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# Risk, flexibility, and investment in Fischer–Tropsch fuels: Insights from real options analysis

Mahsa Mehrara [a,*], Jonas Zetterholm [b], Andrea Toffolo [a], Elisabeth Wetterlund [a,c]

[a] Luleå University of Technology, Department of Engineering Sciences and Mathematics, Energy Science Division, Luleå, Sweden
[b] RISE Research Institutes of Sweden, Energy System Analysis, Gothenburg, Sweden
[c] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

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ABSTRACT

The transition to sustainable transportation fuels requires investment in emerging biomass-to-liquid production pathways under uncertain market and policy conditions. This study applies a real options analysis framework to evaluate the economic viability and timing of investments in biomass- and power-to-liquid pathways by identifying conditions where an investor should invest, defer, or abandon investments. The analysis is conducted for Sweden, reflected by its large biomass base and well-developed forest industry and ambitious defossilization policies. Results indicate that large price gaps between feedstock and produced fuels are not by themselves sufficient to trigger investment; in volatile markets, investors may still defer because the option to wait has economic value. Thus, even at identical price levels across scenarios, outcomes range from commitment to inaction depending on volatility. Moreover, when investments do occur, they are consistently deferred until the final year of the investment window. While modest subsidies may suffice under stable price conditions, volatile markets with high drifts require significantly greater support to counteract the incentive to defer investments. Electricity cost structures and carbon pricing must be targeted to support the transition toward electrified fuel production pathways. The insights from this study can inform the design of policy instruments that align investor incentives with global transition goals.

## 1. Introduction

Renewable liquid fuels play a crucial role in achieving sustainability targets of the transport sector and are central to achieving the EU's climate and energy objectives as outlined in the Fit for 55 package. Beyond their environmental benefits, these fuels can contribute significantly to energy security and industrial resilience. In the context of the Clean Industrial Deal (Clean Industrial Deal - European Commission, 2025), ensuring secure and sustainable transport fuel supply is not only an economic requirement but a strategic imperative, vital for reducing dependence on imports, supporting the circular economy, and meeting long-term climate commitments.

Significant investments have been directed toward mature renewable fuel technologies such as HEFA/HVO (hydrotreated esters and fatty acids/hydrotreated vegetable oil), which have achieved commercial status but rely on limited lipid-based feedstocks and therefore lack long-term scalability (Brandt et al., 2022). In contrast, technologies capable of processing lignocellulosic biomass offer great potential to unlock abundant resources originating from residue streams (e.g., forestry operations, forest industry) but remain largely unrealized (van Dyk, 2024; Segers et al., 2024; Pascual et al., 2022). Capital-intensive energy technologies face multiple, layered risks: price volatility in feedstocks and products, shifting policy frameworks, long lead times, and technological uncertainties (Santos et al., 2014). These conditions are particularly acute for infrastructure-heavy technologies like biofuel plants (International Renewable Energy Agency, 2019), which typically involve high up-front investment, long operating lifetimes, and limited ability to repurpose capital assets (Emhjellen and Alaouze, 2003). Investors must also operate under significant uncertainty, particularly in liberalized energy markets, where price volatility and policy shifts are common (Pindyck, 1991). Altogether, these uncertainties cause risks that complicate investor decisions and hinder large-scale deployment. In biofuel production, electricity can be used for direct (e.g., for heating or conversion) or indirect (supplementing with $H_2$ produced via water electrolysis) electrification, which can increase fuel yields without proportional increases in biomass demand (Dossow et al., 2024; Mesfun et al., 2023). Fully electrified pathways (power-to-liquid, PtL) can eliminate biomass use altogether,

* Corresponding author.
*E-mail address:* mahsa.mehrara@ltu.se (M. Mehrara).

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instead using captured $CO_2$ as feedstock, which can enhance feedstock flexibility and resilience to biomass supply disruptions (Staples et al., 2021; Rojas-Michaga et al., 2023). When based on renewable electricity and eligible $CO_2$, such pathways qualify as renewable fuels of non-biological origin (RFNBOs) under EU regulations, granting access to dedicated markets and compliance incentives. A key product is electro-sustainable aviation fuel (eSAF), positioning this pathway as a critical link between renewable energy and aviation defossilization (Song and Zhao, 2024).

Altogether, this complex uncertainty landscape causes traditional tools for investment analysis, such as discounted cash flow, to often fall short due to their reliance on fixed assumptions and static decision-making frameworks (Pivoriene, 2017). These models fail to account for the opportunity value of deferring, abandoning, or expanding in response to future market signals. By incorporating the ability to account for uncertainty, Brach (2003) demonstrate how conventional methods can account for risks in a probabilistic sense, but neglect the value of managerial flexibility which can preserve and even enhance the value of the project.

Real options analysis (ROA) provides a framework for capturing the option-like characteristics of investment projects, such as the ability to defer, expand, or abandon depending on how external conditions evolve (Regan et al., 2015; Amram and Kulatilaka, 1999). Real options, as the name implies, use options theory to evaluate physical or real assets, as opposed to financial assets (Mun, 2002). This is particularly useful in renewable energy systems, where technology learning, policy volatility, and commodity price fluctuations can substantially alter project profitability over time. Compared to discounted cash flow, ROA better reflects the real-world decision-making process of investors facing deep uncertainty and strategic flexibility.

Kozlova (2017) provides a comprehensive review of ROA applications within renewable energy investments, though it is now somewhat dated. More recent works have applied ROA across a wide range of renewable energy sectors. In power generation, wind and solar investments have been analyzed using ROA to capture the strategic value of flexibility and learning (Loncar et al., 2017; Gazheli and van den Bergh, 2018). Other studies have explored policy-driven investments, such as PV projects under renewable portfolio standards (Bangjun et al., 2022). Applications of ROA for studying carbon capture and storage (CCS) (Agaton, 2021), geothermal energy (Chen et al., 2019), hydrogen (Pomaska and Acciaro, 2022), and biofuels (Zetterholm et al., 2022) have emphasized the importance of modeling market and policy uncertainty in shaping the timing and scale of investment. However, most ROA applications in the biofuel sector focus on lipid-based pathways, despite their limited resource availability, and the literature applying ROA to lignocellulosic-based biofuels remains notably scarce. Prior ROA of investments in biofuel production has shown that price uncertainty creates significant entry premium effects that deter investment despite apparent profitability (McCarty and Sesmero, 2015). Additionally, investment and market risks constitute the primary obstacles to commercialization in these pathways (Zetterholm et al., 2022). Altogether, these studies underscore the growing relevance of ROA in energy investment planning in uncertain, policy-sensitive, and infrastructure-intensive technologies.

Within this broader literature, the application of ROA in the biofuel domain has, to date, been primarily focused on ethanol (Cisneros-López et al., 2020; Sharma et al., 2011) or fuels within the biodiesel / HVO/HEFA area (Zhao et al., 2021; Brandão et al., 2013; Kern et al., 2017), which are the primary biofuels in the EU market. Conversely, ROA applications that cover biomass-to-liquid (BtL) systems based on lignocellulosic feedstocks remain relatively limited, with a few exceptions (Zetterholm et al., 2022; McCarty and Sesmero, 2015). Similarly, existing ROA applications for PtL are scarce (Lee et al., 2023; Fabianek et al., 2024) and remain largely absent from the broader scientific literature. Both BtL and PtL systems are, however, especially compelling as pathways for defossilizing the transport sector, given the possibility to produce fuels compatible with existing fuel infrastructure, such as Fischer–Tropsch liquids (FTL), methanol, and synthetic natural gas. In particular, Fischer–Tropsch synthesis, integrated either with biomass gasification (BtL) or with water electrolysis (PtL), has gained increasing attention as a route for producing both road transport fuels and aviation fuel, commonly referred to in the literature as sustainable aviation fuel (SAF) (Neves et al., 2020; Nyholm et al., 2025; Sánchez et al., 2022). Gasification-based BtL processes benefit significantly from partial (PBtL) or full electrification, as shown previously by, e.g., Mehrara et al. (2025), Dossow et al. (2024). Real options analysis is particularly well-suited for evaluating BtL, PBtL, and PtL pathways, given their early commercialization stage, long asset lifetimes, high sunk costs, and exposure to multiple uncertainties.

In previous work, we have performed process simulations and techno-economic analyses of P/BtL pathways (Mehrara et al., 2025), as well as developed a ROA framework for studying investment decisions related to forest-based fuels (Zetterholm et al., 2022). The present study combines these two elements, integrating engineering and cost data from the former with a further developed ROA framework from the latter, to evaluate investment timing for P/BtL systems under market uncertainty. Within the ROA framework, market evolution of commodity prices is modeled through a geometric Brownian motion (GBM). The approach enables examination of the role of market uncertainties on economically rational investment timing, while accounting for the managerial option of deferring the investment decision. This study specifically evaluates how relative price dynamics affect the timing and value of P/BtL investments, showing how shifts in biomass, $CO_2$, and electricity prices relative to fuel values shape investor behavior. By examining the interaction between cost signals, policy dynamics, and investment timing, we aim to contribute to more nuanced techno-economic assessments and provide guidance for targeted policy design in support of advanced renewable fuels. Lastly, the subsidy levels needed to trigger timely investments are estimated.

The focus is set on the market in Sweden due to its abundant forest biomass resources, ambitious climate targets, and well-established bioenergy infrastructure. The Swedish transport sector faces strict defossilization requirements under both national policy frameworks and EU directives, making it a relevant case for evaluating investment dynamics in emerging P/BtL pathways.

