Evaluating investments in integrated biofuel production - factoring in uncertainty through real options analysis

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Abstract:

In the endeavour to reduce CO_2 emissions from the transport sector, biofuels from forest industry by-products are key. The adaptation of forest-based biorefinery technologies has so far been low which can partly be attributed to uncertainties in the form of policy instability, market prices, and technology costs. These uncertainties in combination with technology learning, which can be expected to reduce future investment costs, could make it favourable to postpone an investment decision. When applying real options theory, it is recognised that there is an opportunity cost associated with the decision to invest, since the option to wait for more favourable market conditions to occur is forfeited. In traditional discounted cash flow analysis, the impact of uncertainty and the value of reducing it (e.g. by waiting), is usually not taken into consideration. This paper uses a real options framework that incorporates the option to postpone an investment to reduce market uncertainties and wait for technology learning to occur. The focus is to investigate how the usage of an investment decision rule based on real options analysis affects technology choice, the economic performance, and when in time it is favourable to invest in pulp mill integrated biofuel production, compared with using a decision rule based on traditional discounted cash flow analysis. As an illustrative case study we examine a pulp mill which has the option, but not the obligation, to invest in either of two different biofuel production technologies that both use the pulp mill by-product black liquor as feedstock: (1) black liquor gasification followed by fuel synthesis, and (2) membrane separation of lignin followed by hydrodeoxygenation. With the usage of the real options framework and the inclusion of the uncertainties regarding future market prices and investment costs, the decision to invest is made later, compared with using traditional cash flow analysis. The usage of real options also reduces the likeliness of a net loss occurring if an investment is made, as well as increases the expected economic returns, showing the added economic value of flexibility in the face of uncertain future conditions.

Keywords:

Integrated biofuel production, Techno-economic analysis, Uncertainty, Real options, Pulp mill.

1. Introduction

There is a need for biofuels[1] in both the short and long-term to reach targets for GHG emission reductions from the transport sector. In forest-rich regions, biofuels can be produced from forestry residues or industrial by- or intermediary products, such as black liquor (BL), bark, or sawdust. Integration of biofuel production with other industries, such as pulp mills or oil refineries, can improve the economic and resource efficiency of these concepts by, e.g. utilisation of excess heat and materials, co-use of existing processing equipment, and logistics benefits [1,2]. The deployment of large-scale forest-based biofuel production has so far been low, which can partly be attributed to policy instability [3], lack of financing [4], and that emerging technologies are subject to significant uncertainties [5], all of which contributes to making the economic performance of industrially integrated forest-based biofuel production subject to uncertainties.

Traditional discounted cash flow analysis is generally evaluated as a "now or never" investment [6], disregarding the fact that decision makers have the opportunity to delay or modify an investment considering changing market conditions [7]. Real options theory includes the decision makers' flexibility by including the decision makers' ability to postpone, adapt, or abandon an investment with respect to changing market conditions [7], and acknowledges that once an investment decision has been made, the option to wait for more information regarding the market uncertainties is forfeited [8]. Compared to discounted cash flow analysis, real options analysis constitutes a more problem-specific tool and requires more advanced mathematics, which can explain why the usage of real options within the industry is limited [9], although it has been suggested by academic literature as a complementary tool to discounted cash flow analysis.

Real options analysis has previously been applied within academic literature to investments into renewable electricity generation [7], where for example Tolis et al. [10] considered a large number of uncertainties, including fuel and product prices, and learning curves, considering the options to postpone the investment. Conversely, the scientific literature on examining biofuel production using real options is so far considerably more limited. Ghoddusi [11] evaluated an ethanol producer with the option of selling its products at two different markets, considering uncertain product prices and production costs, and showed that product price volatilities could have a positive impact on the economic performance. Li et al. [12] investigated the effects of uncertain ethanol prices on the option to delay investment in a biofuel production facility and showed that the uncertainties contributed to a favourability to delay the investment. Similarly, McCarty et al. [13] showed that a high price premium over breakeven prices was required for market entry to occur considering uncertain product prices. However, the considered option of switching the facility between idle and operational did not reduce this price premium. In summary, the body of literature considering the value of real options analysis shows a benefit for including managerial flexibility to wait with an investment for more favourable market conditions, given uncertain commodity prices and investment costs.

