a grid-integrated case where additional electricity supply increases operating hours, typically modelled at around 50% capacity factor, to evaluate how improved utilization changes hydrogen output, shifts the cost structure, and reduces the overall LCOH.

PEM electrolyzer sizing, design, and major equipment

A PEM electrolyzer can ramp quickly and operate flexibly, which makes it well-suited for direct coupling with variable renewable energy such as PV [15]. However, sizing must balance two competing effects: oversized electrolyzer: low utilization and high LCOH due to under-used CAPEX and undersized electrolyzer: PV curtailment at peak hours and missed hydrogen production opportunity. For a 10 MW PV plant in Latvia, the PV-only operating profile implies relatively low annual electrolyzer utilization. Therefore, an electrolyzer capacity smaller than PV peak power is assumed.

A suitable conceptual match is PEM electrolyzer with installed capacity of 6 MW. This size is expected to absorb a large share of PV generation during productive hours while avoiding excessive oversizing that would lead to extremely low-capacity factor.

The conceptual design integrates PV electricity through the site electrical infrastructure into the PEM electrolyzer power supply. The electrolyzer produces hydrogen which is then conditioned and compressed for storage and export. A simplified process chain is depicted in Figure 2.

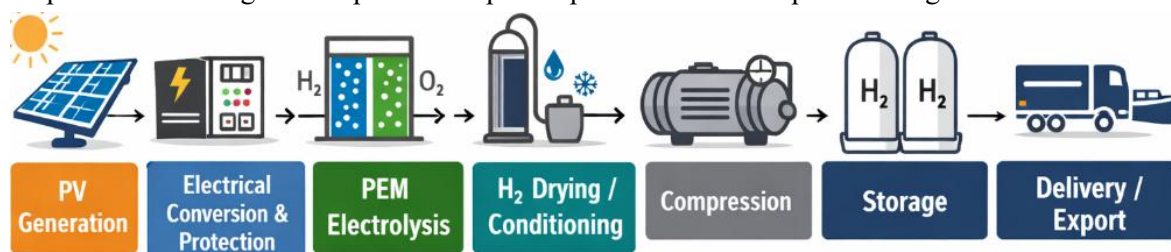


Fig. 2. Simplified process chain for PV – PEM integrated system

The plant concept includes the following major equipment: PEM electrolyzer with stack modules, power supply/rectifier, cooling skid, deionized water loop, instrumentation, and control systems, water treatment and polishing system with filtration and reverse osmosis followed by final polishing to meet PEM water quality requirements, hydrogen conditioning with gas–liquid separation and drying. PEM typically provides high hydrogen purity, but downstream conditioning ensures compliance with end-use specifications [16]. Compression and storage are required for buffering and export (30–60 bar for local buffer storage, or higher for trailer filling). Storage is designed for short-term balancing between production and dispatch. Electrical and safety systems with transformers, switchgear, cabling, earthing, fire and gas detection, ventilation, emergency shutdown, and SCADA integration are also present.

Results

By evaluating the techno-economic performance of a PV-PEM hydrogen production system consisting of a 10 MW solar PV plant coupled to a 6 MW PEM electrolyzer, two operational strategies are compared. Strategy 1 represents a PV-only system without grid integration, where the electrolyzer operates only when PV power is available, and Strategy 2 depicts a PV and grid integration system,

where PV electricity is prioritized but the grid supplies additional electricity to increase annual operating hours and improve electrolyzer utilization. The assessment focuses on the main investment and operating costs (CAPEX and OPEX) and the resulting LCOH.

Baseline assumptions

Hydrogen production is calculated from net electricity input to electrolysis and the specific electricity consumption of the PEM system:

$$m_{H_2} = \frac{E_{el}}{SEC}, \quad (1)$$

where m_{H_2} – annual hydrogen production ($\text{kg} \cdot \text{year}^{-1}$)
 E_{el} – net electricity to electrolysis ($\text{kWh} \cdot \text{year}^{-1}$)
 SEC – specific electricity consumption ($\text{kWh} \cdot \text{kg}^{-1} \text{H}_2$).

