

# Hydrogen-based Energy Transition for Decarbonisation of Eco-Industrial Park Using a Modified Carbon Emission Pinch Analysis (CEPA)

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Carbon Emission Pinch Analysis (CEPA) is a planning tool that addresses carbon constraints across various sectors. This research paper introduces a modified CEPA approach, integrated with the Analytic Hierarchy Process (AHP), to support the decarbonization of multi-energy systems in industrial parks through hydrogen fuel switching. The AHP framework enables prioritising energy sources based on key criteria, providing a structured method for replacing conventional fuels with hydrogen and identifying sustainable pathways for hydrogen production. The approach is demonstrated by plotting a new fuel-switched supply composite curve within the CEPA curves. In the case study, to achieve 20 % GHG reduction target, emissions are reduced to 1.897 MtCO<sub>2</sub>eq by integrating 104.13 ktO<sub>2</sub> of green hydrogen. This is achieved by displacing the grey hydrogen supply, replacing natural gas in thermal applications and reducing dependence on the national electricity grid. Overall, the modified CEPA demonstrates the potential of hydrogen fuel switching to reduce emissions significantly and offers a quantifiable tool for sustainable energy planning in industrial parks with complex energy systems.

## 1. Introduction

Industrial processes and product use contributed as the second most significant greenhouse gas (GHG) emission, accounting for 10 %, equivalent to 32,853.80 GgCO<sub>2</sub>-eq in 2019 (NRECC, 2022). Hydrogen as a new energy medium remains largely untapped despite its widespread use in a few industrial processes (Hydrogen Council, 2020). The industry's hydrogen uptake trends, whether for energy or non-energy usage, are currently concentrated more on traditional applications, such as refining and the chemical sector. With Malaysia's target to achieve Net-Zero Emissions by 2050, there is a need to explore alternative, sustainable energy solutions while meeting the rising energy demand. Utilising hydrogen as an energy source can accelerate decarbonisation and help transform industrial parks into Eco-Industrial Parks. Therefore, evaluating the impact of low-carbon hydrogen in the industrial sector is crucial for monitoring progress in reducing GHG emissions (Incer-Valvede et al., 2023).

Carbon Emission Pinch Analysis (CEPA) is a key tool for evaluating decarbonisation targets within carbon limits (Tan and Foo, 2007). The versatility of the CEPA method is also demonstrated when evaluating the carbon emissions reduction strategies for the electricity sector in New Zealand, as the study emphasised the country's rapid expansion of geothermal energy for meeting long-term carbon reduction goals (Atkins et al., 2010). Similarly, CEPA has been applied to analyse long-term strategies for electric power generation in the United Kingdom by 2050 (Cosutta et al., 2020) and adapted for the decarbonisation study of the transportation sector in Iskandar Malaysia (Ramli et al., 2019). While these studies highlight CEPA applications in various sectors, a notable gap exists in integrating economic considerations. This gap has been acknowledged as a limitation of

the tool, as it does not fully account for the economic impacts of implementing carbon reduction strategies. Several studies have modified the CEPA method to incorporate economic criteria, addressing this limitation by integrating input-output analysis (IOA), thereby allowing for a more holistic view of energy supply prioritisation and its broader impacts (Tan et al., 2018). To strengthen the application of CEPA, key analyses, including return on investment and water footprint, have been incorporated to evaluate the sustainability of energy strategies in the national power sector (Lim et al., 2018). Additionally, a sensitivity analysis was conducted to evaluate the effectiveness of the CEPA framework in hydrogen energy systems, utilising the Modified Extended Power Pinch Analysis (MEPoPA) method to assess power losses and system sizing within hydrogen-based energy systems (Iman et al., 2016).