This work will use a real options framework to evaluate the option of delaying investments in industrially integrated biofuel production (using a pulp mill as a case study), where the economic performance is subject to uncertainties regarding market prices and future investment costs. It will evaluate how the usage of a real options framework influences the preferred time of investment, choice of technology, and economic performance compared to using traditional discounted cash flow metrics. By including the option to postpone the investment, there is a trade-off between starting to earn earlier (positive due to the discounting of future cash flows), and reducing the chance for an economic loss by postponing the investment (to wait for more favourable market conditions).

The comparison of discounted cash flow analysis and real options analysis is implemented on a case study for a pulp mill that has the option, but not the obligation, to invest in two different BL-based biofuel production technologies, delay the investment, or to never invest at all. The focus of the work is to investigate how the different uncertainties regarding commodity prices and learning curves affect the profitability and favourability of the different technologies and when in time the technologies

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[1] The term "biofuel" is in this work used to refer to biofuels for use in the road transport sector

could be expected to be deployed. The overall aim is to evaluate if an investment strategy following a real options framework can lead to improved economic performance for pulp mill integrated biofuel production, which can increase the general knowledge and understanding of why adaption of forest-based biofuel production technologies has been low, and when in time technologies could be of interest for industrial implementation.

2. Case study

Integration of biofuel production with chemical pulp mills is a promising option for biofuel production, where the utilisation of the BL as a feedstock can be of interest. One of the most extensively researched and tested technologies for the utilisation of BL for production of biofuels is entrained-flow gasification (BLG), showing both technical viability from pilot-scale demonstration [14], as well as high potential economic and resource efficiency [15]. Another technology option for the use of BL is hydrotreatment of lignin separated from the BL. The availability of data on lignin separation based biofuel tracks in the open literature is currently very low [16], even though several commercial actors currently investigate this track in Sweden [17–20].

The illustrative case study considers a pulp mill which has the option, but not the obligation, to invest in either of two BL-based biofuel production technologies; BLG with methanol synthesis, or hydrotreatment of lignin separated from the BL. In this study, the lignin separation track is represented by hydrodeoxygenation of membrane separated depolymerised lignin (MSL-HDO).

The two technologies are at different stages in their technological development, where MSL-HDO has a significantly lower technology readiness level (TRL) compared with BLG [21]. In general, estimated investment costs are more uncertain and more often underestimated for technologies with a lower TRL [22], meaning that estimated investment costs for MSL-HDO can be expected to be significantly more unreliable than BLG. Discounted cash flow metrics seem to favour BLG [21]. However, the different uncertainties surrounding the investments given that an investor has the opportunity to delay an investment for more favourable market conditions could mean that MSL-HDO would, in fact, be more profitable than traditional discounted cash flow metrics indicate.

2.1 Technology description

A brief technology description of the two pulp mill integrated biofuels production technologies is presented here, for details, see Jafri et al. [16]. BLG uses the BL as feedstock to an entrained-flow gasifier, which is followed by catalytic synthesis of the syngas to crude methanol, which is distilled to fuel-grade methanol. MSL-HDO uses a membrane to separate a lignin-rich retentate from the BL. The lignin retentate is depolymerised, washed, and liquefied to lignin oil, which is transported to an oil refinery where it is hydrodeoxygenated with hydrogen, and distilled and hydrocracked to diesel and petrol fractions.

The markets for fuel-grade methanol and renewable petrol are currently small or non-existent, as opposed to the well-developed market for renewable diesel. In practice, this introduces one additional uncertainty to these technologies. However, as the aim of this study is to evaluate the usage of a real options framework in comparison to using traditional discounted cash flow metrics for the evaluation of investment decisions, this market size uncertainty is neglected. Both methanol and renewable petrol are assumed to be sold to the same market as a petrol blend-in fuel, represented by the ethanol price on an energy basis. The renewable diesel is assumed to be sold at the price of biodiesel/FAME.

