

On Optimal Hydrogen Pathway Selection Using the SECA Multi-Criteria Decision-Making Method

Caroline Kaitano^a, Thokozani Majazi^{a*}

^a School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, Gauteng, South Africa

* Corresponding Author: thokozani.majazi@wits.ac.za

ABSTRACT

The increasing global population has resulted in the scramble for more energy. Hydrogen offers a new revolution to energy systems worldwide. Considering its numerous uses, research interest has grown to seek sustainable production methods. However, hydrogen production must satisfy three factors, i.e., energy security, energy equity, and environmental sustainability, referred to as the energy trilemma. Therefore, this study seeks to investigate the sustainability of hydrogen production pathways through the use of a Multi-Criteria Decision-Making model. In particular, a modified Simultaneous Evaluation of Criteria and Alternatives (SECA) model was employed for the prioritization of 19 options for hydrogen production. This model simultaneously determines the overall performance scores of the 19 options and the objective weights for the energy trilemma in a South African context. The results obtained from this study showed that environmental sustainability has a higher objective weight value of 0.37, followed by energy security with a value of 0.32 and energy equity with the least at 0.31. Of the 19 options selected, steam reforming of methane with carbon capture and storage was found to have the highest overall performance score, considering the trade-offs in the energy trilemma. This was followed by steam reforming of methane without carbon capture and storage and the autothermal reforming of methane with carbon capture and storage. The results obtained in this study will potentially pave the way for optimally producing hydrogen from different feedstocks while considering the energy trilemma and serve as a basis for further research in sustainable process engineering.

Keywords: Hydrogen, Modelling, Optimization, Energy-trilemma, SECA, multi-criteria-decision-making

INTRODUCTION

Energy is a fundamental component of life and is critical for sustaining modern living standards. Increasing global population and industrialization have driven energy demand to unprecedented levels, placing significant strain on the energy sector [1]. Currently, approximately 85% of energy demand is met by fossil fuels, resulting in substantial CO₂ emissions. This has contributed to a 1.1°C rise in global temperatures since the pre-industrial era, with projections of further increases [2].

The energy sector also faces challenges from economic fluctuations, such as those induced by the COVID-19 pandemic, which temporarily reduced global energy demand, emissions, and investment but left renewable energy less affected [3]. As demand pressures persist, governments and organizations are pursuing policies and

innovations to transition toward sustainable energy systems emphasizing reliability, environmental sustainability, and affordability [4].

Hydrogen is emerging as a promising clean energy carrier capable of addressing the limitations of traditional renewable energy sources, such as intermittency and lack of inherent storage capacity. With a high energy density (120 MJ·kg⁻¹), hydrogen offers versatility in production, storage, and applications, including transportation and grid stabilization [5]. However, the widespread adoption of hydrogen faces challenges related to cost-effective and environmentally sustainable production methods. Current hydrogen generation technologies, primarily reliant on fossil fuels, emit CO₂, necessitating a shift toward carbon-free alternatives.

Hydrogen production pathways vary widely in economic, environmental, and technological performance.

Reforming methods are cost-effective but environmentally damaging, while electrolysis, powered by renewable energy, is sustainable but capital-intensive. Multi-criteria decision-making (MCDM) approaches are essential to evaluate and select optimal hydrogen production pathways that balance energy security, equity, and sustainability [6].

This study aims to identify the optimal hydrogen production pathway for South Africa using an MCDM framework. A literature review informs the methodology, followed by an evaluation of the performance of selected processes.

LITERATURE REVIEW

MCDM methods are effective tools for addressing decision-making problems involving multiple conflicting objectives and stakeholders. Various MCDM techniques have been applied to assess and prioritize hydrogen production technologies. For example, some authors employed the Analytic Hierarchy Process (AHP) [7–8], while others integrated the decision-making trial and evaluation laboratory (DEMATEL) with AHP to improve hydrogen production sustainability [9]. Other studies utilized methods like TOPSIS, VIKOR, and hesitant fuzzy AHP to evaluate hydrogen production pathways based on sustainability criteria [10–11].