## 2. Methodology and input data

A stepwise methodology was developed to quantify how market volatility influences investment decisions in the studied technologies. First, process models for five P/BtL pathways were developed to estimate fixed capital and operating costs for a set of fuel production cases. Second, price trajectories for key commodities were generated using GBM to capture market development and uncertainty. Third, to account for interdependencies in commodity price trajectories, a set of plausible market scenarios was constructed to represent different potential market conditions. Next, expected net present values (eNPVs) corresponding to each price trajectory were computed for each combination of fuel production case and market scenario, applying ROA to compare the eNPVs with the value of deferring at each decision point in the investment horizon. This comparison enabled identification of the simulation runs in which investments were triggered or indefinitely abandoned.

To further explore the economic barriers to early investment, the difference in eNPV between early and late investment windows was translated into a required unit subsidy ( €/MWh) that would compensate for the value of the waiting option. This subsidy metric reflects the minimum support needed to equalize the profitability of early and deferred investment, providing an interpretable indicator for the required policy intervention.

The overall methodological approach is illustrated in Fig. 1, which describes the step-by-step process applied.

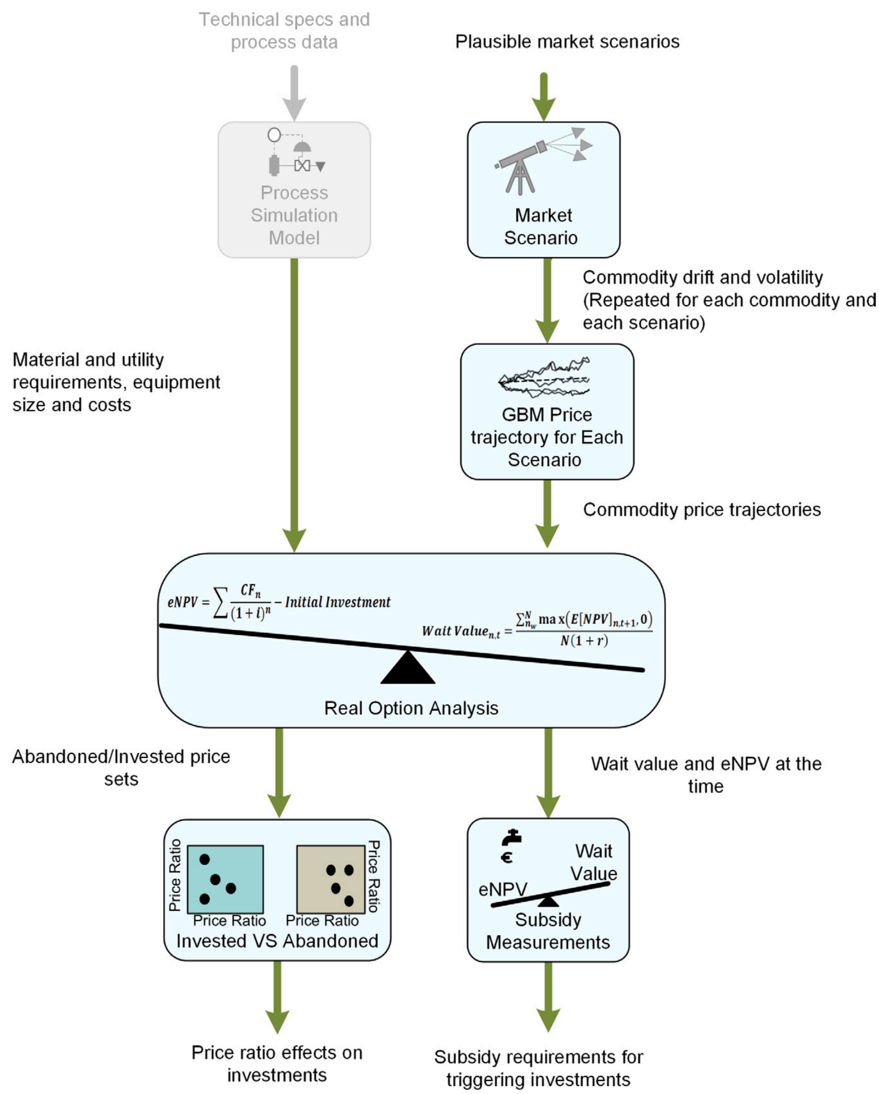


**Fig. 1.** Overview of the methodological steps used to evaluate investment behavior across market scenarios. The gray box and arrow represent the previously performed process simulation of the pathways available in Mehrara et al. (2025).

### *2.1. Technology input data*

In our previous work (Mehrara et al., 2025), we investigated five BtL and PtL fuel production pathways with varying degrees of electrification and carbon capture integration. These pathways formed the basis for the real options evaluation framework presented in this study.

Table 1 presents the details of each pathway at the process level. The baseline *BtL* involves biomass gasification, syngas conditioning, and final conversion through Fischer–Tropsch synthesis. *BtL-CCS* adds a CCS unit which separates $CO_2$ from the acid gas removal (AGR) unit by absorption of monoethanolamine, for permanent storage. *PBtL-CCS* introduces partial electrification through a proton exchange membrane (PEM) electrolyzer supplying $H_2$, thereby eliminating the water-gas shift (WGS) step and allowing a more optimized $H_2$/CO ratio for FT synthesis; CCS is maintained. *PBtL* increases the degree of electrification by increasing the electrolyzer and integrating a reverse water-gas shift (RWGS) reactor to convert $H_2$ and captured $CO_2$ into CO, thus improving carbon utilization. Finally, the *PtL* pathway eliminates biomass entirely by using external biogenic $CO_2$ and electricity. $H_2$ from PEM electrolysis and $CO_2$ are converted to syngas through RWGS, which is then processed in the FT reactor, removing the need for biomass gasification, tar reforming, and AGR.

Table 2 summarizes key energy and mass data for each pathway, reflecting the primary energy and material flows needed to produce FTL. This data served as the foundation for analyzing how commodity price fluctuations impact the economic performance of each pathway.

Table 3 presents the set of fuel production cases assessed in this study, applying the five technological pathways with varying degrees of electrification and carbon capture integration (see Section 2.1) and with different market variations. The *-CCS* suffix denotes cases that include CCS, enabling $CO_2$ storage revenues. Since several technology pathways incorporate $H_2$ produced via electrolysis, it is essential to account for how market classification and value attribution apply to renewable fuels. In particular, cases with the *-e* suffix introduce a fractional allocation approach to address eligibility for RFNBO classification. In this approach, the share of fuel considered RFNBO-compliant is determined by the proportion of $H_2$ derived from electrolysis as per the RED recommendations (Research Institutes of Sweden (RISE), 2025). This ensures that only the electrolytic $H_2$-linked portion of the final fuel output is subject to RFNBO market pricing.

### *2.2. Commodity price simulation and uncertainty*

Future prices were assumed to follow a geometric Brownian motion (GBM), which is characterized by two key parameters: the drift, which

**Table 1**
Unit-level process components across studied technology pathways.

| Process unit | BtL | BtL-CCS | PBtL-CCS | PBtL | PtL |
|---|---|---|---|---|---|
| Pretreatment & Gasification | × | × | × | × | – |
| ASU[a] | × | × | × | – | – |
| Gas Cleaning | × | × | × | × | – |
| SMR[b] | × | × | × | × | ×[c] |
| (R)WGS[d] | × | × | × | × | – |
| PEM | – | – | × | × | × |
| AGR[e] | × | × | × | × | – |
| FT Synthesis | × | × | × | × | × |
| CCS | – | × | × | – | – |
| Condensing Turbine Steam Cycle | × | × | × | × | – |

[a] Air Separation Unit.
[b] Steam Methane Reformer.
[c] Electrified SMR.
[d] (Reversed) Water Gas Shift.
[e] Acid Gas Removal.

**Table 2**
Energy and mass flows for the studied technology pathways. Negative values correspond to inputs and positive values correspond to output flows. For details, see Mehrara et al. (2025).

| Flow type | BtL | BtL-CCS | PBtL-CCS | PBtL | PtL |
|---|---|---|---|---|---|
| *Energy flows* (MW) | | | | | |
| Forest residues | −100 | −100 | −100 | −100 | – |
| Electricity | 2.42 | −5.34 | −33.0 | −85.2 | −126 |
| FTL | 56.3 | 56.3 | 78.7 | 111 | 56.5 |
| *Mass flows* (kg/s) | | | | | |
| Forest residues | −11.1 | −11.1 | −11.1 | −11.1 | – |
| Bio-$CO_2$ | 5.00[a] | 5.00[b] | 4.52[b] | – | −3.89 |
| FTL | 1.22 | 1.22 | 1.69 | 2.38 | 1.26 |

[a] $CO_2$ released to atmosphere.
[b] $CO_2$ stored in CCS.

represents the expected directional trend over time, and the volatility, which captures the degree of random fluctuation around that trend. In order to capture future market uncertainties, Monte Carlo simulations were used to simulate different price trajectories (1000 trajectories per price and scenario). Each trajectory was generated using an initial price $P_0$ and drift and volatility parameters according to the market scenario.

The model was implemented in Python, relying on NumPy and Pandas for data handling functionality and Seaborn for visualization.

**Drift assumptions.** The drift parameter $\mu$ reflects the expected long-term directional trend in price evolution, influenced by structural factors such as supply–demand balances, production cost developments, and policy support mechanisms. Lower drift values represent scenarios of market saturation or competition, leading to slower price growth. In contrast, higher drift values reflect a future with strong policy incentives, and increasing demand for sustainable fuels.

**Volatility assumptions.** The volatility parameter $\sigma$ captures the degree of uncertainty or fluctuation around the expected price trajectory. It reflects fluctuations due to supply chain disruptions, geopolitical instability, seasonal demand shifts, and speculative behavior. For fossil-based and conventional fuels, historical price data provide a solid empirical basis. For emerging fuels, such as FTL, there is no historical market data. To address this, we selected analogous fuel markets that already exhibit price dynamics comparable to conventional gasoline, and used them to estimate volatility.