3. Method

To apply real options theory on an investment decision, structuring of the investment and identification of options is an essential part. In practice, real options analysis forces stakeholders to be explicit regarding assumptions and projections for the problem formulation and hence it can be used in the process of investment strategy formulation. In this paper, a real options framework is developed that accounts for the option to delay an investment (or never make the investment) considering uncertain commodity prices and future technology learning. The real options framework

utilises Monte-Carlo simulations to represent future commodity prices and investment costs and is implemented in Python using external libraries for added functionality: Numpy [23,24] for math functionality, Pandas [25,26] for data handling, and Matplotlib [27,28] and Seaborn [29] for visualisations.

This chapter starts with a description of the investment decision strategies compared in this study; the real options framework (3.1.1) including the equations used to model future uncertainties, and a description of the investment strategy based on the discounted cash flow analysis (3.1.2). Section 3.2 presents the method for compensating for different technology readiness levels concerning estimated investment costs, and section 3.3 presents the input data for the case study.

3.1 Investment decision strategies

3.1.1 Real options framework

This section describes the real options framework used. More explicitly, the future uncertainties modelled along with the *decision rule used* for the option to delay the investment are described. The uncertainties incorporated in the framework are *future commodity prices* and *technology learning*.

Using the investment strategy as decided by the real options framework, the decision maker evaluates the expected net present value (NPV) against the value of making the investment decision next year. The expected NPV for an investment is calculated using the current (known) prices and investment costs, and the expected future price curves for the commodities. The value of making the investment decision next time-step is calculated by simulating *N* future scenarios for prices and investment costs next year, and evaluates the *future expected NPV* for each specific future scenario *n* and discounting back this *future expected NPV* one-year. For scenarios resulting in a negative NPV, the investment is not made, giving the options value of waiting with the investment as:

$$Waitvalue_t = \left(\sum_{n=1}^{N} max\big(E[NPV]_{n,t+1}, 0\big) \right) \Big/ N(1+r) \tag{1}$$

where r is the discount rate, N is the total number of future simulated scenarios, and $E[NPV]_{n,t+1}$ is the expected NPV in future simulated scenario n in the next time step. The *investment decision rule* used is that the decision to invest is made if the current expected NPV is higher than the option value of waiting with the investment one year.

Future commodity prices are assumed to follow a Geometric Brownian motion, which has commonly been applied in the literature to represent energy prices, see for instance [12,30], where the price at time t can be represented by:

$$P_t = P_{t-1} + \mu P_{t-1} dt + \sigma P_{t-1} dW \tag{2}$$

where μ is the drift parameter (representing a general, time-based price trend), σ is the volatility, dt is the size of the time step, and dW is the increment of a standard Wiener process. The expected future price $E[P_t]$ can then be described by [31]:

$$E[P_t] = P_0 e^{\mu t} \tag{3}$$

A significant benefit of waiting with an investment is the possibility to benefit from *technology learning* which may lower the expected investment cost. Future investment costs are implemented as has previously been done in [31,32] and is described by:

$$I_t = I_0 \Phi^{N_t} \tag{4}$$

where I_t is the investment cost in time-step t, I_0 is the initial investment cost, N_t is a random Poisson variable with mean λt counting the number of innovations, and $\Phi \in [0,1)$ is a constant that reflects the

size of each innovation occurring. The expected investment cost $E[I_t]$ is an exponentially declining function [31] which can be described by:

$$E[I_t] = I_0 e^{-\lambda t(1-\Phi)} \tag{5}$$

3.1.2 Discounted cash flow

The real options framework assess the option to invest now with the option of waiting one year and making the investment then if the investment is proven to be profitable. The value of using the real options framework, which includes the value of postponing the investment, is compared with using a discounted cash flow analysis-based investment decision strategy of investing as soon as the expected NPV > 0 for any of the considered investment options. For scenarios where the expected NPV is never higher than 0, the investment is never made. Comparing this mechanism with the results from the real options model, the significance of including the option to defer the investment is clarified.