Recent advancements in MCDM include integrating fuzzy logic to handle subjective and vague human judgments, such as using the Z-number Best Worst Method (ZBWM) and ELECTRE models [12] or employing fuzzy SWARA and IVIF-WASPAS [13]. Despite these innovations, most methods remain subjective, relying heavily on expert opinions, which introduce inconsistencies and uncertainties. Moreover, these methods typically separate criteria weighting from alternative ranking, thereby limiting integration and efficiency.

Few studies have addressed hydrogen production within the framework of the energy trilemma. Additionally, geographical context, such as the South African unique energy landscape, has received little attention. South African abundant resources and environmental challenges necessitate tailored hydrogen production strategies. However, research gaps persist in addressing the interplay of energy trilemma factors and region-specific conditions.

This study introduces the Simultaneous Evaluation of Criteria and Alternatives (SECA) method, a multi-objective nonlinear programming model that simultaneously calculates criteria weights and ranks alternatives. SECA overcomes the limitations of traditional MCDM methods by optimizing and ranking solutions in a unified framework. The study focuses on identifying the optimal hydrogen production pathway for South Africa, accounting for the complexities of the energy trilemma, thereby

filling a critical gap in published literature and offering practical insights for stakeholders in energy policy and planning.

METHODOLOGY

The study follows three key stages: (1) Defining selection criteria and identifying suitable hydrogen production options, (2) Constructing a decision-making matrix, and (3) Developing a multi-objective nonlinear programming model for optimization.

Environmental sustainability, economic viability, and reliability/availability were chosen as selection criteria, addressing the core challenges in hydrogen production pathway selection. The SECA model [14], a multi-objective nonlinear approach, is applied to determine the optimal method in the South African context. It optimizes three objectives: (1) maximizing overall performance, (2) minimizing deviation in criterion weights within-criterion variation, and (3) minimizing deviation in criterion weights based on between-criterion variation. Unlike traditional methods, SECA does not require expert input for scoring criteria and relies on standard deviation and correlation as reference points for weight minimization.

To enhance model applicability, the study replaces the original SECA normalization method with Min-Max Normalization, addressing the issue of zero-value elements in evaluation matrices. This modification expands the usability of the model across diverse datasets and ensures a more comprehensive assessment framework.

A multi-criteria decision-making (MCDM) problem with n alternatives and m criteria is represented by the decision matrix:

$$x = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \quad (1)$$

Where x_{ij} represents the performance of alternative i alternative on criteria j with $x_{ij} \geq 0$. Normalization is applied based on benefit and cost criteria using Min-Max scaling:

$$x_{ij}^N = \begin{cases} \frac{x_{ij} - \max x_{ij}}{\max x_{ij} - \min x_{ij}}, j \in BC \\ \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}}, j \in CC \end{cases} \quad (2)$$

where BC and CC are benefit and cost criteria, respectively.

The SECA model determines criteria weights directly from the decision matrix, using standard deviation (σ_j) and correlation (r_{jl}). The standard deviation, which indicates the dispersion of data, captures the within-criterion variation. The correlation calculates the contrast intensity in the interaction of the alternatives in each criterion to assess the between-criterion conflict.

$$\sigma_j = \sqrt{\frac{1}{m} \sum_{i=1}^m (X_{ij} - \bar{X}_{ij})^2}, \quad \pi_j = \sum_{i=1}^m (1 - r_{ji}) \quad (3)$$

The normalized reference points for weight calculation are given by:

$$\sigma_j^N = \frac{\sigma_j}{\sum_{i=1}^m \sigma_i}, \quad \pi_j^N = \frac{\pi_j}{\sum_{i=1}^m \pi_i} \quad (4)$$

The multi-objective nonlinear programming model consists of three objectives:

1. Maximizing overall performance:

$$\max S_i = \sum_{j=1}^m w_j x_{ij}^N \quad \forall i \in \{1, 2, \dots, n\} \quad (5)$$

2. Minimizing deviation from standard deviation-based reference weights:

$$\min \lambda_b = \sum_{j=1}^m (w_j - \sigma_j^N)^2 \quad (6)$$

3. Minimizing deviation from correlation-based reference weights:

$$\min \lambda_c = \sum_{j=1}^m (w_j - \pi_j^N)^2 \quad (7)$$

Subject to:

$$\sum_{j=1}^m w_j = 1, \quad \varepsilon \leq w_j \leq 1, \quad \forall j \in \{1, 2, \dots, m\} \quad (8)$$

where ε is a small positive value (set to 10^{-3}) ensuring a lower bound on weights.