**Price calculation.** The price in time step $t$ was calculated following the methods outlined by De Giovanni and Massabò (De Giovanni and Massabò, 2018):

$$P_t = P_{t-1}\,(1 + \mu\,dt + \sigma\,dW) \tag{1}$$

where $t$ is the current time step, $P$ the price, $\mu$ the drift, $\sigma$ the volatility, $dt$ the size of the time step, and $dW$ the increment of a standard Wiener process. A 10-year time horizon was selected for the investment decision analysis to reflect a realistic window within which capital-intensive biofuel facilities are expected to either commit to investment or abandon the opportunity. Moreover, price projections beyond a 10-year horizon become increasingly uncertain and speculative, particularly for emerging energy commodities such as synthetic fuels and $CO_2$ as fuel feedstock.

The expected price $P_t$ in a specific time step is given by Murto (2007):

$$E[P_t] = P_0\,e^{\mu t} \tag{2}$$

This represents exponential price development driven solely by the drift term, and forms the baseline over which stochastic effects are superimposed in the GBM formulation.

### 2.3. Commodity price inputs and market scenario design

Price simulations were carried out using the GBM-based equations outlined above. To ensure coherence among the independently simulated price trajectories generated using GBM, a set of three market scenarios was defined. Since GBM models each commodity price as an isolated stochastic process, a structured method was used to relate the price dynamics of electricity, biomass, $CO_2$, and fuel in a consistent manner. The scenarios thus applied predefined combinations of drift and volatility parameters across commodities, introducing plausible market evolutions.

For fuel products, two different markets were considered: *FTL* which represents fuels intended for the road transport fuel market and that can be produced via either of the studied pathways (BtL, PBtL or PtL). In addition, eSAF was considered, targeting the aviation sector via PtL conversion processes. To access this market, eSAF represents fuels produced via electrified pathways (PtL and PBtL) that comply with RFNBO standards. This distinction allowed us to capture the effect of entering the eSAF market through electrification, where price trajectories typically exhibit higher growth rates.

The *Stable* scenario is characterized by low drift and volatility for all commodities, representing a market with minimal policy pressure or transformation. The *Transition Pushed* scenario is defined by high drift and volatility, reflecting a future shaped by ambitious climate targets and active policy intervention. Finally, the *Asymmetric Electrification Focus* scenario is constructed to reflect divergent policy momentum across sectors, with high growth in electricity and $CO_2$ prices, but limited change in biomass prices.

These scenario definitions allowed the GBM-generated price trajectories to be combined into coherent market narratives suitable for the subsequent techno-economic assessment. The input parameters for the GBM simulations were determined from future price scenarios (setting volatility), and empirical price data (setting initial price, and drift).

**Table 3**
Defined fuel production technology pathways with applied market variations, and their corresponding fuel production case labels.

| Technology pathway | Fuel production case label | Case description |
|---|---|---|
| BtL | BtL | Biomass-to-liquid — fuel product assumed to follow the FTL market |
| BtL-CCS | BtL-CCS | Biomass-to-liquid with CCS — fuel product assumed to follow the FTL market |
| PBtL-CCS | PBtL-CCS | Power- and biomass-to-liquid with CCS — fuel product assumed to follow the FTL market |
| | PBtL-CCS-e | Power- and biomass-to-liquid with CCS — fuel product assumed to be partially allocated to FTL and eSAF markets, respectively |
| PBtL | PBtL | Maximum power- and biomass-to-liquid — end product assumed to follow the FTL market |
| | PBtL-e | Maximum power- and biomass-to-liquid — fuel product assumed to be partially allocated to FTL and eSAF markets, respectively |
| PtL | PtL | Power-to-liquid — fuel product assumed to follow the FTL market |
| | PtL-e | Power-to-liquid — fuel product assumed to follow the eSAF market |

**Table 4**
Initial prices ($P_0$) of each commodity. All scenarios assume the same initial price.

| Commodity | $P_0$ | Unit | Notes | Source |
|---|---|---|---|---|
| Biomass | 36 | €/MWh | Average price of biomass in 2024 | Swedish Energy Agency (2025) |
| Electricity | 51 | €/MWh | Average price of electricity in Sweden (bidding zone SE4) in 2024 | ENTSO-E (2025) |
| $CO_2$ | 64 | €/t $CO_2$ | Average price of EU-ETS in 2024 | European Energy Exchange (EEX) (2024) |
| FTL | 98 | €/MWh | Assuming market will evolve from no price premium compared to conventional fuel, based on FAME price average (2008–2022) | Refinitiv (2025) |
| eSAF | 98 | €/MWh | Assuming same as for FTL | |

The initial commodity prices, $P_0$, used in the analysis are shown in Table 4. Those were kept constant across all scenarios, as they reflect the market conditions at the time the study was conducted.

To determine the drift, $\mu$, for the simulated commodity prices, we assumed the expected future price in 2050 and derived the drift from Eq. (2). The expected future price of $CO_2$ was derived from the World Energy Outlook 2025 (World Energy Outlook, 2024), focusing on the European region or advanced economies with declared net zero pledges, depending on the scenario. For 2050, we set the expected price to the shadow price obtained from simulations using the TIMES Sweden model (Forsberg et al., 2024; Sandberg, 2022). The model simulations were carried out by an in-house expert in the TIMES framework, which set the resulting drift values summarized in Table 5.

To determine the volatility $\sigma$ for the simulated commodity prices, we relied on historical price data for each commodity where available, or for related commodities when necessary. For biomass, we used data from the Swedish market for district heating production, electricity was based on the Swedish electricity spot market, and $CO_2$ was derived from the EU-ETS prices. For FTL and eSAF, we derived the assumed volatilities from the market price for existing mature liquid fuels, using petrol and biodiesel as examples. Petrol represents a more mature and heavily traded commodity, whereas biodiesel, though also mature, has been subject to higher volatilities. These assumptions rely on FTL and eSAF becoming mature traded commodities, with volatility scenarios reflecting potential market dynamics. The resulting volatility values assigned to each scenario are listed in Table 6.

In each scenario, for each key commodity $i \in \{\text{electricity}, \text{biomass}, CO_2, \text{FTL}, \text{eSAF}\}$, price trajectories were generated over a time horizon $T$, representing plausible market evolutions under different assumptions:

$$P_t^i \sim GBM(\mu_i, \sigma_i), \quad t = 0, 1, \ldots, T \tag{3}$$

Fig. 2 shows the resulting commodity price trajectories, illustrating how differing assumptions on market dynamics and policy ambition shape long-term price development and associated uncertainties.

The Stable scenario assumed minimal drift and low volatility, reflecting a continuation of existing support levels and relatively predictable commodity markets. As an example, the negative drift value for biomass implies a decrease in biomass price from 36 €/MWh in 2024, to 24 €/MWh in 2050. Although useful as a baseline, this scenario may underestimate the scale of forthcoming climate-driven disruptions and the variability observed in real-world biomass and electricity markets.

The Transition Pushed scenario was designed to be more reflective of recent EU policy developments, such as Fit-for-55, RED III, and the push for electrification and carbon pricing through the EU ETS. It captures higher volatility and drift in commodity prices, matching observed fluctuations for increased market as defossilization policies ramp up.

Finally, the Asymmetric Electrification Focus scenario was designed to reflect a stronger bias toward electricity-centric solutions, assuming more aggressive electrification incentives and $CO_2$ price growth, but uneven support across biomass and fuel sectors. While speculative, it mirrors strategic priorities emerging from certain national policies, and reflects potential future asymmetries in market development.

Taken together, these scenarios serve as structured lenses to explore investment dynamics. The scenarios were designed to be consistent and based on reasonable assumptions, using data from sources like the IEA and historical market trends. The above scenarios are not intended to predict one specific outcome, but rather to provide a simplified representation of possible futures, each highlighting a different driver, such as market stability, ambition level, and uneven support.

### *2.4. Real options framework*

The GBM-simulated price trajectories served as input for the ROA. For each commodity, the simulated price trajectories represent possible future states over the investment horizon. These prices were used to calculate annual revenues and operating costs for every pathway

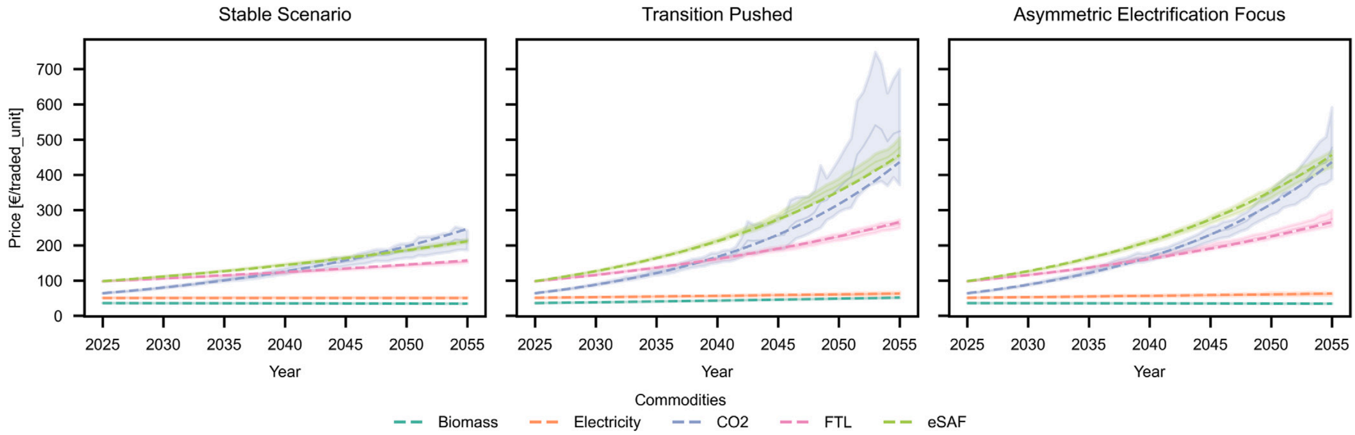


**Fig. 2.** Simulated commodity price trajectories using GBM, under the three modeled market scenarios. Each panel displays the evolution of biomass, electricity, $CO_2$, FTL, and eSAF prices from 2025 to 2055 for Stable scenario (right), Transition Pushed scenario (middle), and Asymmetric Electrification Focus scenario (left). Dashed lines represent the expected price trajectory for each commodity, while shaded bands indicate the 95% confidence intervals from 1000 GBM simulations.