3.2 TRL compensated investment costs

Technologies at different stages of technology development are associated with different magnitudes of uncertainties regarding their estimated investment costs. The so-called "RAND report" [22] showed that investment costs are generally underestimated and that the "underestimation rate" is higher for technologies at a lower TRL. To account for this fact, in this paper, the ratio of the estimated to the actual investment costs (*CostGrowth*) follows an empirical formula as:

$$\begin{aligned} CostGrowth = Intercept - (&-b_1 PctNew - b_2 Impurities - b_3 Complexity \\ &- b_4 Inclusiveness - b_5 ProjectDefinition) \end{aligned} \tag{6}$$

where the parameters *Intercept*, b_1, b_2, b_3, b_4, and b_5 have been estimated empirically, see [22]. *PctNew* is the percent of the investment cost estimates that include technology which is unproven in commercial use, *Complexity* is the count of all the process steps in the plant, *Inclusiveness* is the percentage of the total items that are included in the cost estimate, and the *ProjectDefinition* is the level of site-specific engineering and information in the cost estimate.

3.3 Case study input data

For the implementation of this case study, a 10-year investment window is used, and an economic lifetime for both technologies of 20 years is assumed. The Monte Carlo-method using 10,000 scenarios to simulate future price curves and investment costs is used. The case is evaluated for two assumed discount rates, 8% and 15%. All economic data is given for the monetary value year of 2018. No lead, build, or start-up times for the investments are considered, and the facility is assumed to instantaneously start production at full capacity as soon as the investment decision is made.

3.3.1 Technology cost and technology learning

The investment costs are given as a first of a kind facility, as described in [21]. The investment costs from the literature, and the estimated parameters and the cost growth according to (6) are displayed in Table 1.

Table 1. Investment cost and cost growth data.

	BLG	MSL	Source/note
Investment cost [MEUR$_{2018}$][1]	378	57.8	[21]
PctNew[2]	33.3	88.9	Assumed as equipment with a TRL>7 in [21]
Impurities[2]	5	5	Assumed the same as for biomass gasification in [5]
Complexity[2]	6	9	Counting the number of process steps in [16] and counting the process integration as one process step
Inclusiveness[2]	100	100	BLG has had many studies estimating the cost, MSL-HDO is most likely lower, but has been assumed the same as BLG due to several commercial actors investigating the track.
Project definition[2]	4	6	Level of engineering + information on plant-specific data, see [22]
CostGrowth	1.4	2.6	Calculated from (6), see section 2.2

[1]The investment cost represents first of a kind investment costs, calculated to the monetary value year of 2018 using the Chemical Engineering Plant Cost Index (CEPCI).
[2]Input to (6), see section 2.2

The technology learning, see (4), is dependent on the two parameters Φ (counting the size of the innovation), and λ (influencing the frequency of innovation occurrence). This assumes that there will be other actors that invest in the technology. As both these parameters affect the same results, λ was assumed to be 1, and Φ was chosen so that the expected investment cost, see (5), followed an assumed learning curve with a learning rate of 20% (as has been observed for Brazilian ethanol [33]) and a doubling of the installed capacity every fifth year, resulting in a Φ of 0.94. The same technology learning was assumed for both BLG and MSL-HDO. Below are the simulated investment costs for BLG, and MSL-HDO for the considered investment window. The figure shows the highest, lowest, and average investment cost for each time-step.
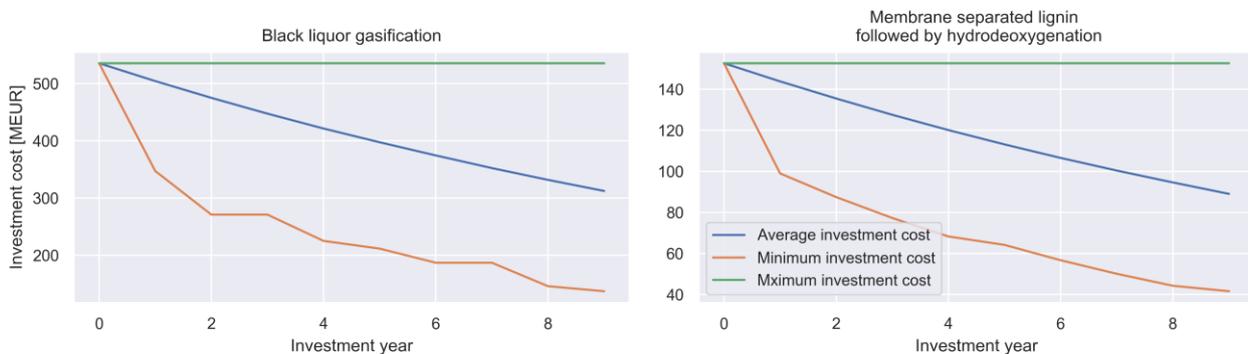

Figure 1. Future simulated and TRL-compensated investment costs, see (4) and (6), displaying the scenarios with the lowest, highest, and average learning curve.