To transform the multi-objective problem into a single-objective optimization, a weighted sum method is applied:

$$\max Z = \lambda_a - \beta(\lambda_b + \lambda_c) \quad (9)$$

with constraints:

$$\lambda_a \leq S_i, \quad S_i = \sum_{j=1}^m x_{ij}^N w_j, \quad \forall i \in \{1, 2, \dots, n\} \quad (10)$$

$$\lambda_b = \sum_{j=1}^m (w_j - \sigma_j^N)^2, \quad \lambda_c = \sum_{j=1}^m (w_j - \pi_j^N)^2 \quad (11)$$

The parameter β balances deviations from reference weights, and different β values generate alternative rankings. The stability of rankings is evaluated using the Spearman correlation coefficient, ensuring consistency in final rankings.

CASE STUDY

A pathway database was developed from the literature. The data was collected according to affordability, availability, and environmental sustainability criteria. The affordability was characterized by the cost of hydrogen (\$/kg), and the data was adapted from [15].

Environmental sustainability data was collected from different sources in the literature [16–19]. This criterion was characterized by global warming potential (GWP), which is the amount of carbon dioxide produced by the process per amount of hydrogen produced (kg CO₂ / kg H₂).

Availability is the third criterion, and it measures the raw materials required in a particular process to obtain hydrogen. The measure was rated regarding how much raw material is available. Raw material availability was chosen because neglecting resource availability may cause a model to select a production process that is not well suited to a region of interest. In this research, a rigorous methodology was employed to calculate the availability rating of critical raw materials. The availability rating was determined using the following equation, which was modified from the general efficiency equation:

$$\text{Availability rating} = \frac{\text{Total raw material available}}{\text{Total raw material required}} \quad (12)$$

The study considered the total quantities of raw materials required for a 100-year projection assuming stoichiometry. The availability rating for each raw material was calculated individually, offering a detailed assessment of their respective contributions to the overall availability. Furthermore, an average availability rating was computed to provide a holistic perspective on the raw material supply chain. The results reveal a surplus beyond the required quantities, emphasizing the robustness of the production system and its capability to meet demands efficiently. This comprehensive approach to assessing availability contributes valuable insights to the optimization of hydrogen production processes.

A hydrogen demand value of 6 million tons per annum obtained from [20] was used to calculate the amount of raw materials required per pathway. This was done using stoichiometric ratios, assuming 100 % conversion of the limiting reactant. The average raw materials required for a particular pathway were used as the availability rating.

RESULTS AND DISCUSSION

A decision-making matrix was developed based on a pathway database comprising 19 hydrogen production routes. The matrix was constructed using GAMS modeling software with the Antigone solver to handle the

complex interrelationships and variables within the decision framework.

Table 1: The evaluation matrix of the pathway database

Process	Cost (\$/kg)	GWP (kgCO ₂ / kg H ₂)	Availability rating
SMR with CCS (S1)	4.84	3.40	11.65
SMR without CCS (S2)	4.43	12.00	11.65
CG with CCS (S3)	3.48	15.50	2.10
CG without CCS (S4)	2.86	24.20	2.10
ATR of methane with CCS (S5)	3.16	3.98	7.78
Methane Pyrolysis (S6)	3.18	5.00	3.02
Biomass Pyrolysis (S7)	3.75	2.40	6.26
Biomass Gasification (S8)	4.14	2.67	6.26
Direct bio Photolysis (S9)	3.77	0.70	6.26
Indirect bio photolysis (S10)	2.51	67.00	6.26
Dark Fermentation (S11)	4.65	16.29	6.26
Photo Fermentation (S12)	5.12	0.60	3.13
Solar PV Electrolysis (S13)	28.23	2.00	3.13
Solar thermal electrolysis (S14)	15.15	2.50	3.13
Wind Electrolysis (S15)	12.71	0.97	3.13
Nuclear Electrolysis (S16)	11.25	2.00	3.13
Nuclear Thermolysis (S17)	4.66	0.63	3.13
Solar Thermolysis (S18)	15.91	0.68	3.13
Photo-Electrolysis (S19)	18.73	2.00	3.13

To ensure consistency, all cost data were standardized to the reference year 2021 using the Chemical Engineering Plant Cost Index (CEPCI). The matrix provides a structured framework for evaluating and comparing pathways against the energy trilemma criteria. **Table 1** presents the evaluation matrix.