The literature findings indicate that CEPA is a versatile and valuable tool for analysing carbon emission reductions across various sectors and developing long-term decarbonisation strategies. The primary strength of the method lies in its ability to visualise and identify the pinch points where carbon emissions can be effectively reduced through various technological and strategic interventions. The method typically focuses on analysing a single type of energy source and plotting carbon emission factors to identify optimal carbon reduction strategies. However, a recurring gap in existing studies is the lack of integration of multifaceted criteria at the industry park level, such as economic, industry value chain, and multi-energy systems. While CEPA effectively identifies low-carbon technologies, it does not provide clear guidance on prioritising energy sources based on broader criteria and the interdependencies of multi-sector systems, rather than GHG emission order. Research on Multiple Objectives Pinch Analysis (MOPA) was conducted to address resource conservation involving two objectives, balancing cost and resource quality using the pinch method, specifically for the power sector (Priya and Bandyopadhyay, 2017). The adoption of the CEPA method for carbon planning in industrial parks remains limited due to its inapplicability to the micro-level operations of demand and supply. This research proposes an enhanced version of the CEPA methodology to incorporate the Analytic Hierarchy Process (AHP) approaches, enabling better decision-making when evaluating complex energy transition systems. This highlights the opportunity to integrate CEPA with AHP for improved analysis (Andiappan et al., 2019). The proposed methodology in this study is also modified to accommodate the industrial park's multi-energy systems, including hydrogen, thermal, and power supply and demand. This provides a more comprehensive assessment for targeting minimal carbon-emission energy transition options towards hydrogen energy, considering various types of energy supply and demand in the eco-industrial park.

## 2. Methodology

A modified methodology for CEPA curves, which restructures demand and supply for multi-energy systems in industrial parks, is developed by integrating AHP to prioritise energy supply options based on criteria. This approach guides the replacement of conventional fuels with hydrogen and the selection of hydrogen production methods. The analysis will be demonstrated through several scenarios optimising low-carbon hydrogen energy transitions in industrial settings.

### 2.1 Step 1: Data Collection and Processing

- i. Obtain the GHG emission factors for each energy medium and supply type from the literature and standardise to the unit of  $tCO_2eq/ktoe$ , considering the conversion efficiency shown in Table 1.
- ii. For demand curve data, identify the energy demand based on different energy mediums, such as hydrogen, thermal, and electricity, with their load in the industrial park in the unit of ktoe. Then, sequence the energy medium based on their demand load (Column 1-3, Table 2(a)). The energy loss or reserve margin required for thermal energy and electricity is explicitly considered in the demand data at 10 % and 15 % (Rows 4 and 6, Table 2(a)).
- iii. For supply curve data, following the energy medium sequence, identify the energy supply types that can supply the energy medium, with their supply load in the unit of ktoe. When there are multiple supply types for the medium, sequence them according to their emission factor (Columns 1-3, Table 2(b)).

Table 2 provides an example of a dataset based on 2018 data, including supply and demand loads (Energy Commission, 2020), as well as specific emission factors.

### 2.2 Step 2: Construct the Modified CEPA Supply and Demand Curves

- i. Calculate total GHG emissions by multiplying each load by its emission factor (Column 5, Table 2).
- ii. Calculate the cumulative emissions and energy loads for the demand curve data (Part (a), Table 2) for energy types with the highest emission factor to the lowest, with zero emissions and load assumed to initiate the cumulation calculation.
- iii. Calculate the supply curve's cumulative energy load and emission (Part (b), Table 2) based on the energy types with the highest emission factor to the lowest. New rows between energy medium types are added

to the supply curve table (Rows 3, 6 and 11, part (b), Table 2). These rows align with the cumulative energy load and emission values for each type of energy medium in the supply curve to the same value as in the cumulative on the demand curve. These rows are important for plotting the curves to benchmark the excess/deficit energy supply and over/below carbon emission compared to demand.

*Table 1: Data tabulation for GHG emissions factors for each energy type.*

Category	Energy Medium/Supply Types	GHG Emission Factor (tCO <sub>2</sub> eq/ ktoe)	Reference
Energy Demand	Hydrogen	1,846.03	(Quintel, 2025)
	Thermal	2,632.93	(Climatiq, 2025)
	Electricity	4,743.50	(Noussan et al., 2024)
Energy Supply Source	Solar	640.99	(Cosutta et al., 2020)
	Hydrogen	1,846.03	(Quintel, 2025)
	Natural Gas	2,337.07	(Ramli, 2019)
	Biodiesel	2,964.22	(GHG Protocol, 2025)
	Biomass	4,605.42	(Bruckner et al., 2014)
	National Grid	10,345.63	(MEIH, 2018)