3.3.2 Commodity prices

The future commodity prices, see (2), are modelled using the drift and volatility as estimated from historical price data. The estimated volatility and drift of the prices of biomass, electricity, hydrogen (calculated as a factor 1.6 larger than the natural gas price [21]), ethanol, and biodiesel/FAME are displayed in Table 2.

Table 2. Commodity price data estimates.

	Biomass	Electricity	Hydrogen	Ethanol	Biodiesel
Initial price[1]	7.47	44.4	42.6	70.1	81.0
Drift	0.0204	0.0384	0.0420	0.00393	0.0330
Volatility	0.106	0.254	0.201	0.212	0.167
Price data source[2,3]	[34]	[35]	[35]	[36–38][3]	[36–38][3]

[1]Prices are given in EUR/MWh on an HHV basis.
[2]Historic price data has been adjusted for inflation.
[2]Data was extracted from figures using [39].
[3]The historic price data series for the different commodities can be found at [40].

Future price curves, equation (2), are simulated using initial price, drift, and volatility from Table 2. In Fig. 2, the average, the 15th and the 85th percentile of the price distributions are displayed.
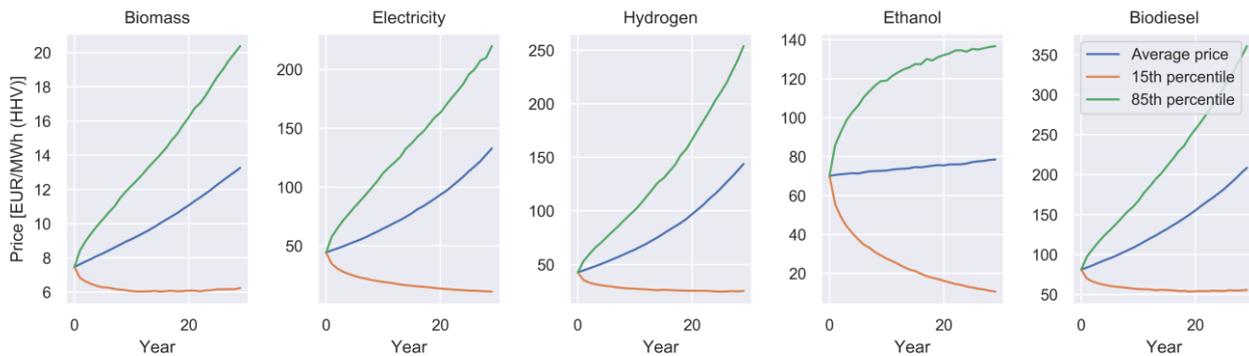

Figure 2. Future simulated commodity prices, see (2), displaying the average, 15th and 85th percentile prices from the distributions.

3.3.3 Technology performance

The net energy performance for the technologies, as well as the scale of the biofuel production for each technology choice, are presented in Table 3. The balances are presented as the net energy balances of the facilities as integrated with the host industry, where the pulp mill, for instance, must import additional biomass to cover reduced steam production in for the integration of BLG. The transport of the lignin oil from the pulp mill to the oil refinery is excluded in this study, as the cost of this is small compared to the other costs. Annual operating time is assumed to be 8000 h/a for both technology choices.

Table 3. Energy balance, size of the facilities, and performance data are taken from [21].