Normalizing the decision-making matrix

The data in **Table 1** were normalized using Equation

(2). Affordability and environmental sustainability were identified as cost criteria, given that they need to be minimized. Conversely, availability was identified as a benefit criterion, given that it needs to be maximized.

Criteria weights analysis

Determining criteria weights is crucial for prioritizing processes. The SECA model was solved for β values (0.1, 0.2, 0.3, 0.4, 0.5, 1, 2, 3, 4, 5, 6, 7), extending the initial study by [14] to observe trends beyond $\beta = 5$. Twelve sets of criteria weights were generated, with variations shown in **Figure 1**. The optimal β was selected where consecutive solutions differed by less than 0.01, ensuring near-constant weights.

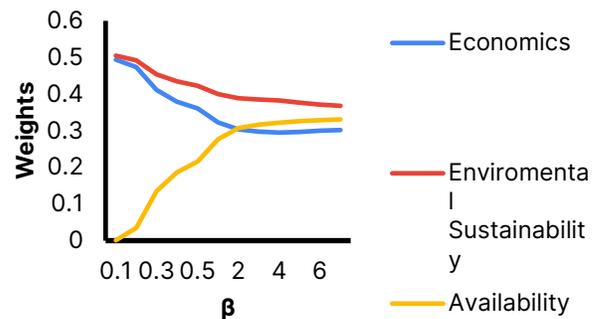


Figure 1: The variation of criteria weights related to β

A clear decrease in the objective function value was observed as β increased, as shown in **Figure 2**. The parameter β played a critical role in influencing criteria weights, with some criteria gaining importance while others diminished as β increased. This dynamic interaction optimized the decision-making process by balancing trade-offs between criteria.

A transition point was identified where criteria weights stabilized, signaling the critical balance of the model. Notably, this stabilization coincided with the maximum value of the objective function, indicating the optimal state of the model. Thus, β acted as a lever to achieve a stable and balanced weighting while optimizing the overall objective function.

For β values exceeding 3, criteria weights exhibited increased stability, with differences between consecutive weights dropping below 0.01 as β approached 5. This indicated a balanced state between decision criteria, leading to the selection of $\beta = 5$ for determining final weights.

The resulting criteria weights highlighted environmental sustainability as the most significant factor (0.373), emphasizing eco-friendly practices. Availability, particularly of raw materials, ranked second (0.316), underscoring resource reliability. Affordability received the lowest weight (0.310), indicating lower priority in the decision-making process. This prioritization reflects a focus

on sustainability and resource availability.

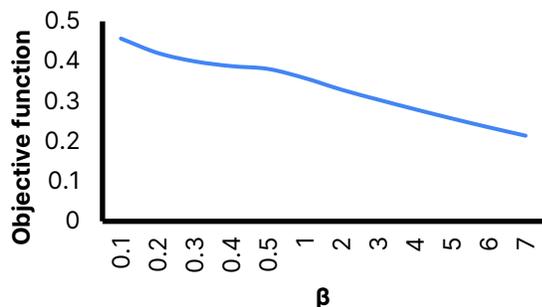


Figure 2: Objective function with varying β

Analysis of the performance of alternatives

The overall performance of each alternative S_i was assessed using the SECA model with normalized data and criteria-specific β values. The rankings, aligned with the original pathway database (e.g., S1 correspond to "SMR with CCS"), enabled the identification of the most promising pathways based on the three selected criteria.