**Table 5**
Drift parameters ($\mu$) for each commodity under different market scenarios. Scenario abbreviations: S = Stable scenario, TP = Transition Pushed scenario, AEF = Asymmetric Electrification Focus scenario.

| Commodity | Scenario | $\mu$ | Notes | Source |
|---|---|---|---|---|
| *Biomass* | S | −0.0016 | Assuming an expected price of 24 €/MWh in 2050, as derived from model runs from TIMES Sweden | |
| | TP | 0.0120 | Assuming an expected price of 49 €/MWh in 2050, as derived from model runs from TIMES Sweden | |
| | AEF | −0.0016 | Assumed same as scenario S | |
| *Electricity* | S | 0 | Electricity market assumed to remain stable and governed by volatility, as has historically been the case | Zetterholm et al. (2022) |
| | TP | 0.007 | Assuming an expected price of 60 €/MWh in 2050, as derived from model runs from TIMES Sweden | Forsberg et al. (2024) |
| | AEF | 0.007 | Assumed same as scenario TP | |
| *$CO_2$* | S | 0.045 | Assuming an expected price of 158 €/ton $CO_2$ in 2050 per the STEPS scenario | World Energy Outlook (2024) |
| | TP | 0.064 | Assuming an expected price of 250 €/ton $CO_2$ in 2050 per the NZE scenario | World Energy Outlook (2024) |
| | AEF | 0.064 | Assumed same as scenario TP | |
| *FTL* | S | 0.0157 | Assuming an expected price of 145 €/MWh in 2050, as derived from model runs from TIMES Sweden | |
| | TP | 0.0333 | Double drift compared to scenario S assumed | |
| | AEF | 0.0333 | Double drift compared to scenario S assumed | |
| *eSAF* | S | 0.0256 | Assuming an expected price of 186 €/MWh in 2050, as derived from model runs from TIMES Sweden | |
| | TP | 0.0513 | Double drift compared to scenario S assumed | |
| | AEF | 0.0513 | Double drift compared to scenario S assumed | |

under each scenario. By embedding these stochastic price trajectories into cash flow models, the resulting expected NPVs (eNPV) across all simulations were calculated and used to evaluate the option value of flexibility to defer or avoid investment in response to market volatility.

### *2.4.1. Calculation of expected net present value*

In order to evaluate the fuel production cases under each market scenario, the expected net present value (eNPV) was calculated for each case based on the net cash flow at each time step.

Investment costs were estimated as fixed capital investment, following the methodology described in Mehrara et al. (2025). Equipment purchase costs were obtained from process simulation results and scaled to the plant capacity using the corresponding scaling exponent. Direct installation, indirect costs, and contingencies were then added using standard cost factors to obtain the total capital investment. Table 7 summarizes the specific investment costs for the different fuel production cases.

To calculate the net cash flow, the following costs and revenues were considered.

**Costs:**

- Biomass [ €/MWh]: Feedstock cost in all biomass-based pathways (BtL, BtL-CCS, PBtL-CCS, PBtL).
- Electricity [ €/MWh]: Required for electrolysis and other unit operations in electrified pathways (PBtL-CCS, PBtL, PtL).
- $CO_2$ taxes [ €/t$CO_2$]: Applied only in pathways where $CO_2$ is emitted and not captured (BtL).

**Revenues:**

- Electricity [ €/MWh]: Surplus electricity sent to the grid (BtL).
- FTL/eSAF product sales [ €/MWh]: Main revenue stream, based on output fuel classification (see description in the previous section).
- $CO_2$ storage credit [ €/t$CO_2$]: Earned in CCS pathways (BtL-CCS, PBtL-CCS) by storing captured biogenic $CO_2$.
- $CO_2$ utilization credit [ €/t$CO_2$]: Applied in PtL when $CO_2$ is used as a feedstock, reflecting the use of circular carbon under RFNBO frameworks.

The $CO_2$ price allocations used for the market analysis in this paper stand on two fundamental assumptions. First, we assumed that fossil

**Table 6**
Volatility parameters ($\sigma$) for each commodity under different market scenarios. Scenario abbreviations: S = Stable scenario, TP = Transition Pushed scenario, AEF = Asymmetric Electrification Focus scenario.

| Commodity | Scenario | $\sigma$ | Notes | Source |
|---|---|---|---|---|
| *Biomass* | S | 0.086 | Assuming same volatility as Swedish market for biomass used in district heating production (1993–2024) | Swedish Energy Agency (2025) |
| | TP | 0.110 | Assuming same volatility as Swedish market for biomass used in district heating production (2020–2024) | Swedish Energy Agency (2025) |
| | AEF | 0.086 | Assumed same as scenario S | |
| *Electricity* | S | 0.150 | Assuming halved volatility of scenario TP | |
| | TP | 0.300 | Assuming the same volatility as electricity spot market (bidding zone SE4) in Sweden (2022–2024) | ENTSO-E (2025) |
| | AEF | 0.30 | Assumed same as scenario TP | |
| *$CO_2$* | S | 0.42 | Assuming the same volatility as EU-ETS prices (2020–2024) | European Energy Exchange (EEX) (2024) |
| | TP | 0.52 | Assuming the same volatility as EU-ETS prices (2012–2024) | European Energy Exchange (EEX) (2024) |
| | AEF | 0.42 | Assuming the same volatility as EU-ETS prices (2020–2024) | European Energy Exchange (EEX) (2024) |
| *FTL* | S | 0.165 | Assuming the same volatility as the average EU petrol price (2008–2022) | European Commission (2025) |
| | TP | 0.267 | Assuming same volatility as world market biodiesel (FAME) price (2008–2022) | Refinitiv (2025) |
| | AEF | 0.267 | Assumed same as scenario TP | |
| *eSAF* | S | 0.165 | Assumed same as FTL | |
| | TP | 0.267 | Assumed same as FTL | |
| | AEF | 0.267 | Assumed same as FTL | |

**Table 7**
Specific total cost of investment for the studied fuel production cases, corresponding to the cases described in Mehrara et al. (2025) when integrated with a condensing turbine.

| Fuel production case | BtL | BtL-CCS | PBtL-CCS | PBtL | PtL |
|---|---|---|---|---|---|
| Specific investment (M €/$MWh_{FTL}$) | 3.55 | 3.67 | 3.00 | 2.83 | 3.42 |

emissions and negative emissions are treated symmetrically, such that one ton of fossil $CO_2$ can be compensated by one ton of biogenic $CO_2$ removal. Consequently, biogenic $CO_2$ is priced equivalently to fossil $CO_2$ emissions. Second, we assumed that $CO_2$ utilized in PtL production can carry economic value. In line with ISO 14044 allocation principles and Life Cycle Assessment literature (Müller et al., 2020), $CO_2$ as a feedstock can be regarded either as a valued product or as a waste. In the latter case, the $CO_2$-utilizing process provides the additional function of "waste $CO_2$ treatment". This framing supports our assumption that PtL plants may receive compensation for taking over $CO_2$ streams from emitters, which in techno-economic terms corresponds to treating $CO_2$ as a negative-cost feedstock. This is also consistent with previous techno-economic studies of $CO_2$ utilization (Otto et al., 2015). These studies considered not only free $CO_2$ feedstock, but also scenarios in which $CO_2$ emitters pay utilization plants to take over their emissions, effectively treating $CO_2$ as a negative-cost input. However, it is crucial to emphasize that this assumption is not supported by current stated or implemented policy frameworks. At present, no regulatory mechanism guarantees such $CO_2$ crediting in practice. The assumption is therefore introduced purely for exploratory purposes, to assess how PtL pathways would perform under an optimistic policy environment in which such credits might become available. The results should consequently be interpreted as an upper-bound estimate of PtL economic performance.

The simulated prices (Fig. 2) were then linked to the annual economic performance of each fuel production case. The revenue at time $t$, denoted $R_t$, was modeled as a function of the output fuel price $P_t^{\mathrm{FTL}}$, and $CO_2$ $P_t^{\mathrm{CO_2}}$ credits when relevant (see Table 3); while the operating cost $C_t$ was calculated as a function of input prices including electricity, biomass, and $CO_2$ (Li et al., 2015):

$$R_t = f(P_t^{\mathrm{Electricity}}, P_t^{\mathrm{FTL}}, P_t^{\mathrm{eSAF}}, P_t^{\mathrm{CO_2}}) \quad C_t = g(P_t^{\mathrm{Electricity}}, P_t^{\mathrm{Biomass}}, P_t^{\mathrm{CO_2}}) \tag{4}$$

The net cash flow at each time step was then defined as:

$$CF_t = R_t - C_t \tag{5}$$

For each of the $N$ simulated price trajectories, the expected net present value (eNPV) was calculated using a discount rate $r$ (set to 8%):

$$eNPV^{(n)} = \sum_{t=0}^{T} \frac{CF_t^{(n)}}{(1+r)^t} - TCI, \quad n = 1, \dots, N \tag{6}$$

Where *TCI* is the initial total capital investment corresponding to each pathway. This formulation enables a comparative evaluation of investment attractiveness across different pathways and market scenarios, while explicitly accounting for price volatility and policy-driven market trends.