	Total biofuel production [MW_HHV]	Normalised energy balance[3]					
		Biomass	Electricity	Hydrogen	Methanol	Green Gasoline	Green Diesel
BLG[1]	110	-0.620	0.274	0	1	0	0
MSL-HDO[2]	34	0	-0.334	-0.359	0	0.182	0.818

[1] Black liquor gasification
[2] Membrane separated depolymerised lignin followed by hydrodeoxygenisation
[3] Energy balance normalised against 1 MW HHV biofuel production

4. Results and discussion

An initial economic evaluation using traditional discounted cash flow analysis, without considering flexible investment timing was done to illustrate the economic performance of the two technology options. Shown in Fig. 3, are the distributions of the actual (simulated) economic performance of the technologies if the investments would be carried out in one of three different time-steps (year 0, 5 or

9, respectively), regardless if the expected NPV indicates a negative return on the investment for a specific scenario.
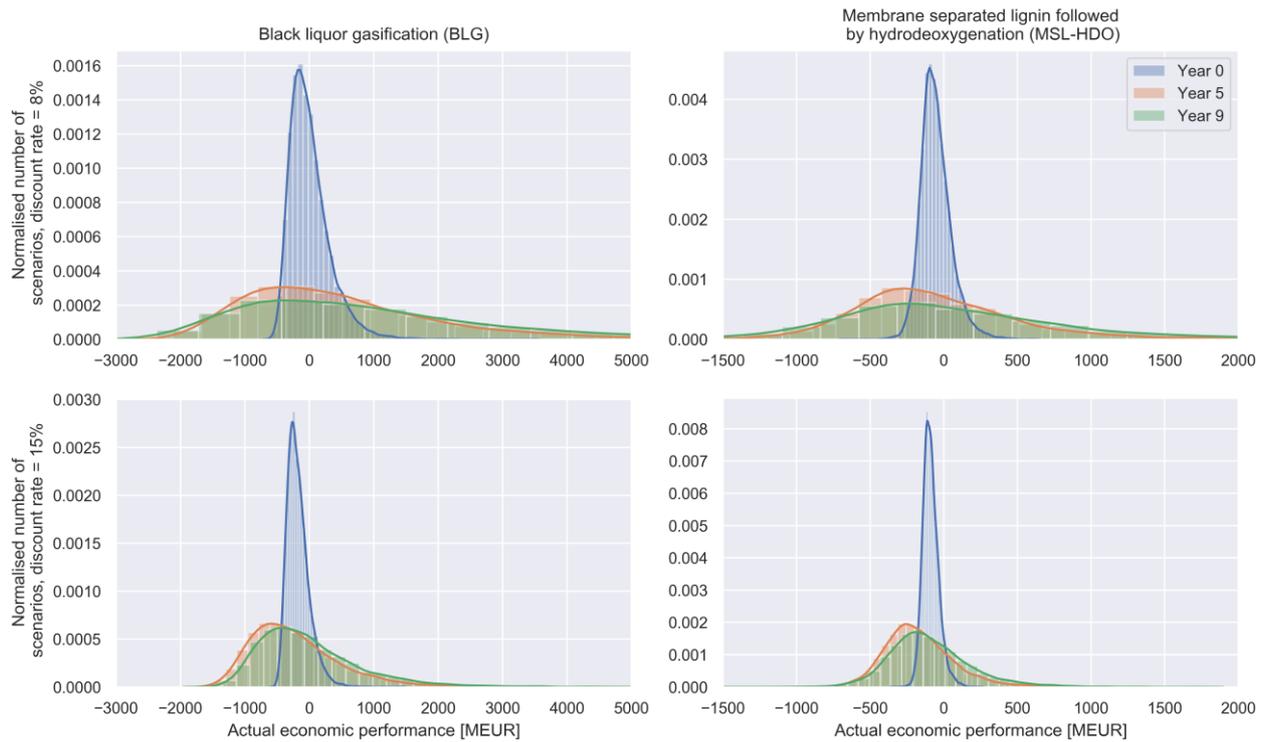

Figure 3. The actual economic outcome for the simulated scenarios depending on investment year, technology and discount rate. Top: discount rate of 8%, bottom: discount rate of 15%.

The results for this case study show a slightly better performance for the BLG technology compared to the MSL-HDO, by having on average, a higher actual economic outcome. Further, the share of scenarios resulting in a net profit is on average 16% and 10% higher for the BLG technology, for a discount rate of 8 and 15%, respectively. MSL-HDO results in a net loss in most of the scenarios for both discount rates, with the highest share of profitable scenarios occurring at the 8% discount rate in investment year nine where 31% of the scenarios were profitable. The BLG has a higher share of profitable scenarios, but there is still a large share of scenarios where the investment would make a net loss. That the future outcome is highly uncertain indicates that the use of flexible decision-making and real options theory could be beneficial by identifying when in time and at what economic conditions that investment in either technology would be favourable.