Electrolyzer capacity factor is calculated as:

$$CF = \frac{E_{el}}{P_{PEM} \cdot 8760} \quad (2)$$

The LCOH is calculated using annualized CAPEX and annual operating costs:

$$LCOH = \frac{CAPEX \cdot CRF + OPEX_{annual} + C_{electricity}}{m_{H_2}} \quad (3)$$

The capital recovery factor is defined as:

$$CRF = \frac{r(1+r)^n}{r(1+r)^n - 1} \quad (4)$$

For this study: $r = 8\%$ and $n = 20$ years, resulting in $CRF \approx 0.102$. Table 1 shows the basic technical and financial assumptions applied consistently in both cases.

Table 1

Basic technical and financial assumptions

Parameter	Value
PV installed capacity (MW)	10
PEM electrolyzer installed capacity (MW)	6
Electrical losses (conversion and system), %	6
Electrolyzer availability, %	95
PEM specific electricity consumption (SEC), $\text{kWh} \cdot \text{kg}^{-1} \text{H}_2$	54
PV annual yield, $\text{MWh} \cdot \text{MW}^{-1} \cdot \text{year}^{-1}$	1000
Grid electricity price, $\text{EUR} \cdot \text{MWh}^{-1}$	40
Project lifetime, years	20
Discount rate (WACC), %	8
Capital recovery factor (CRF)	0.102

The parameters summarized in Table 1 represent the primary input variables of the techno-economic model used to calculate hydrogen production, electrolyzer utilization, and LCOH. These assumptions are selected to reflect representative technical and economic conditions for PV-PEM systems in Latvia. The PV installed capacity (10 MW) and annual yield (1000 MWh per MW per year) are based on regional solar resource data for the Kurzeme coastal region. The electrolyzer capacity (6 MW), electrical losses (6%), and availability (95%) are typical engineering assumptions ensuring realistic system operation and efficiency. The specific electricity consumption of $54 \text{ kWh} \cdot \text{kg}^{-1} \text{H}_2$ corresponds to current commercial PEM electrolyzer performance reported in recent literature. Economic parameters, including electricity price ($40 \text{ EUR} \cdot \text{MWh}^{-1}$), project lifetime (20 years), and discount rate (8%), represent standard values used in energy infrastructure assessments. The capital recovery factor is derived consistently from these financial assumptions, ensuring methodological coherence in LCOH calculation.

Strategy 1: PV-only operation

In the PV-only operation, the 10 MW PV plant generates approximately 10,000 MWh·year⁻¹. After electrical conversion losses and electrolyzer availability, the net electricity delivered to the PEM electrolyzer is approximately 9,400 MWh·year⁻¹. Using the representative PEM electricity consumption of 54 kWh·kg⁻¹ H₂, annual hydrogen output is calculated as:

$$m_{H_2} \approx \frac{9,400,000}{54} \approx 174,000 \text{ kg} \cdot \text{year}^{-1} = 174 \text{ t} \cdot \text{year}^{-1} \quad (5)$$

As Latvia's solar resource is highly seasonal, the electrolyzer utilization remains limited, resulting in a capacity factor of around 18%, which is a major cost driver in PV-only hydrogen production.

Strategy 2: PV and grid top-up operation

In the grid-integrated case, PV electricity is still prioritized, but the grid is used to increase electrolyzer operating hours and stabilize production. A representative operating target is 50% capacity factor, which corresponds to annual electricity input:

$$E_{el} = 6,000 \text{ kW} \cdot 8760 \cdot 0.50 \approx 26,280,000 \text{ kWh} \cdot \text{year}^{-1} \quad (6)$$

Hydrogen production increases to:

$$m_{H_2} = \frac{26,280,000}{54} = 487,000 \text{ kg} \cdot \text{year}^{-1} = 487 \text{ t} \cdot \text{year}^{-1} \quad (7)$$

The performance comparison of both strategies is summarized in Table 2.