Real options theory posits that investors make rational and informed decisions to maximize the project's value while managing risk under uncertainty throughout its lifetime. It incorporates the option to postpone investment within a defined investment window, during which the investor can either proceed or defer until the final decision point, where they must invest or abandon the opportunity. In many cases, deferring investment is advantageous, as investors can wait for new information about economic conditions. Suppose the expected net present value is equal to or exceeds the value of postponing the investment defined as "Wait Value" ($WV$). In that case, the investment is executed, and the option to invest later is forfeited. These decisions adhere to the following rules (Zetterholm et al., 2022):

$$\begin{aligned} t < T_{\max} \quad & \begin{cases} [eNPV]_{n,t} > WV_{n,t} & invest \\ [eNPV]_{n,t} \le WV_{n,t} & postpone \end{cases} \\ t = T_{\max} \quad & \begin{cases} [eNPV]_{n,t} \ge 0 & invest \\ [eNPV]_{n,t} < 0 & abandon \end{cases} \end{aligned} \tag{7}$$

where $T_{\max}$ is the investment window, and *WV* is calculated according to:

$$WV_{n,t} = \frac{\sum_{n_w=1}^{N} \max([eNPV]_{n,t+1}, 0)}{N(1+r)} \tag{8}$$

Here, $N$ represents the total number of simulations (1000), while $n$ refers to a specific Monte Carlo simulation where the $WV$ is compared against the expected net present value ($[eNPV]_{n,t}$). $n_w$ denotes a particular nested simulation used to account for the stochastic nature of potential future developments and to calculate the $WV$ for scenario $n$, $t$ is the current time step, $eNPV$ is the expected net present value, and $r$ is the discount rate. For each point along the trajectory, there are $N$ nested simulations to determine the $WV$. $WV$ was then normalized over the total energy output in each pathway in order to be comparable across pathways:

$$WV = \frac{WV_{n,t}}{E_{\text{total},c}} \tag{9}$$

where $E_{\text{total},c}$ is the total energy output (in MWh) of the fuel production case $c$ over its operating lifetime which was assumed to be 20 years.

### 2.5. Analysis framework

#### 2.5.1. Opportunity cost and estimation of subsidy required to offset the value of waiting

To quantify the Opportunity Cost (OC) of investing immediately, we calculated the difference between the expected value of WV and the expected NPV (eNPV) of immediate investment at each decision point. A positive OC indicates that deferring the investment yields a higher value than does acting immediately.

$$OC = [WV_c^t] - [eNPV_c^t] \tag{10}$$

$\phi$ can be used as a metric for quantifying the increase in wait value between a previous decision point and the actual investment year to calculate the level of support needed to counteract the incentive to defer investment:

$$\phi = OC_c^{late} - OC_c^{early} \tag{11}$$

This quantity reflects how much more economically attractive deferral becomes over time. We then translated this OC into an equivalent per-unit subsidy $S_c$ ( €/MWh), defined as:

$$S_c = \frac{\phi}{E_{\text{total},c}} \tag{12}$$

This formulation assumes that the subsidy is evenly distributed per unit of output.

The resulting $S_c$ values were computed for all pathways across market scenarios to enable a comparative assessment of the financial effort required to induce earlier investment.

#### 2.5.2. Commodity price relation analysis

To evaluate how relative commodity prices shape investment behavior, we defined input/output price ratios that express the exposure of each pathway to key $eNPV$ drivers. At each time step, the following ratios were computed:

$$\frac{P_t^{\text{Electricity}}}{P_t^{\text{FTL/eSAF}}};\ \frac{P_t^{\text{Biomass}}}{P_t^{\text{FTL/eSAF}}};\ \frac{P_t^{\text{CO}_2}}{P_t^{\text{FTL/eSAF}}} \tag{13}$$

For each scenario, the price ratios were captured whenever an investment decision occurred. Further on they were categorized based on the decision: abandoned or invested. To facilitate interpretation across variables spanning different orders of magnitude, these ratios were transformed to a logarithmic (base-10) scale prior to visualization. As a result of this visualization, wide ranges can be compressed, allowing ratios that differ by several orders of magnitude to be visualized together. It also maintains symmetry around parity: values above and below unity are equally distant from zero. Furthermore, the median price ratios of abandoned cases were estimated to assess how much they vary across years, and whether substantial differences may act as a signal for deferral.

## 3. Results and discussion

The results are presented and discussed in three sections. The first step is to discuss the overall investment decision results of the real option analysis, and the effect that opportunity costs have on these investments (Section 3.1). Following that, the price effects in each market scenario on the investment decisions are examined (Section 3.2), followed by an assessment of subsidies needed to bring the delayed investments forward to earlier years (Section 3.3). The chapter concludes with a discussion that synthesizes the key findings across the different results, highlighting common trends, contrasting outcomes, and the broader implications (Section 3.4).

### 3.1. Real options in action: OC trends and investment deferral

Across all fuel production cases and in all market scenarios, the results clearly showed that if investments did occur, they were consistently delayed until the very last year of the evaluation window. Fig. 3 shows the final-year investment rates across fuel production cases and market scenarios, using a radar chart to highlight differences in relative technology case attractiveness. These investment rates are thus defined as the fraction of Monte Carlo simulations in which an investment has been triggered by the end of the 10-year investment window. These values were derived from a comparison of the projected NPV and the wait value at each time step across all simulations. The investment rates show that the wait value outweighs the NPV in all years when the option to wait is available. The data for this figure are also presented in Table B.1 in Appendix. The plotted values thus represent the share of simulations where investment occurred at year 10, while all earlier opportunities were abandoned. This aligns with real options logic, where investors defer action to reduce uncertainty unless sufficiently strong incentives arise (Kitzing et al., 2020).

In the Stable scenario, where price dynamics are characterized by low or even negative drift (biomass $\mu = -0.0016$) and low volatility, investment remained concentrated in partially electrified pathways. PBtL and PBtL-CCS reached investment levels of 46% and 59%, respectively. Entering the RFNBO market raised investment in PtL from only 21% to 41% in PtL-e, highlighting the value of compliance. This reflects investor hesitance in a steady, non-volatile environment where electricity prices remain static and carbon prices rise slowly. In such conditions, incentives are insufficient to justify the capital risk associated with fully electrified pathways unless they can access the RFNBO market.

The Transition Pushed scenario, with higher drift and volatility across all commodities, results in greater appeal for RFNBO-compliant options. PtL rose from 35% to nearly 58% when moving into the RFNBO market (PtL-e). Meanwhile, PBtL and PBtL-CCS fell slightly to around 50%–57%. Even under policy-driven upward trends, heightened volatility amplifies uncertainty, discouraging broader investment and leading to a redistribution across cases.

The Asymmetric Electrification Focus scenario produced mixed outcomes. PBtL-CCS and PBtL-CCS-e achieved the highest investment shares, at 67%–72%. For PtL, entering the RFNBO market again proved beneficial; PtL-e investment ratio rose by 16%. This outcome underscores the limitations of a partial policy push where, even though electricity prices increase in line with electrification incentives, stagnation in biomass prices and only moderate $CO_2$ price growth fail to fully tip the balance in favor of fully electrified pathways. Instead, investors lean toward partially electrified and CCS-integrated options, while RFNBO compliance offers a measurable boost in competitiveness for electrified fuels.

To understand the deferral behavior of the investors in the above-mentioned scenarios, Fig. 4 presents the evolution of the mean OC for each pathway across the investment horizon. An increase in OC over time reflects a growing economic advantage to waiting, suggesting that future conditions are expected to improve the profitability of

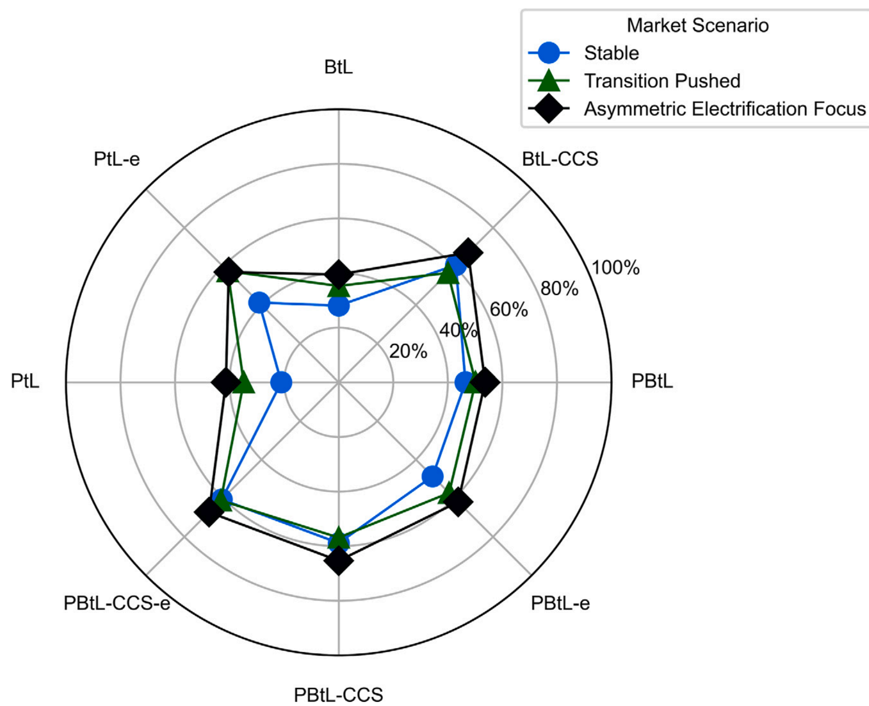


**Fig. 3.** Investment decision rate for each market scenario and each fuel production case. The investment decision rate represents the fraction of decisions in the final year that result in investment, as all investment decisions are deferred until the final year.

