We need stable, long-term policy support! - evaluating the economic rationale behind the prevalent investor lament for forest-based biofuel production

Zetterholm, Jonas[a,*], Mossberg, Johanna[b], Jafri, Yawer[a], Wetterlund, Elisabeth[a,c]

[a] *Luleå University of Technology, Energy Science/Energy Engineering, Luleå, Sweden*
[b] *RISE Research Institutes of Sweden, Bioeconomy, Gothenburg, Sweden*
[c] *International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*

Abstract

Uncertain and unstable policy support has often been claimed to be a major cause of the slower than expected deployment of technologies for production of advanced biofuels. We investigate the economic rationale of this claim by applying a real options framework incorporating uncertainties regarding energy prices, investment costs, and prevalence of policy support, which was linked to the greenhouse gas (GHG) performance of the produced biofuel. Six industrially relevant forest-based technologies for production of drop-in biofuels were evaluated. The technologies were integrated with a pulp mill and an oil refinery and are at different stages of their technical development. The results show that there is a limited economic rationale behind the claim that policy uncertainties are a major source for the stalled deployment of forest-based biorefinery technologies. Rather, the stalled deployment is mainly related to the uncertainties regarding investment costs and future energy prices, resulting in technologies with lower sensitivity with respect to these uncertainties have a larger chance of becoming commercially relevant investment options. If policy support is intended to promote investment in technologies with high GHG performance, it must be directed specifically to these technologies, otherwise, it is more beneficial to invest in technologies with more favourable conditions for investment and operational costs, but lower GHG performance.

Keywords: Real options; Drop-in biofuels, Pulp mill, Integration, Uncertainty

Acronyms

BLG black liquor gasification-catalytic synthesis

EU ETS EU Emissions Trading System

*Corresponding author, jonas.zetterholm@ltu.se

FCC fluidised catalytic cracking

GHG greenhouse gas

HDO hydrodeoxygenation

Hydropyr catalytic hydropyrolysis-hydroconversion

LPG liquefied petroleum gas

LSH lignin separation-hydrotreatment with natural gas derived hydrogen

LSH-E lignin separation-hydrotreatment with electrolysis derived hydrogen

Pyr-FCC fast pyrolysis with upgrading via fluidised catalytic cracking

Pyr-HDO fast pyrolysis with upgrading via hydrodeoxygenation

RED Renewable Energy Directive (2009/28/EC)

RED II Revised Renewable Energy Directive (2018/2001/EU)

TRL technology readiness level

1. Introduction

Biorefineries have been highlighted as a key to reach fossil fuel reduction targets as they have the potential to produce both upgraded biofuels, as well as chemicals and materials (Fulton et al., 2015; Connolly et al., 2014). However, concerns have been raised regarding land-use change, competition for food crops, and greenhouse gas (GHG) mitigation potential (Stattman et al., 2018; Ziegler, 2008), making it important that the biomass feedstock is sustainably sourced. To address these concerns the EU Renewable Energy Directive (2009/28/EC) (RED) was introduced setting a target for use of biofuels, specified a minimum GHG performance for the biofuels, and prohibited the use of sensitive land areas and capped the use of agricultural crops for biomass feedstock sourcing (European Commission, 2009). However, the directive failed at promoting biofuels with higher environmental performance (Stattman et al., 2018). The Revised Renewable Energy Directive (2018/2001/EU) (RED II) introduced to partly address sustainability concerns with previous legislation with higher targets for sustainability, where for example usage of waste and residues are promoted (Parliament and Council of the European Union, 2018; Mai-Moulin et al., 2021), encouraging the development of advanced biofuels (Stattman et al., 2018).

Although there have been some deployments of biorefineries in the EU, a majority of projects are based on so-called first-generation feedstock (such as sugars and starch), and few are based on second generation feedstock (such as forest residues) (Hassan et al., 2019). The hitherto slow deployment and underdeveloped production capacity of second-generation biorefineries have been accredited to low energy prices, uncertain market conditions, and lack of long-term stable legislation (European Commission et al., 2018; Fallde et al., 2017; European Commission et al., 2017). The uncertainty of future policy conditions, in particular, has been highlighted in previous research as a major point that must be addressed to facilitate an environment where new biorefinery technologies can be deployed (Palgan and McCormick, 2016; Hellsmark et al., 2016; Huenteler et al., 2014), as the current energy and environmental policy landscape is neither long-term nor predictable (Näyhä and Pesonen, 2012). However, while this could be the main reason for industrial actors being unwilling to invest, it is not necessarily true from an economic rationale point of view.