Table 2

Energy balance and hydrogen production results

Indicator	Strategy 1	Strategy 2
PV electricity generation, MWh·year ⁻¹	10,000	10,000
Net electricity to electrolysis, MWh·year ⁻¹	9,400	26,280
Electrolyzer capacity factor, %	18	50
Annual hydrogen production, tH ₂ ·year ⁻¹	174	487

CAPEX and OPEX

For the selected configuration, the installed CAPEX of the hydrogen production plant is approximately EUR 8 million. The PV plant CAPEX is treated separately as an optional reference, where a 10 MW PV installation typically falls in the range of EUR 5.5-7.5 million, depending on grid connection and EPC conditions.

For operating costs, fixed annual OPEX (service, maintenance, labour, overheads, and stack replacement reserve) is estimated at approximately 0.36 million EUR·year⁻¹. In Strategy 1, PV-only operation, electricity cost is assumed to be internal PV supply at zero transfer price. In Strategy 2, grid integration introduces a major additional cost component. For illustration, a representative average grid electricity price of 40 EUR·MWh⁻¹ is applied:

$$C_{electricity} = 26,280 \text{ MWh} \cdot 40 \text{ EUR} \cdot \text{MWh}^{-1} = 1.05 \text{ million EUR} \cdot \text{year}^{-1} \quad (8)$$

The CAPEX and OPEX summary for both cases is presented in Table 3.

Table 3

CAPEX and OPEX summary

Cost item	Strategy 1	Strategy 2
CAPEX (H ₂ plant only: 6 MW PEM, BoP, compression, storage), million EUR	8	8
CAPEX (PV plant optional reference), million EUR	5.5-7.5	5.5-7.5
Total PV + H ₂ system CAPEX (optional combined scope), million EUR	13.5-15.5	13.5-15.5
Annual OPEX (fixed, excl. electricity), million EUR·year ⁻¹	0.36	0.36
Annual electricity cost, millions EUR	0	1.05 (40 EUR·MWh ⁻¹)
Total annual OPEX incl. electricity, million EUR·year ⁻¹	0.36	1.41

LCOH calculation and results

LCOH is calculated by annualizing CAPEX using CRF and dividing total annual cost by annual hydrogen production. Annualized CAPEX for the hydrogen plant is:

$$CAPEX_{annual} = 8.0 \text{ million EUR} \cdot 0.102 \approx 0.82 \text{ million EUR} \cdot \text{year}^{-1} \quad (9)$$

Total annual cost is then:

$$C_{annual} = CAPEX_{annual} + OPEX_{annual} + C_{electricity} \quad (10)$$

Finally:

$$LCOH = \frac{C_{annual}}{m_{H_2}} \quad (11)$$

The resulting LCOH values and cost drivers for both cases are summarized in Table 4.

Table 4

LCOH results and cost breakdown

Indicator	Strategy 1	Strategy 2
Annualized CAPEX, million EUR·year ⁻¹	0.82	0.82
Total annual cost (CAPEX, OPEX, electricity), million EUR·year ⁻¹	1.18	2.23
Hydrogen output, kg·year ⁻¹	174,000	487,000
LCOH, EUR·kg ⁻¹	6.8	4.6
Dominant cost driver	CAPEX	Electricity

The PV-only system produces approximately 174 tH₂·year⁻¹ and results in LCOH of around 6.8 EUR·kg⁻¹ H₂, mainly due to low electrolyzer utilization (~18% capacity factor) which makes capital recovery the dominant cost driver. In contrast, grid integration increases electrolyzer utilization to 50%, raising hydrogen production to approximately 487 tH₂·year⁻¹ and reducing LCOH to around 4.6 EUR·kg⁻¹ H₂ under an assumed grid electricity price of 40 EUR·MWh⁻¹. Therefore, the key trade-off is between low-cost renewable electricity but low utilization (PV-only) and higher utilization but higher operating electricity cost (PV plus grid).

Discussion

The results demonstrate that the techno-economic performance of the PV-PEM system in the Kurzeme coastal region is primarily limited by the seasonal variability of solar resources. Although the annual PV generation is sufficient, its uneven temporal distribution leads to low electrolyzer utilization under PV-only operation. The obtained capacity factor of approximately 18% confirms that solar intermittency significantly constrains system efficiency in Northern European conditions. As a result, CAPEX becomes the dominant contributor to LCOH, accounting for nearly 70% of total hydrogen cost. This finding highlights that underutilization of capital-intensive equipment is a key economic barrier in PV-based hydrogen systems.