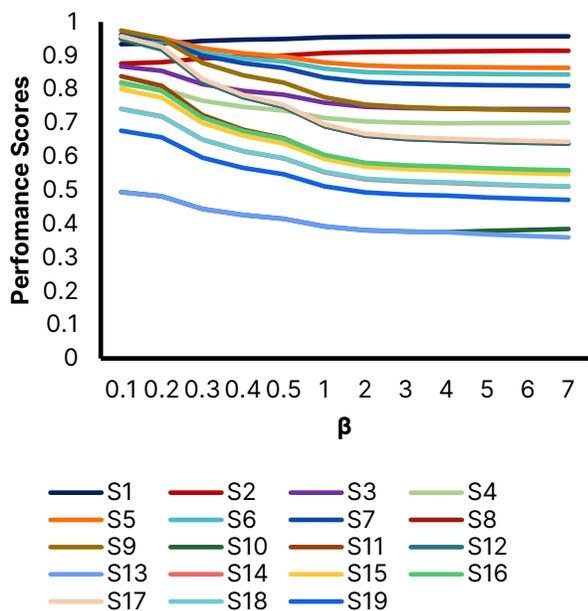


Figure 3: Variations in the performance scores related to β

Figure 3 provides a graphical representation of performance scores, offering a clear visual understanding of pathway performance and trends for informed decision-making. Rankings were determined based on S_i , with the highest score indicating superior performance. For $\beta \geq 3$, rankings remained stable (Spearman's correlation coefficient = 1), validating $\beta = 5$ as the optimal value for final rankings.

Among 19 pathways, steam reforming with CCS emerged as the top option with $S_i = 0.956$, balancing energy trilemma criteria due to reduced CO_2 emissions, technological maturity, and low raw material costs. This finding aligns with [21], who also identified its robustness using different criteria. Steam reforming without CCS ranked second ($S_i = 0.913$), followed by autothermal reforming with CCS ($S_i = 0.845$).

Indirect bio-photolysis and solar PV electrolysis were the least preferred pathways, with S_i values of = 0.448 and 0.400, respectively, primarily due to high economic costs. These results provide a clear framework for selecting the most effective and economically viable hydrogen production pathways, supporting energy sustainability objectives.

CONCLUSION

In conclusion, this study demonstrated the effectiveness of the SECA multi-criteria decision-making method in optimizing hydrogen production pathway selection within the South African energy landscape, addressing availability, affordability, and environmental sustainability. Using a multi-objective nonlinear programming model, SECA adjusted criteria weights and ranked alternatives, identifying environmental sustainability as the most critical factor, followed by availability and affordability. A β value of 5 provided the most stable results, with steam reforming with CCS emerging as the optimal pathway, followed by steam reforming without CCS and autothermal reforming with CCS, while indirect bio-photolysis and solar PV electrolysis ranked lowest due to economic constraints. These insights offer strategic guidance for aligning hydrogen production with sustainability and resource reliability in South Africa.

ACKNOWLEDGEMENTS

Financial support from the National Research Foundation is gratefully acknowledged.

REFERENCES

1. DOE. The South African Energy Sector Report (2019).
2. U.S Energy Information Administration. Country Analysis Executive Summary: South Africa. Independent Statistic & Analysis. 1-15 (2021).
3. PWC. COVID-19: What it means for the energy industry. PWC / United States, 1-10 (2020). <https://www.pwc.com/us/en/library/covid-19/coronavirus-energy-industry-impact.html>.
4. EIA. U.S. Energy Facts Explained. Department of Energy. 6 (2023). <https://www.eia.gov/energyexplained/us-energy->