Using traditional discounted cash flow analysis to analyse investments usually constitutes a "now or never" approach (Gazheli and van den Bergh, 2018) since the investor does not have the option to adapt their investment strategy in face of future uncertainties. This approach may thus be unsuitable for investment analysis that includes time-based uncertainties. By instead using real options analysis for the economic evaluation, inclusion of the value of the decision-makers flexibility to adapt, postpone or abandon the investment in respect to changing market conditions is enabled (Trigeorgis, 1996). This means that if the investment decision has been made, the option of waiting for more information regarding the market development is forfeited (Dixit et al., 1994), which creates an opportunity cost associated with the investment decision. Although real options analysis has been suggested as a complementary tool to discounted cash flow, its usage within the industry has been limited, which can be explained by that it constitutes a more problem-specific tool that requires more advanced mathematics (Sandahl and Sjögren, 2003).

For the case of evaluation of biorefinery technologies, also academic application of real options analysis has to date been relatively limited. Real options analyses of biofuel projects have shown that the risk of policy shift can induce both a postponement and a speedup of the investment decision, depending on the direction of the change (Liu et al., 2018; Hassett and Metcalf, 1999). However, it is not only policy support that is uncertain, but also other factors which can result in postponed investment, such as future energy market prices (Li et al., 2015). The future market uncertainties can result in that a significantly higher biofuel selling price is required, compared to the breakeven biofuel selling price, for the investment to be economically rational according to real options theory (McCarty and Sesmero, 2015). This can partly be mitigated with a flexible production strategy, which can result in improved economic performance due to uncertainties in biofuel selling price (Ghoddusi, 2017). In order to properly examine if there is an economically rational argument that policy uncertainty is the main contributor to the lack of investments in advanced biofuel production technologies, it is crucial to also investigate how emerging biorefinery technologies are affected by the interactions between policy and energy market uncertainties. To the best of our knowledge, previous work has to date not yet explored these interactions.

To investigate the validity of the claim that policy uncertainty is a major hindrance to the deployment of biorefinery technologies, we here develop and apply a real options framework. The real options framework incorporates the option for a given decision-maker (investor or plant-owner) to postpone a biorefinery investment in face of future market uncertainties and interactions between policy support level and policy uncertainty. Additional objectives of this work are to identify how investment cost uncertainties affect the technologies, and to assess how policy price and policy uncertainty affect early GHG emissions reduction.

The developed real options framework is applied to a case study for Swedish market conditions. Sweden is chosen as a case study because of its high supply potential of residual biomass (de Jong et al., 2017; Hamelin et al., 2019), and well-developed biomass markets which are a result of the large presence of traditional forest industry (i.e., sawmills, and pulp and paper mills). In addition, the recent introduction of a reduction obligation in Sweden can be expected to create both a market for blend-in biofuels, and a biofuel market price which is contingent on the fuel's GHG performance (Furusjö and Lundgren, 2017). The reduction obligation, a policy support mechanism that targets biofuels in the Swedish road transport sector, enforces a penalty if a fuel supplier fails to meet GHG emission reduction targets via blend-in of biofuels (Swedish energy agency, 2019). While this mechanism is aimed at promoting biofuels with high GHG performance, it is also subject to the uncertainty that the policy support will disappear. Finally, Sweden has seen significant interest from industrial actors with several promising ongoing research and development projects for biorefinery technologies at different technology readiness level (TRL). Particular interest is placed on technologies that combine integration with pulp and paper mills and oil refineries for the production of drop-in biofuels (Jafri et al., 2019a,b), which enables benefits regarding both heat and material integration, and utilisation of already existing industrial infrastructure.

The paper is structured as follows: Firstly, the investigated technologies are presented in section 2. This is followed by a description of the developed real options framework in section 3.1, and the input data and methods to calculate input data in section 3.2 - 3.6. Section 3.7 summarises the evaluated scenarios and the key performance indicators used for the evaluation. The results are presented for simulated prices and investment costs in section 4.1, and the the results according to the investment strategy from the real options framework are presented in section 4.2 - 4.4, followed by overall conclusions in section 5.

2. Technology descriptions

The chosen technologies represent a selection of industrially relevant technologies for the production of advanced drop-in biofuels. The technologies are integrated with pulp mills and oil refineries in order to be able to benefit from both heat and material integration, and to enable the use of existing infrastructure to produce transport range fuels. The feedstocks are either based on forest residues, or black liquor (a by-product in the kraft pulping process).

The technologies included in the study are summarised in table 1, with their respective average TRL, used to adjust the literature assessed investment cost, see section 3.5. A summary of the assessed TRL of each processing step in the technologies is found in Appendix A.

Table 1: Outline of technologies included in study.