*Table 2: Data tabulation for energy supply scenarios.*

Energy Medium	Energy Supply Types	Energy (ktoe)	Emission Factor (tCO <sub>2</sub> eq/ ktoe)	Total Emission (tCO <sub>2</sub> eq)	Cumulative Energy (ktoe)	Cumulative Emissions (tCO <sub>2</sub> eq)								
(a) Demand Curve														
					0.00	0.00								
Hydrogen		26.02	1,846.03	48,033.70	26.02	48,033.70								
Thermal		130.44	2,632.93	343,439.39	156.46	391,473.09								
Thermal (losses/reserve)		13.04			169.50	391,473.09								
Electricity		391.30	4,743.50	1,856,131.55	547.76	2,247,604.64								
Electricity (losses/reserve)		58.70			606.46	2,247,604.64								
(b) Supply Curve														
					0.00	0.00								
Hydrogen	Grey Hydrogen	29.14	1,846.03	53,793.31	29.14	53,793.31								
					26.02	48,033.70								
Thermal	Natural Gas	142.43	2,337.07	332,868.88	171.57	386,662.19								
					Biodiesel	35.61	2,964.22	105,555.87	207.18	492,218.07				
									169.50	391,473.09				
Electricity	Solar	64.10	640.99	41,087.46	271.28	533,305.53								
					Natural Gas	284.87	2,337.07	665,761.13	556.15	1,199,066.66				
									Biomass	42.73	4,605.42	196,789.60	598.88	1,395,856.26
													National Grid	142.43
					606.46	2,247,604.64								

- iv. Plot the source and demand curves with the cumulative emissions (y-axis) and the cumulative energy load (x-axis). An example based on Table 2 is plotted in Figure 1.
- v. The overlapping supply curve on the load (x-axis) represents the excess supply of the earlier energy medium, which could be optimised or repurposed as another energy medium.

### 2.3 Step 3: AHP Analysis to Prioritise the Transition to Hydrogen Energy

- i. The AHP involves structured steps to support decision making. First, the decision problem is defined, including identifying the primary goal, criteria, and alternatives. Next, a pre-analysis is done to ensure all criteria are clearly understood.
- ii. The AHP analysis is conducted based on criteria related to supply chain factors (generation, transmission, distribution, storage, and utilisation) and the enablers (funding, infrastructure, regulation, skills, and technology) to support hydrogen fuel switching in industrial parks. The input obtained is based on the secondary report, literature information, and stakeholder engagement, including a workshop.
- iii. Then, a pairwise comparison is carried out, where each criterion is compared with others to assess its relative importance. These comparisons are organised into a matrix and then normalised to make the

values comparable. The next step is to calculate the weights (or priorities) for each criterion based on the normalised values. A consistency check is also performed to verify the reliability of the comparisons. The overall scores are used to rank the alternatives, helping identify the best option.

#### 2.4 Step 4: Fuel-Switching Strategy using Hydrogen for Carbon Emission Reduction

The fuel-switching strategies are decided based on observing the CEPA curves for the energy system in the industrial park, and the energy to be switched or supplied is decided based on the AHP ranking results. A new fuel-switched supply curve is plotted on the CEPA curve based on an improved situation to verify the proposed improvements. The fuel-switching strategy could be decided based on the following heuristics:

- i. To match the supply and demand load for each type of energy medium:
  - a. When there is an excess in energy supply (overlapping on the supply curve), the production of the energy supply type with the lowest priority in the AHP ranking should be reduced.

When the energy supply is deficient (represented by the horizontal line on the supply curve), producing the hydrogen energy supply type with the highest priority in the AHP ranking should be prioritised.

- ii. To achieve the targeted emission for each type of energy medium:
  - a. When the cumulative supply's emission is higher than demand, the fuel switching initiative must be conducted to replace the supply with the lowest priority with the preferred supply type in the AHP ranking.
  - b. When the supply emission is lower than the demand, this is an ideal case in which no corrective actions are required.