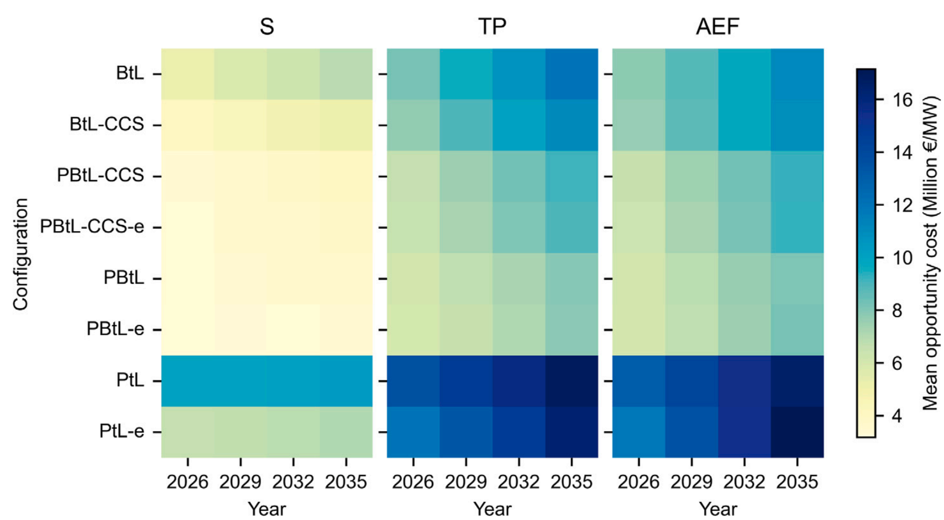


**Fig. 4.** Mean opportunity cost (OC, defined as WV minus eNPV per MW of produced fuel) for each fuel production case and year, under each market scenario: S = Stable scenario (left), TP = Transition Pushed scenario (middle) and AEF = Asymmetric Electrification Focus scenario (right).

the investment. This provides a direct explanation for the deferred investment behavior shown in Fig. 3.

In the Stable scenario, low drift and volatility across all commodities lead to lower wait values compared to the other scenarios (Fig. 4). Even though the growth in the OCs was comparatively small, they were still large enough to defer investment, especially for fully electrified fuel production cases or even in BtL cases without CCS. The lower OC also means less incentive to abandon, making investments easier to trigger. This is reflected in Fig. 3, where BtL-CCS, PBtL-CCS, and PBtL-CCS-e, which benefit from electrification and/or CCS, show among the highest investment rates.

In the Transition Pushed scenario, strong drift and volatility in FTL, electricity, and $CO_2$ lead to high and rapidly increasing wait values (Fig. 4). This also means that the OC of acting early is higher as there is more to gain by waiting. As a result, despite strong future profitability, many investments were still deferred until the end of the decision window. This highlights a paradox typical of real options analysis under uncertainty: strong future prospects can actually defer investment when the value of waiting continues to grow (Alexander et al., 2021).

The Asymmetric Electrification Focus scenario shows similar behavior but with uneven incentives. Electricity and $CO_2$ prices grow, while biomass prices decline. Still, the OC remained high, and the wait value continued to rise throughout the time horizon, reinforcing deferral.

Across all market scenarios, a consistent pattern emerged: fuel production cases with flatter OC trajectories over time tend to exhibit lower abandonment rates by the final year. This reflects a more stable investment incentive but may also be influenced by greater eNPV dispersion under high-volatility conditions. When the gap between wait

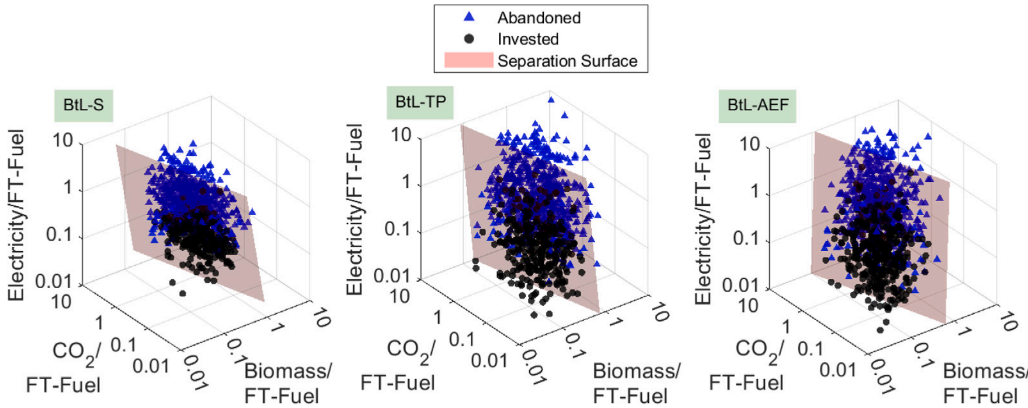


**Fig. 5.** Comparison of BtL fuel production case across the market scenarios. S = stable, TP = Transition Pushed, AEF = Asymmetric Electrification Focus.

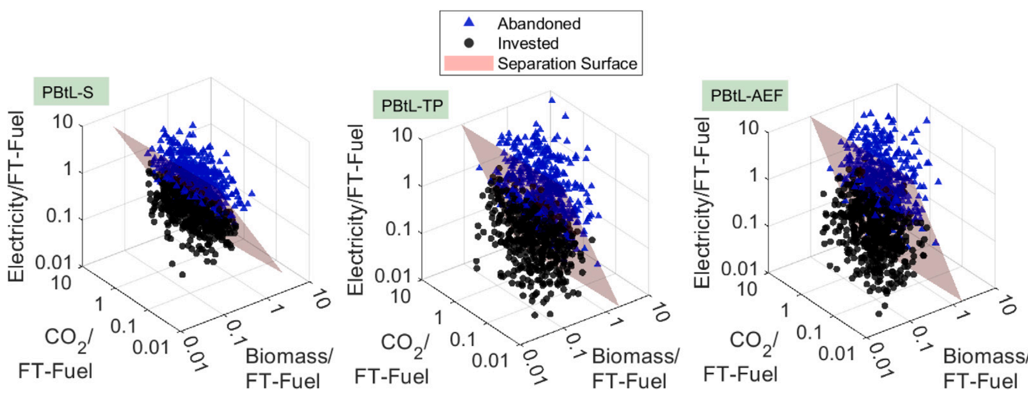


**Fig. 6.** Comparison of PBtL fuel production case across the market scenarios. S = stable, TP = Transition Pushed, AEF = Asymmetric Electrification Focus.

value and eNPV remains relatively stable, investors perceive a clearer window for commitment, making it easier to time investment decisions before the horizon ends. In contrast, pathways with steeply increasing OC signal that the value of waiting continues to grow, which prolongs hesitation and increases the likelihood of missed opportunities or non-investment. This dynamic highlights how not only the absolute value of OC, but also its evolution over time, influences long-term investment behavior under uncertainty.

To verify the adequacy of the simulation sample size, the number of Monte Carlo runs was increased from 1000 to 2000 for selected cases. The resulting investment timing patterns and mean OC trends were consistent with those obtained using 1000 simulations, indicating that the baseline results are not sensitive to further increases in the number of iterations. However, increasing the number of simulations was not pursued further due to the high computational costs.

### *3.2. Influence of scenario assumptions on investment outcomes*

Investment outcomes are presented as a function of relative commodity price ratios, where biomass, $CO_2$, and electricity prices are normalized against the FTL/eSAF selling price. To allow for a consistent comparison across inputs with values spanning different orders of magnitude, these ratios are represented on a log10 scale. For interpretability, axis tick marks are labeled with the original ratio values, so the figures can be read directly in terms of commodity/FT-Fuel price ratios. The FT-Fuel label in the figures denotes fuel output (eSAF or FTL), as detailed in Table 3. Separation planes are also represented in each figure, which distinguish between occurred investments and abandoned investments. This plane provides a visual benchmark, illustrating the approximate threshold in the ratio space at which investment becomes more likely, and making it possible to identify which price dynamics drive divergence in outcomes across the scenarios. To illustrate these dynamics, the investment outcomes are presented for three representative fuel production cases (BtL, PBtL, PtL-e), across corresponding plots shown in Figs. 5–7.

For BtL (Fig. 5), the scenario comparison highlights the relative stability of biomass-driven pathways. In the Stable scenario, biomass/FT-Fuel ratios remained consistently below parity, while electricity and $CO_2$ ratios hovered close to one, resulting in little separation between invested and abandoned cases. In the Transition Pushed scenario, the shift in the separation planes is primarily driven by higher $CO_2$ taxation, the greater volatility in electricity ratios does not substantially alter outcomes for BtL. In the Asymmetric Electrification Focus scenario, the pattern remained largely unchanged, with biomass ratios still below parity and electricity costs having minimal influence. Overall, BtL shows weak sensitivity to changing market signals, with outcomes shaped more by the steady availability of biomass than by fluctuations in electricity or $CO_2$ prices.