The two investment decision strategies, investing when NPV>0 and investing according to the real options framework, respectively, were used for the simulated future scenarios (commodity prices and investment costs). Fig. 4 shows the time of investment, the technology chosen, and if no investment has been made for the two assumed discount rates according to the two investment decision strategies. The output data from the model can be found at [40].
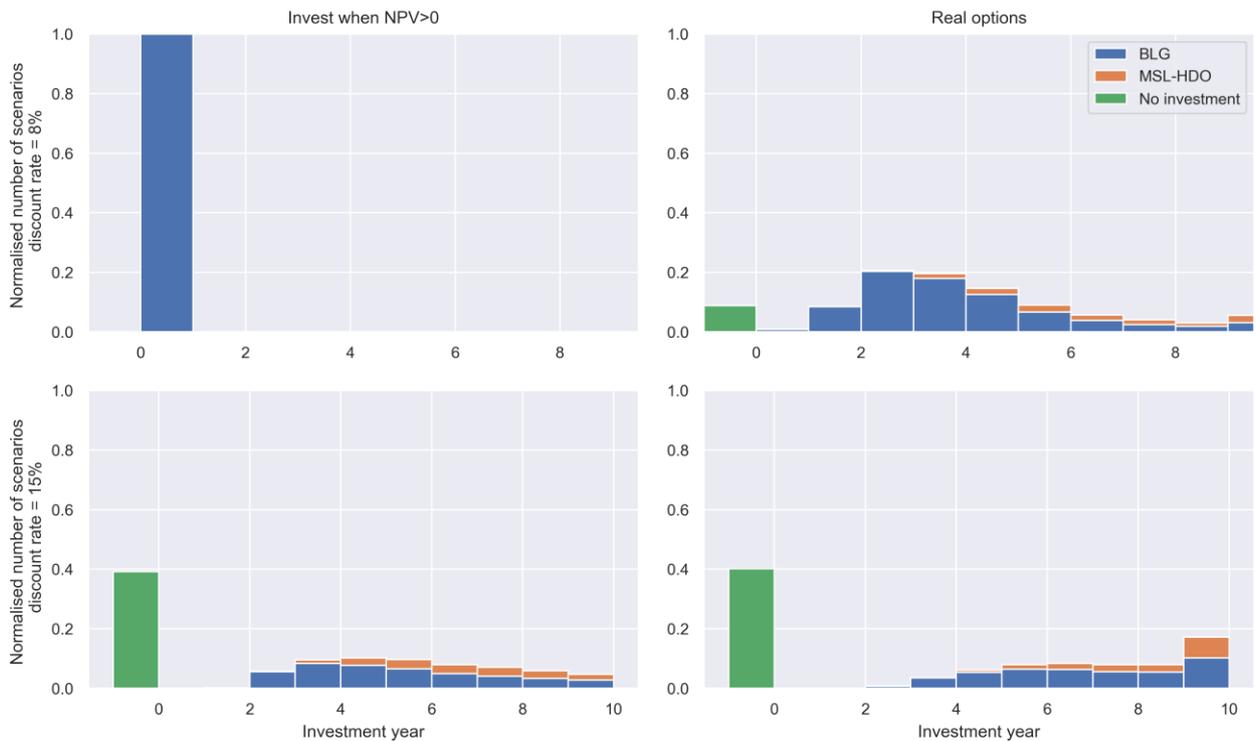
Figure 4. Year of investment according to left: straight discounted cash flow and investing when expected NPV>0, and right: implementing the real options framework, assuming a discount rate of top: 8%, bottom: 15%.

As could be expected, the investment according to the real options framework favours a delay in the investment compared to investing as soon as the expected NPV>0. Notably, for the 8% discount rate, investment occurs directly when using the investment decision strategy NPV>0 as the expected NPV of BLG is positive in the first time-step. For the higher discount rate, the differences are smaller, which can be attributed to the future earnings being discounted at a higher rate.