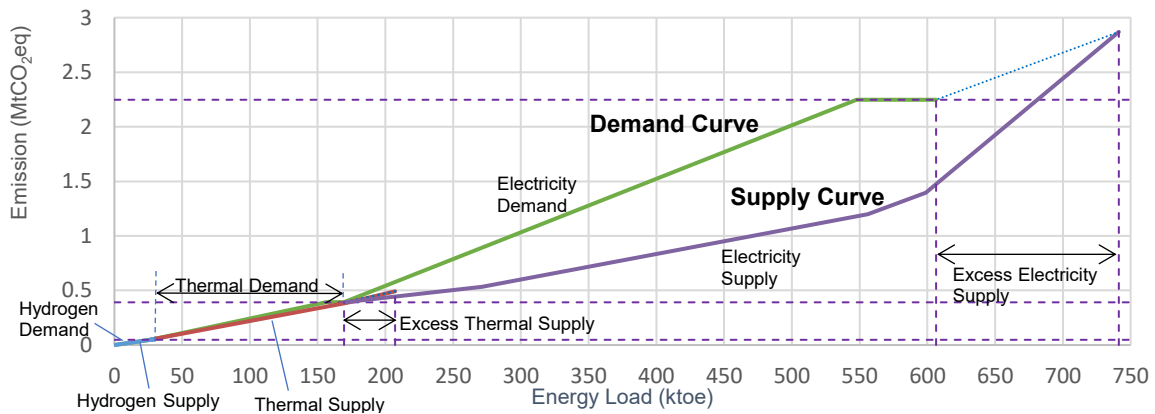


Figure 1: Modified CEPA supply and demand curves with excess energy supply.

### 3. Results and Discussion

Figure 1 presents the modified CEPA diagram, where the purple (electricity supply) and red (thermal supply) lines both rise above the green line (demand) threshold, indicating excess supply conditions. For thermal energy, the demand is 169.50 ktoe, while the supply reaches 207.18 ktoe, highlighting a surplus that can be optimised. Similarly, electricity energy shows a demand of 619.50 ktoe against a supply of 741.31 ktoe, suggesting an oversupply and the opportunity to reduce energy input or replace it with a lower-emission source. The final AHP ranking process in Table 3 is arranged from highest to lowest score (Abd Aziz et al., 2024), indicating that the most selected energy source to be replaced is the energy coming from the national grid due to its high emission source. The most selected hydrogen production technology is green hydrogen, due to its lowest emission source. Green hydrogen energy sources can be introduced for two purposes, depending on the situation: to provide a new supply in a deficit situation or to replace an excess of the existing conventional energy source.

Fuel switching can be employed in this case to reduce the excess energy supply and its associated carbon emissions, as shown in Figure 1. The fuel switching could be done according to the energy source priority list generated using the AHP method. Based on the AHP result, natural gas thermal generation should be reduced to avoid an excess supply of thermal energy. To achieve the reduction in emissions while meeting the demand, natural gas is reduced from 142.43 ktoe to 130.56 ktoe, and biodiesel-based thermal energy supply is also reduced to 12.93 ktoe. For the electricity side, the national grid supply is reduced by 40.51 ktoe and the natural gas-based electricity supply is reduced by 43.64 ktoe, to meet the energy demand and emissions. Figure 2(a) shows the CEPA graphs for the fuel-switched scenario, highlighting the energy reduction and green hydrogen integration, which result in total GHG emissions of 2.248 MtCO<sub>2</sub>eq.

Table 3: Final AHP ranking result.

Preferred energy source (thermal and electricity)		Preferred hydrogen production technology	
Alternatives	Ranking	Alternatives	Ranking
Large Scale Solar	1	Green Hydrogen (Solar-based)	1
Biodiesel	2	Grey Hydrogen	2
Biomass	3	Blue Hydrogen	3
Natural Gas	4	Turquoise Hydrogen	4
National Grid	5	Orange Hydrogen	5