Feedstock	Technology	Average TRL[1]	Abbreviation
Black liquor	Lignin separation-hydrotreatment with natural gas derived hydrogen	5.2	LSH
	Lignin separation-hydrotreatment with electrolysis derived hydrogen	5.0	LSH-E
	Back liquor gasification-catalytic synthesis	7.0	BLG
Forest residues	Fast pyrolysis with upgrading via hydrodeoxygenation	6.0	Pyr-HDO
	Fast pyrolysis with upgrading via fluidised catalytic cracking	6.5	Pyr-FCC
	Catalytic hydropyrolysis-hydroconversion	4.8	Hydropyr

[1]For details on TRL-level of each specific processing step, see Appendix A.

2.1. Black liquor-based technologies

Black liquor is a lignin-rich by-product from the kraft pulping process, which currently is combusted in a recovery boiler for the production of process steam and recovery of the pulping chemicals. In the black liquor-based biofuel production pathways considered here, a part-stream of the black liquor is diverted from the flow to the recovery boiler to be used as feedstock for biofuel production. In this way, a pulp mill can increase the pulp production capacity if the recovery boiler is otherwise a bottleneck in the production[1]. The two technology options examined in this work are lignin separation followed by hydrotreatment (LSH and LSH-E), and black liquor gasification followed by catalytic synthesis (BLG). In the two LSH pathways, the lignin is separated from the black liquor and used as feedstock for the biofuel production, while BLG utilises the pure black liquor directly as feedstock.

[1]No economic consideration is received from value creation from eventual debottlenecking of pulp production.

2.1.1. Seperation-hydrotreatment

The lignin is membrane-separated from the black liquor, returning the pulping chemicals to the pulp mill (Anheden et al., 2017). The separated lignin is purified and stabilised in the form of lignin oil before it is sent to the oil refinery, where it is hydrotreated and upgraded to diesel and petrol (Suncarbon AB, 2020). The technology has relatively low technological maturity and operational experience, compared to fast pyrolysis and BLG (Anheden et al., 2017), but benefits from not requiring facilities with high production capacity to be profitable, due to low specific investment cost (Jafri et al., 2019b).

The source of hydrogen will heavily influence the GHG performance of the process, and two options for the technology are studied. The first option considers that the hydrogen is produced at the refinery from natural gas, LSH, while the second option considers the investment in an electrolyser to produce hydrogen from electricity and water, LSH-E.

2.1.2. Gasification-catalytic synthesis

The pure black liquor is gasified in an entrained flow gasifier to produce syngas and green liquor, where the latter contains the pulping chemicals and is returned to the pulp mill. The syngas is synthesised to methanol which is transported to the oil refinery, where it is upgraded to the main product petrol, with some co-production of LPG, via the methanol-to-gasoline process.

The gasification of black liquor has been demonstrated as a viable route to simultaneously produce biofuels and recover pulping chemicals, and has been successfully demonstrated in pilot-scale (Landälv et al., 2014). The pathway has a relatively high TRL and has been suggested to be economically favourable (Akbari et al., 2018; Andersson et al., 2016). Although BLG has a relatively high TRL, it is also associated with a relatively high specific investment cost.

2.2. Forest residues-based technologies

The technologies relying on forest residues as feedstock are based on fast pyrolysis (Pyr-HDO and Pyr-FCC) and catalytic hydropyrolysis-hydroconversion (Hydropyr), respectively. In these pathways, forest residues are converted to pyrolysis liquids, which are subsequently upgraded to petrol and diesel blends. The pyrolysis step is integrated with a pulp mill and the upgrading takes place at an oil refinery. While the pyrolysis pathways do not necessarily have to be integrated with pulp mills, this design was selected in order to make the supply chains directly comparable with the black liquor-based pathways. Additionally, heat integration with pulp mills has been shown to be economically favourable (Zetterholm et al., 2018), and the integration can provide benefits in terms of logistics and know-how from the experience of the pulp mill in operating large-scale biomass supply chains[2].

[2]No economic benefit from this is considered in this work, as the benefit is difficult to quantify.

2.2.1. *Fast pyrolysis*

The fast pyrolysis facility is heat integrated at the pulp mill and forest residues are imported as feedstock to produce pyrolysis liquids, which is subsequently transported to the oil refinery for upgrading to diesel and petrol. The fast pyrolysis technology is at a relatively high TRL (Anheden et al., 2017). Several technology options for upgrading the pyrolysis liquids into diesel and petrol have been previously investigated (Sorunmu et al., 2020), of which this work includes two options: hydrodeoxygenation (HDO), and fluidised catalytic cracking (FCC), respectively.