The impact on the choice of technology using the two different methods for deciding when in time to invest is not significant for the discount rate of 15%. However, for the discount rate of 8%, the usage of the real options framework shows that the MSL-HDO is of interest, which is not shown when only using the discounted cash flow based investment strategy.

The real options framework should increase the actual economic payoff for the investments and thus reduce the number of scenarios where an investment results in a net loss. Fig. 5 show the actual (simulated) economic outcomes of the scenarios where investment has occurred according to the two investment strategies for the two assumed discount rates.
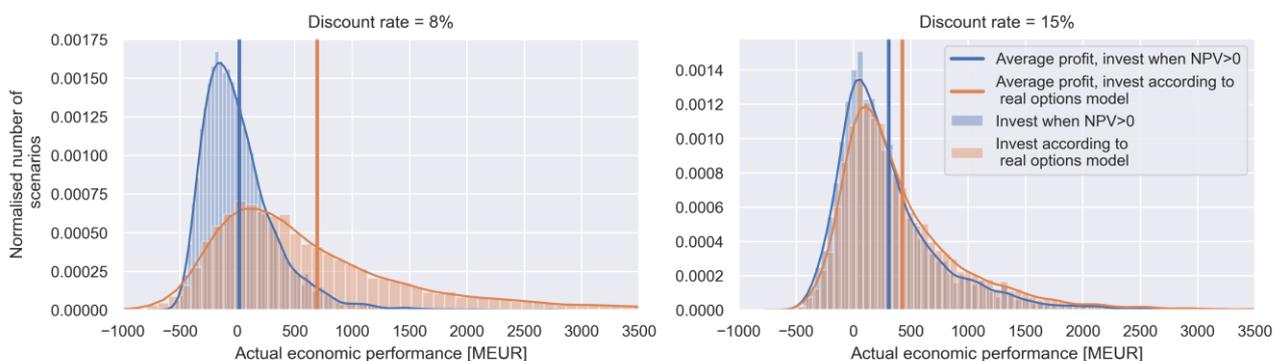

Figure 5. Actual economic performance according to the two investment rules, left: discount rate 8%, right: discount rate 15%.

By comparing Fig. 5 with Fig. 3, the impact of employing flexible decision making in the evaluation of the technologies is highlighted as the share of scenarios where a net loss occurs is significantly reduced. In addition to this, Fig. 5, shows the potential added value of employing the real options framework compared with using discounted cash flow analysis, in the form of improved economic performance, and a reduction in the share of scenarios where a net loss occurs. For this case study, the average profits increased by 680 MEUR, and 110 MEUR for 8% and 15% discount rates, respectively, when the real options framework was applied. The share of scenarios where investment would result in a net loss thus decreased from 57% to 23% for the 8% discount rate, and 25% to 19% for the 15% discount rate.

This work has focused on the impact on the time of investment and economic performance by using a real options framework showing that the option to postpone the investment can improve the chance of a net profit when investing. By employing a real options framework in the evaluation of emerging technologies, it is possible to both identify when in time investment in those technologies could be favourable and to account explicitly for specific uncertainties regarding the investment. The delay in the time of investment pointed out by the case study when real options analysis was employed may be a way to describe why the industrial implementation of technologies for forest-based biofuel production has been low, although academic literature has suggested that it would be economically favourable.

5. Conclusions

The usage of a real options framework results in postponed investments compared to when using traditional discounted cash flow analysis. It thus results in a reduced likeliness of a net loss of a given project and increases the resulting expected profits, thus clearly showing the added economic value of considering decision maker flexibility in the face of uncertain future conditions. Additionally, it highlights how uncertainties regarding future market prices and investment costs contribute to a favourability of making an investment decision later, which could be a way to identify when in time different technologies could be of interest for industrial implementation.

For the case study with pulp mill integrated biofuel production, the usage of the real options framework was shown to favour a later adaption of the technologies compared to investing according to traditional discounted cash flow analysis. The choice of technology was impacted for the lower assumed discount rate, however not for the higher indicating that more analysis regarding the impact of the assumed discount rate could be of interest for further studies. Future work should also investigate how the parameters used to describe the market uncertainties are influencing the results.

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