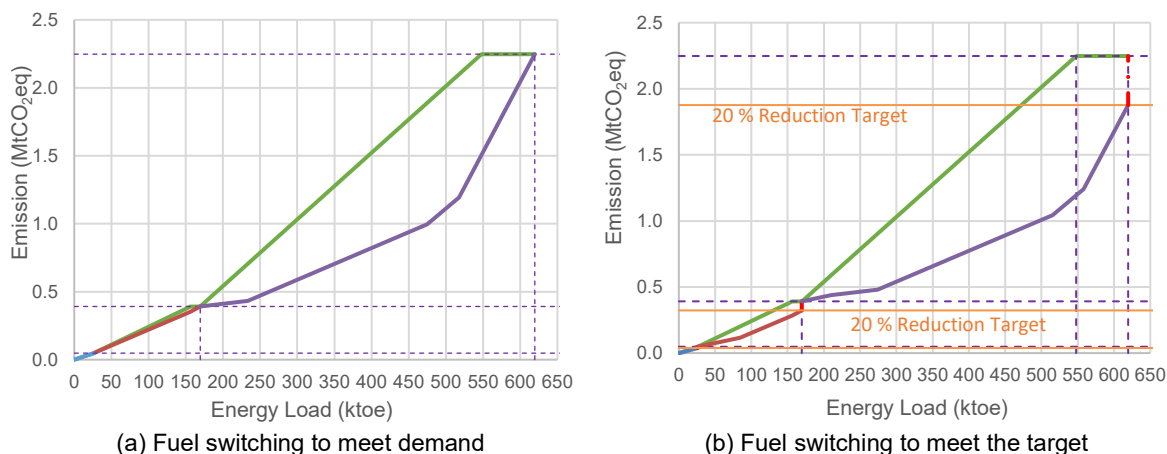


Figure 2: Fuel Switching Modified CEPA Supply and Demand Curves

To demonstrate hydrogen-based fuel switching, the case study is further analysed to achieve the target of a 20 % reduction in GHG emissions, from 2.248 MtCO<sub>2</sub>eq to 1.798 MtCO<sub>2</sub>eq. The reduction target is cascaded down for all energy mediums in the industrial park, which are 371,226.31 MtCO<sub>2</sub>eq, 68,687.88 MtCO<sub>2</sub>eq, and 9,606.74 MtCO<sub>2</sub>eq for electricity, thermal and hydrogen. Given its low-emission profile and strong performance across multiple evaluation criteria, green hydrogen is prioritised as the replacement option. The required volume of green hydrogen is determined through a technical calculation approach, which ensures that total electricity demand is met while achieving the targeted emissions reduction. The results indicate that a total of 104.13 ktoe of green hydrogen is required for integration, replacing the national grid's electricity supply and natural gas-based thermal and grey hydrogen supplies. The results are illustrated in the modified CEPA supply and demand curves in Figure 2(b).

#### 4. Conclusions

The oversupply of energy can lead to suboptimal performance of the industrial park, resulting to high GHG emissions. This issue must be addressed by aligning energy supply with dynamic demand conditions, while also accounting for system losses and reserve margins. Such alignment is essential for effective decarbonisation strategies within a multi-energy system framework. A systematic approach is applied using the AHP with a CEPA method to benchmark and fuel-switch the multi-energy supply, optimising the energy supply and minimising emissions. Instead of relying solely on the emission factors for each energy supply, the AHP prioritises energy sources for fuel substitution. The study also considered hydrogen-based fuel switching as a lower-emission alternative, specifically green hydrogen, as part of fuel-switching strategies. This approach is demonstrated through a case study, where emissions are reduced to 1.897 MtCO<sub>2</sub>eq (20 % reduction) by integrating 104.13 ktoe of green hydrogen. This involves replacing the grey hydrogen supply, displacing natural gas for thermal energy and reducing reliance on the national grid for electricity. Future research will utilise linear programming for a more in-depth analysis. This method will help industrial park operators and policymakers plan the shift to hydrogen energy for decarbonisation. Some of the research limitations include the work's focus on conventional energy sources for thermal and electrical applications, as well as general hydrogen production technologies, for a fuel-switching strategy. The evaluation of carbon reduction impact is based on assumed energy generation for steady-state planning at the industrial park. Further research could focus on incorporating those elements to guide the hydrogen energy transition of the industrial park.

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