The comparison of operational strategies shows that increasing electrolyzer utilization is the most effective way to reduce hydrogen cost. The integration of grid electricity increases the capacity factor to 50%, resulting in a substantial increase in hydrogen production and a reduction in LCOH. However, this improvement shifts the cost structure from CAPEX-dominated to electricity cost-dominated, indicating a fundamental trade-off between low-cost renewable energy and higher operational expenses. This trade-off is critical for system design in regions with moderate solar potential.

The selected system configuration, with a 6 MW electrolyzer coupled to a 10 MW PV plant, represents a balanced approach between minimizing PV curtailment and avoiding excessive oversizing. At the same time, the results suggest that PV-only systems are not economically optimal in such climates without additional flexibility measures. Integration with the grid or other energy sources appears necessary to achieve stable operation and improved cost efficiency.

The results also underline the importance of electricity price assumptions in determining overall system economics. The use of a representative grid price significantly influences LCOH in the grid-integrated scenario, indicating that future market conditions will play a crucial role in hydrogen competitiveness. The study confirms that improving electrolyzer utilization, rather than marginal

efficiency gains, is the key driver for reducing hydrogen production costs in PV-based systems under assumed conditions.

Conclusions

The assessment confirms that a 10 MW solar PV plant in Ventspils can technically support green hydrogen production using a 6 MW PEM electrolyzer, benefiting from PEM's fast ramping and high operational flexibility. With a mid-case PV yield, annual PV generation is approximately 10,000 MWh \cdot year $^{-1}$, of which about 9,400 MWh \cdot year $^{-1}$ is delivered to electrolysis after losses and availability. Using a representative PEM consumption of 54 kWh \cdot kg $^{-1}$ H $_2$, the PV-only configuration produces around 174,000 kg \cdot year $^{-1}$ (174 tH $_2$ \cdot year $^{-1}$). This corresponds to a low electrolyzer utilization of about 18% capacity factor (1,600 full-load hours \cdot year $^{-1}$), which strongly increases hydrogen unit cost.

CAPEX of the hydrogen plant (electrolysers, BoP, compression, storage) is estimated at 8 million EUR, while fixed annual OPEX is approximately 0.36 million EUR \cdot year $^{-1}$. Under PV-only operation, the calculated LCOH is 6.8 EUR \cdot kg $^{-1}$ H $_2$, with CAPEX contributing 69% (4.7 EUR \cdot kg $^{-1}$), confirming that low utilization makes investment recovery the dominant cost driver. Including the PV plant, total system CAPEX is approximately million EUR 13.5-15.5, depending on PV EPC and grid connection conditions.

When grid integration is introduced to increase electrolyzer operation to around 50% capacity factor, annual electricity input rises to 26.3 GWh \cdot year $^{-1}$ and hydrogen output increases to 487 tH $_2$ \cdot year $^{-1}$. In this higher-utilization case, LCOH decreases to 4.6 EUR \cdot kg $^{-1}$ H $_2$ assuming 40 EUR \cdot MWh $^{-1}$ electricity cost, but electricity becomes the largest operating cost component. The comparison demonstrates that the key economic lever for Ventspils is improving electrolyzer utilization, not minor efficiency gains. Hydrogen storage and compression remain essential for operational buffering and export readiness, especially under seasonal PV supply. PV-only concept is technically feasible but cost-limited, while PV and grid integration provides a more competitive pathway by spreading CAPEX across higher annual hydrogen production.

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Author contributions

Conceptualization, A.B., L.J., A.L.; methodology, A.L., L.J., A.B.; software, S.L.; validation, A.B., L.J.; investigation, A.B., L.J., A.L.; data curation, S.L.; writing – original draft preparation, A.B., L.J.; writing – review and editing, A.L.; visualization, S.L.; project administration, A.B.; funding acquisition, A.B., L.J., A.L. All authors have read and agreed to the published version of the manuscript.

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