- facts/.
5. Chih YK, Chen WH, You S, Hsu CH, Lin HP, Raza Naqvi S, Ashokkumar V. Statistical optimization of hydrogen production from bio-methanol steam reforming over Ni-Cu/Al₂O₃ catalysts. *Fuel*, 331,125691. (2023).
<https://doi.org/10.1016/j.fuel.2022.125691>.
 6. Abdel-Basset M, Gamal A, Chakraborty RK, Ryan MJ. Evaluation of sustainable hydrogen production options using an advanced hybrid MCDM approach: A case study. *International Journal of Hydrogen Energy*, 46,4567–4591 (2021).
<https://doi.org/10.1016/j.ijhydene.2020.10.232>.
 7. Pilavachi PA, Chatzipanagi AI, Spyropoulou AI. Evaluation of hydrogen production methods using the Analytic Hierarchy Process. *International Journal of Hydrogen Energy*, 34,5294–5303 (2009).
<https://doi.org/10.1016/j.ijhydene.2009.04.026>.
 8. Chung Y, Hong S, Kim J. Which of the technologies for producing hydrogen is the most prospective in Korea?: Evaluating the competitive priority of those in near-, mid-, and long-term. *Energy Policy*, 65, 115-125 (2014).
<https://doi.org/10.1016/j.enpol.2013.10.020>.
 9. Ren J, Manzardo A, Toniolo S, Scipioni A. Sustainability of hydrogen supply chain. Part I: Identification of critical criteria and cause-effect analysis for enhancing the sustainability using DEMATEL. *International Journal of Hydrogen Energy*, 38, 14159-14171 (2013).
<https://doi.org/10.1016/j.ijhydene.2013.08.126>.
 10. Ramazankhani ME, Mostafaeipour A, Hosseininasab H, Fakhrzad MB. Feasibility of geothermal power assisted hydrogen production in Iran. *International Journal of Hydrogen Energy*, 41,18351–18369 (2016).
<https://doi.org/10.1016/j.ijhydene.2016.08.150>.
 11. Acar C, Beskese A, Temur GT. Sustainability analysis of different hydrogen production options using hesitant fuzzy AHP. *International Journal of Hydrogen Energy*, 43, 18059–18076 (2018).
<https://doi.org/10.1016/j.ijhydene.2018.08.024>.
 12. Lin R, Lu S, Yang A, Shen W, Ren J. Multi-criteria sustainability assessment and decision-making framework for hydrogen pathways prioritization: An extended ELECTRE method under hybrid information. *International Journal of Hydrogen Energy*, 46, 13430–13445 (2021).
<https://doi.org/10.1016/j.ijhydene.2021.01.018>.
 13. Seker S, Aydin N. Assessment of hydrogen production methods via integrated MCDM approach under uncertainty. *International Journal of Hydrogen Energy*, 47, 3171–3184 (2022).
<https://doi.org/10.1016/j.ijhydene.2021.07.232>.
 14. Keshavarz-Ghorabae M, Amiri M, Zavadskas EK, Turskis Z, Antucheviciene J. Simultaneous evaluation of criteria and alternatives (SECA) for multi-criteria decision-making. *Informatica (Netherlands)*, 29, 265–280 (2018).
<https://doi.org/10.15388/Informatica.2018.167>.
 15. Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, 67, 597–611 (2017).
<https://doi.org/10.1016/j.rser.2016.09.044>.
 16. Mehmeti A, Angelis-Dimakis A, Arampatzis G, McPhail S J, Ulgiati S. Life cycle assessment and water footprint of hydrogen production methods: From conventional to emerging technologies. *Environments - MDPI*, 5, 1-19 (2018)
<https://doi.org/10.3390/environments5020024>.
 17. Acar C, Dincer I. Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *International Journal of Hydrogen Energy*, 39, 1-12, (2014).
<https://doi.org/10.1016/j.ijhydene.2013.10.060>.
 18. Al-Qahtani A, Parkinson B, Hellgardt K, Shah N, Guillen-Gosalbez G. Uncovering the true cost of hydrogen production routes using life cycle monetisation. *Applied Energy*, 281, 115958 (2021).
<https://doi.org/10.1016/j.apenergy.2020.115958>.
 19. Bhandari R, Trudewind C A, Zapp P. Life cycle assessment of hydrogen production via electrolysis - A review. *Journal of Cleaner Production*, 85, 151-163, (2014).
<https://doi.org/10.1016/j.jclepro.2013.07.048>.
 20. DTIC. Green Hydrogen Commercialisation Strategy For South Africa: Executive Summary. 1-26 (2022).
 21. Chau K, Djire A, Khan F. Review and analysis of the hydrogen production technologies from a safety perspective. *International Journal of Hydrogen Energy*, 47, 13990–14007 (2022).
<https://doi.org/10.1016/j.ijhydene.2022.02.127>.

© 2025 by the authors. Licensed to PSEcommunity.org and PSE Press. This is an open access article under the creative commons CC-BY-SA licensing terms. Credit must be given to creator and adaptations must be shared under the same terms. See <https://creativecommons.org/licenses/by-sa/4.0/>