For PBtL-e (Fig. 6), the three scenarios illustrate how investment behavior shifts with changing price dynamics. In the Stable scenario, electricity/FT-Fuel and $CO_2$/FT-Fuel ratios remain close to parity, while biomass/FT-Fuel ratios stay consistently below one, resulting in weak price signals and limited separation between invested and abandoned cases. Under the Transition Pushed scenario, electricity ratios fall well below parity and $CO_2$ ratios rise more strongly, creating a clearer distinction on the separation plane and favoring investment in RFNBO-compliant pathways. By contrast, the Asymmetric Electrification Focus scenario is characterized by electricity ratios above parity and only modest $CO_2$ growth, which shifts the separation plane toward abandonment and suppresses investment attractiveness. Together, these figures

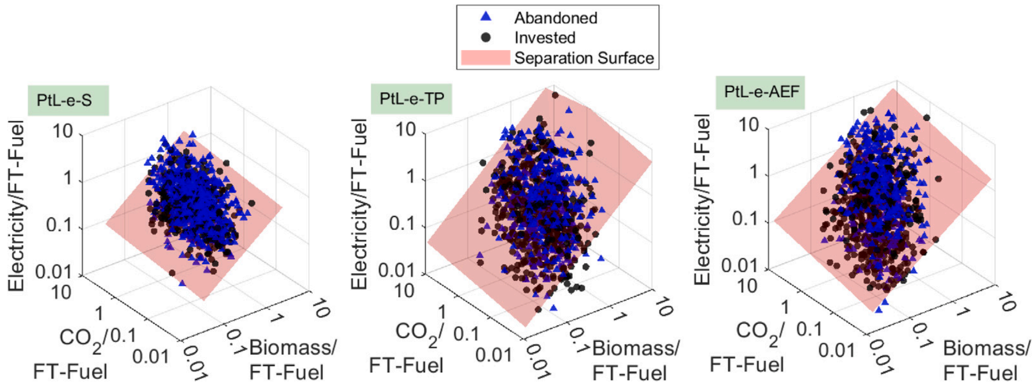


**Fig. 7.** Comparison of PtL-e fuel production case across the market scenarios. S = stable, TP = Transition Pushed, AEF = Asymmetric Electrification Focus.

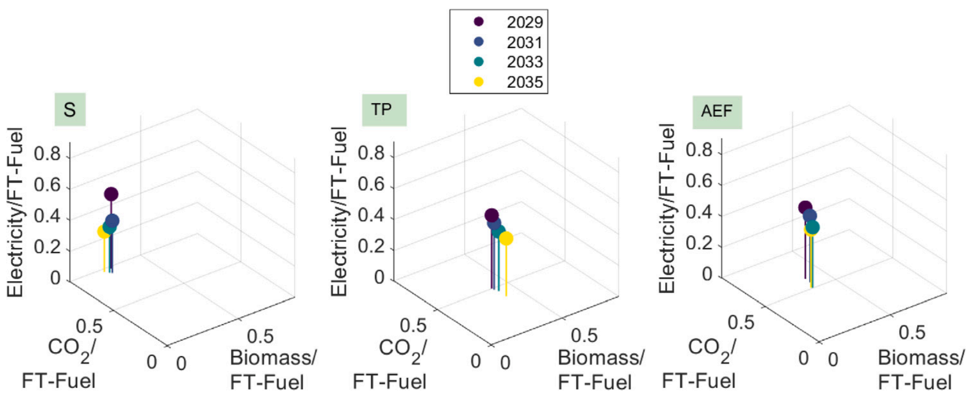


**Fig. 8.** Median of price ratios across scenarios and time steps. Each panel represents one market scenario, Stable, Transition Pushed, and Asymmetric Electrification Focus; showing the median values of biomass/FTL, $CO_2$/FTL, and electricity/FTL ratios at which investment did not occur across simulation runs. S = Stable scenario, TP = Transition Pushed scenario, AEF = Asymmetric Electrification Focus scenario.

show that PBtL-e is highly scenario-dependent, gaining ground when electricity is cheap and $CO_2$ is costly, but penalized when electricity becomes expensive.

For PtL-e (Fig. 7), the scenario comparison illustrates its strong dependence on electricity and $CO_2$ dynamics. In the Stable scenario, electricity/FT-Fuel ratios remained close to parity and $CO_2$ ratios increased only slowly, limiting favorable signals despite biomass being absent, and resulting in a weak separation between invested and abandoned cases. Under the Transition Pushed scenario, electricity ratios fell well below parity while $CO_2$ ratios climbed above one, producing a strong dual incentive that shifted the separation plane clearly toward investment and makes RFNBO-compliant PtL particularly attractive. In contrast, the Asymmetric Electrification Focus scenario shows electricity ratios persistently above parity and $CO_2$ ratios only modestly higher, which penalizes PtL-e by clustering outcomes on the abandonment side of the plane. This makes PtL-e the most scenario-sensitive pathway, gaining sharply under supportive electricity and $CO_2$ conditions but losing competitiveness when electricity is expensive.

For completeness, the full set of 3D price ratio plots covering all cases and scenarios is provided in the Appendix, complementing the nine representative plots highlighted here. The general discussion around the scenarios can be summarized as: In the Stable scenario, ratios remained close to parity, providing no strong incentive for immediate investment. Electricity prices are only moderately below the FT-Fuel benchmark, while the $CO_2$ price trajectory implies weak costs in case of unabated emissions. Biomass is consistently below parity, but its relative stability does not influence the timing decision. What distinguishes the cases that eventually approach investment is the convergence of electricity ratios toward lower values and $CO_2$ ratios toward higher relative values compared to abandoned cases, while biomass ratios remain flat across both.

In the Transition Pushed scenario, electricity/FT-Fuel ratios fall below parity. At the same time, $CO_2$/FT-Fuel ratios rise above one, reflecting a growing relative cost of emissions. This combination created a strong dual price signal: lower electricity prices reduce the cost of hydrogen production for syngas conditioning, while higher $CO_2$ prices increase the economic benefit of $CO_2$ avoidance and capture. These dynamics favor electrification and CCS integration, with RFNBO-compliant options gaining additional support from market access advantages.

By contrast, the Asymmetric Electrification Focus scenario is characterized by positive electricity/FT-Fuel ratios. The separation plane highlighted that abandoned cases dominate when electricity ratios are highest and $CO_2$ ratios remain near parity. Whereas invested cases were associated with periods of somewhat lower electricity ratios combined with modestly higher $CO_2$ ratios.

Fig. 8 plots the trajectories of median price ratios over time for each scenario. Each point corresponds to a year, with projection lines down to the base plane to aid interpretation of their position in ratio space.

The trajectories illustrate that investment deferment cannot be attributed simply to markets shifting toward substantially better conditions. Across all three scenarios, the paths traced from Year 3 to Year 9 are short, with only modest shifts in median ratios. In the Transition Pushed and Asymmetric Electrification Focus market scenarios, higher volatility introduces some variation, yet the overall changes remained limited. The Stable scenario made this even clearer, with ratios staying

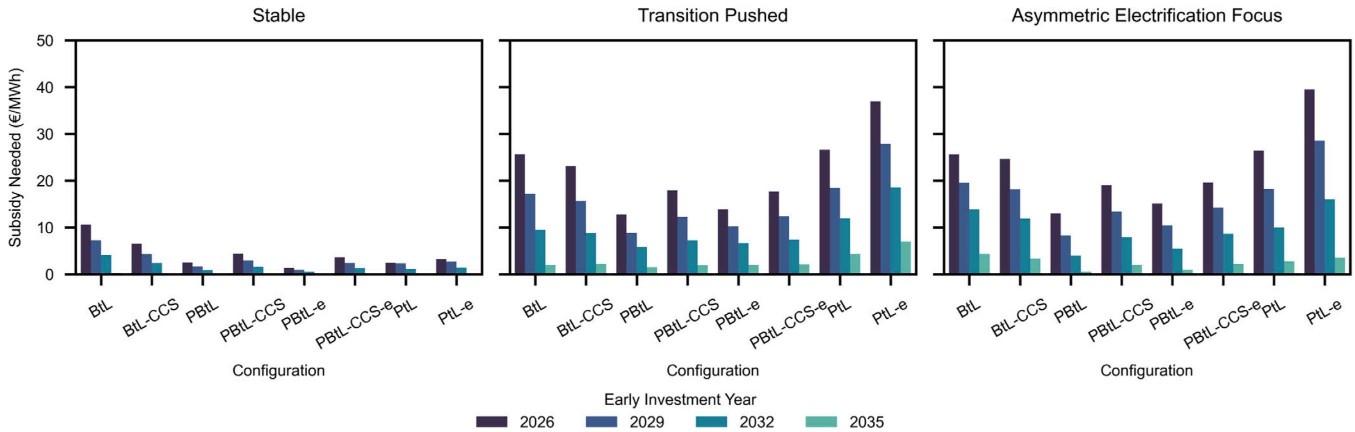


**Fig. 9.** Subsidy levels (€/MWh) required to incentivize early investment (2026, 2029, 2032, 2035) instead of deferred commitment for each pathway under three market scenarios: Stable, Transition Pushed, and Asymmetric Electrification Focus.

tightly clustered across years. These results suggest that investors are not waiting for dramatically more favorable signals, but rather that deferral reflects the added option value of waiting under uncertainty. The depicted 3D diagrams focus on the limited movement of each trajectory, strongly emphasizing how little the median ratios change over time.

### 3.3. Subsidies required

While the heatmaps in Fig. 4 provided a comparative view of the mean OC between expected project returns and wait value across time, they do not directly quantify what level of intervention would be needed to shift investor behavior. To complement this perspective, Fig. 9 presents the required subsidies (€/MWh) needed to offset the wait value. These subsidies can be interpreted as representative of a needed guaranteed premium above the direct market value of the product.

In the Stable scenario, the required subsidies remain relatively low across all fuel production cases, staying below 11 €/MWh even for early investments in year 1, which corresponds to roughly an 11% increase in the fuel price compared to the starting year. Conventional BtL and BtL-CCS required the greatest subsidies in early years, while partially electrified and CCS-integrated cases (PBtL, PBtL-CCS, PBtL-CCS-e) fall much lower, dropping below 2 €/MWh by 2035. This indicates that under stable market conditions with low volatility, small increases in revenue could be sufficient to trigger earlier investment. In the Stable scenario, an interesting contrast emerged between fully electrified and hybrid pathways. For PtL, entering the RFNBO market (PtL-e) resulted in higher subsidy needs than PtL, since the additional revenue volatility of the eSAF trajectory outweighs its modest price premium for a pathway fully exposed to electricity costs. In contrast, PBtL-e benefited from the same RFNBO price uplift while its mixed biomass-electricity input base cushions the volatility effect, leading to lower subsidy requirements than PBtL.

In the Transition Pushed scenario, subsidies were substantially higher, particularly for electrified cases. Early investments in 2026 required about 27 €/MWh for PtL and 46 €/MWh for PtL-e, corresponding to increases of up to 50% relative to the starting fuel price. Electrified and capital-intensive pathways are more exposed to uncertain electricity and $CO_2$ prices, raising early investment risk. Hybrid pathways (PBtL and PBtL-CCS/-e) showed moderate needs (2-18 €/MWh), suggesting greater resilience due to balanced reliance on electricity and biomass.

In the Asymmetric Electrification Focus scenario, a similar divergence persisted. Early investments in PtL and PtL-e required 30–40 €/MWh in 2026, compared to less than 5 €/MWh for the same cases in the Stable scenario. Even by 2035, these highly electrified cases still required higher subsidies than in the Stable scenario. Conversely, hybrid cases such as PBtL-e and PBtL-CCS-e approached near-zero subsidy requirements. This contrast underscores how asymmetric incentives, where electricity prices remain high despite policy support for electrification, can suppress RFNBO competitiveness, while more balanced cases retain a robust investment profile.

Cross-technology comparison reveals structural differences in subsidy needs. Due to limited exposure to electricity price uncertainty, pure biomass-based cases (BtL and BtL-CCS) generally needed less support than fully electrified ones. However, this statement is not valid for the stable scenario. This contrast can be explained by the underlying drift and volatility assumptions for electricity and $CO_2$ across scenarios (Tables 5–6). In the Stable scenario, electricity prices are assumed to remain flat with relatively low volatility ($\mu = 0$, $\sigma = 0.15$), which minimizes the risk premium for electrified pathways. At the same time, $CO_2$ prices exhibit a positive drift ($\mu = 0.045$) with high volatility, increasing the value of CCS integration and, crucially, the revenues from $CO_2$ utilization in PtL pathways. This effect reduced subsidy needs for partially or fully electrified cases, but it also implies that results are highly sensitive to assumptions about $CO_2$ price trajectories and crediting. By contrast, in the Transition Pushed and Asymmetric Electrification Focus scenarios, electricity prices rise over time ($\mu = 0.007$) and face doubled volatility ($\sigma = 0.30$). These conditions penalize fully electrified options. Meanwhile, PBtL cases, which combine electricity and biomass inputs, stood out for their consistent ability to reach the lowest subsidy needs by 2035 across all scenarios, signaling both flexibility and resilience.

### 3.4. Results overview

The investment decision rates represent the share of realizations in which investment is ultimately undertaken in each scenario. Higher price drifts do not necessarily accelerate investment, as expectations of improving future conditions encourage deferral. However, once the decision horizon is reached, these same expectations translate into higher overall investment rates. To understand the drivers behind delayed investments, the analysis first examined the evolution of the mean OC across scenarios and cases. OC represents the benefit of postponing investment rather than committing immediately, and thus serves as a direct indicator of the incentive to wait under uncertainty. Tracking its development over time provides insight into how market volatility, price drift, and policy signals interact to shape investor behavior beyond what can be inferred from cost or subsidy levels alone. In the Stable scenario, OC value increased slowly and uniformly between pathways, indicating low but consistent incentives to defer. The limited differentiation between cases and the low volatility in input prices yielded a relatively flat investment landscape that required only modest financial intervention to change behavior. In contrast, the Transition Pushed scenario, characterized by high drift and volatility, produces steep OC value gradients, particularly for electrified and CCS-integrated pathways. Although this creates stronger long-term profitability signals for investments, it also increases the incentive to postpone investments unless synchronized policies that support electrification and credit high carbon efficiency are in place to entice early investment. The Asymmetric Electrification Focus scenario reinforces this dynamic: despite high $CO_2$ pricing and electrification-focused signals, investor hesitation remains pronounced due to high electricity costs and policy misalignment, leading to fragmented and deferred investment responses. The results herein, following insights presented by Zetterholm et al. (2022), indicated that early investment is unlikely unless support is both timely and large enough to outweigh the value of waiting.

Each market scenario brings different insights. In the Stable scenario, where price trends are steady and growth is limited, investors defer not because conditions are unfavorable, but because there is little to gain from early action. Here, decisions appeared to be less driven by price ratios and more by the OC of waiting. In contrast, the Transition Pushed and Asymmetric Electrification Focus scenarios, with their steeper drifts and greater volatility, show stronger alignment between favorable price ratios and investment decisions. However, even in these contexts, many cases only trigger investment under highly attractive conditions, reflecting investor caution and the growing value of strategic timing under uncertainty. Furthermore, the required subsidy analysis translated the OC into concrete financial policy levers. While the Stable scenario demands low subsidies (typically well below 10 €/MWh) to advance investment, the Transition Pushed scenario requires far stronger intervention, as steep future profitability growth amplifies the incentive to wait and raises the cost of early action. The Asymmetric Electrification Focus scenario adds a policy dimension to this calculus: electrification-favored signals drove up the wait value of electric-intensive pathways, resulting in higher support needs for fully electrified pathways and a persistent risk of deferred action even when long-term viability was apparent.

## 4. Conclusions

This study has explored the investment behavior of emerging Fischer–Tropsch-based fuel production pathways under market uncertainty, using a real options framework across three contrasting market scenarios. The analysis revealed that investment timing and technology selection are not governed by static profitability thresholds alone, but rather by a complex interplay between market dynamics, market volatility, and the economic value of waiting. A dominant feature across all scenarios is the clustering of investment decisions at the end of the decision window (year 10), with many trajectories that result in full abandonment. This late clustering highlights that, under current market conditions, deferring investments is economically preferable unless strong cost or policy incentives are in place. Such behavior underscores the importance of aligning policy support with market signals, rather than assuming that profitability trends alone will be sufficient to attract investment. The main outcomes of this study can be summarized as:

- Investment decisions in emerging fuel pathways are highly sensitive not only to price levels, but also to the relative structure of prices across inputs and outputs, particularly electricity, biomass and $CO_2$/fuel ratios.
- Aligning electricity and $CO_2$ price signals is critical for enabling RFNBO pathways to scale, as only the joint effect of controlled electricity costs and stringent carbon pricing creates conditions under which partial electrification is competitive. This implies that where electrification is desirable, given likely biomass constraints, relying solely on $CO_2$ price signals will be insufficient, and complementary measures addressing electricity market dynamics will be necessary.
- Stable scenarios may require mechanisms that accelerate action even when price conditions appear acceptable, while markets with more ambitious climate targets may need to reduce actual input costs to close the gap between economic feasibility and investor action.
- The subsidy analysis quantifies the level of support required to advance investments and reveals case-specific resilience. Pathways requiring minimal subsidy may serve as robust near-term options, while others will only be unlocked by sustained, stronger policy intervention. Partially electrified pathways seem to require the least amount of subsidies in any of the introduced market scenarios.

These findings underscore the need for more refined policy frameworks that take into account how investors respond to uncertainty and changing conditions. Policies should not only send clear and consistent price signals, but also help reduce the costs and risks investors face. By addressing both the value of waiting and the reasons behind that hesitation, well-designed policies can lower investment deferrals and speed up the rollout of sustainable fuel technologies. For FT-based pathways, this suggests that policy may need to actively ensure support for RFNBO-compatible configurations, while subsidy mechanisms could bridge the gap for more capital-intensive options. It should also be noted that the results for PtL and PtL-e are strongly influenced by the assumption that $CO_2$ utilization can generate economic value which is not supported by current regulatory frameworks. Even under these highly optimistic assumptions regarding the negative cost input of $CO_2$, PtL pathways still do not exhibit earlier investment decisions or higher investment rates in the final year compared to the other technologies. This indicates that, in scenarios where $CO_2$ utilization is not credited as a revenue stream, the relative investment attractiveness of PtL pathways would be further reduced.

Future research should extend this system-level perspective to retrofit strategies, where existing BtL facilities could be designed for stepwise electrification. Such pathways may offer a more practical balance between near-term feasibility and long-term competitiveness, complementing the insights gained here on greenfield investment behavior.

## CRediT authorship contribution statement

**Mahsa Mehrara:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Jonas Zetterholm:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andrea Toffolo:** Writing – review & editing, Supervision, Formal analysis. **Elisabeth Wetterlund:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Chat-GPT 4.0 to receive suggestions aimed at improving the readability and language of parts of the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mahsa Mehrara reports financial support was provided by Swedish Energy Agency. Mahsa Mehrara reports financial support was provided by Bio4Energy. If there are other authors, they declare that they have

**Table B.1**
Investment percentages for each technology under different scenarios.

| Technology | Stable | Transition pushed | Asymmetric Electrification Focus |
|---|---|---|---|
| BtL | 28.1% | 35.3% | 39.5% |
| BtL-CCS | 60.8% | 56.7% | 67.2% |
| PBtL | 46.5% | 50.2% | 53.7% |
| PBtL-e | 48.7% | 57.3% | 62.0% |
| PBtL-CCS | 58.9% | 56.9% | 67.3% |
| PBtL-CCS-e | 60.7% | 61.2% | 72.2% |
| PtL | 21.1% | 34.9% | 41.4% |
| PtL-e | 41.3% | 57.6% | 57.1% |

no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Interactive SVM surface

Interactive 3D MATLAB figures (.fig) for all price ratio plots are available in the supplementary repository https://doi.org/10.5281/zenodo.17136053.

## Appendix B. investment ratios

See Table B.1.

## Data availability

Data will be made available on request.

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