Using the HDO upgrading pathway, the pyrolysis liquids undergo conversion in a two-step catalytic hydrodeoxygenation process, followed by hydrocracking to petrol and diesel. The upgrading of pyrolysis liquids to transport fuels has been subject to significant research (Zacher et al., 2014) but operational data from long-term/sustained pilot demonstration is not widely available in the scientific literature. In the FCC upgrading pathway, the pyrolysis liquids are co-processed with fossil feedstock in the FCC unit at the refinery to produce diesel and petrol (Pinho et al., 2017). Compared to the HDO pathway, the FCC upgrading of pyrolysis liquids has significant lower hydrogen requirements. It should, however, be noted that the technical limit of blended-in pyrolysis liquids in the fossil feedstock amounts to a maximum of 10wt% percent (Pinho et al., 2017).

2.2.2. *Hydropyrolysis*

The catalytic hydropyrolysis-hydroconversion facility also is heat integrated with the pulp mill. In this pathway, forest residues are imported as feedstock to the pulp mill to directly produce unrefined diesel and petrol, which is transported to the oil refinery for blending and final upgrading. While the technology is currently at a low TRL (Jafri et al., 2019b), it has a major advantage compared to the other pyrolysis-based technologies in that the deoxygenation is occurring directly within the hydropyrolysis process (Dabros et al., 2018; Marker et al., 2013). This results in a low requirement of integration at the oil refinery. A majority of the product is petrol (also true for the BLG pathway), which could make it interesting for future drop-in biofuel markets, which otherwise typically are dominated by diesel type fuels, as well as in future scenarios with relatively high petrol prices compared to diesel.

3. Methods and data

Fundamental for the real options framework developed and applied for this study is that the decision-maker (investor or plant-owner) has the option to (1) invest now, (2) postpone the investment decision, or (3) decide not to invest (section 3.1). The framework was implemented using Monte-Carlo simulations to simulate future uncertain market conditions. Future energy prices were simulated assuming a Geometric Brownian motion (section 3.2), policy uncertainty was simulated assuming a Poisson jump process (section 3.3), the GHG footprint of the technologies was assessed using two methods (section 3.4), and the

TRL-adjusted investment costs were based on an empirically developed correlation between projected and actual investment costs in pioneering process plants (section 3.5). The developed real options framework was applied and evaluated based on various performance indicators, as presented in section 3.7.

The model was implemented in Python (Millman and Aivazis, 2011) relying on Numpy (Harris et al., 2020) and Pandas (McKinney et al., 2011, 2010) for improved maths and data handling functionality, and Matplotlib (Hunter, 2007) and Seaborn (Waskom et al., 2020) for visualisations.

3.1. Real options framework

In our real options framework, the investor is in each time-step (set to 1 year) of each specific simulation faced with the decision options to either invest directly, or postpone the investment decision to the following time-step. This is iterated for each time-step until the end of the investment horizon (set to 10 years) where the investor no longer has the option of postponing the investment decision and instead is faced with the decision to either invest immediately or abandon the investment. The end of the investment horizon thus represents the end of the viability to invest in the selected technologies.

The investment decision is based on the expected net present value ($E[NPV]$), calculated from the known investment cost in the specific simulation (the TRL-adjusted investment cost), the energy balance of the technology, and the expected future energy prices. If the expected net present value is equal to or greater than the value to postpone the investment ($Waitvalue$), the investment is made, and the investor no longer has the option to invest in a later time step. The decisions follow the rules:

$$t < 10 \begin{cases} E[NPV]_{n,t} > Waitvalue_{n,t} & \text{invest} \\ E[NPV]_{n,t} \leq Waitvalue_{n,t} & \text{postpone} \end{cases}$$

$$t = 10 \begin{cases} E[NPV]_{n,10} \geq 0 & \text{invest} \\ E[NPV]_{n,10} < 0 & \text{abandon} \end{cases}$$

The $Waitvalue$ for each specific simulation was calculated according to:

$$Waitvalue_{n,t} = \frac{\left(\sum_{n_w=1}^{N} \left(max\left(E[NPV]_{n_w,t+1}, 0\right)\right)\right)}{N(1+r)} \tag{1}$$

where N is the total number of (nested) simulations, n is the specific Monte Carlo simulation where the $Waitvalue$ is compared against the expected NPV ($E[NPV]_{n,t}$). n_w is a specific (nested) simulation used to represent the stochastic nature of the possible future developments to determine the waitvalue for scenario n, t is the current time-step, $E[NPV]$ is the expected net present value, and r is the discount rate. For each specific scenario n, there are thus N simulations to determine the waitvalue.

In total, the real options framework utilised 2500 Monte-Carlo simulations, and the calculation of the *waitwalue* utilised 2500 (nested) Monte Carlo simulations.

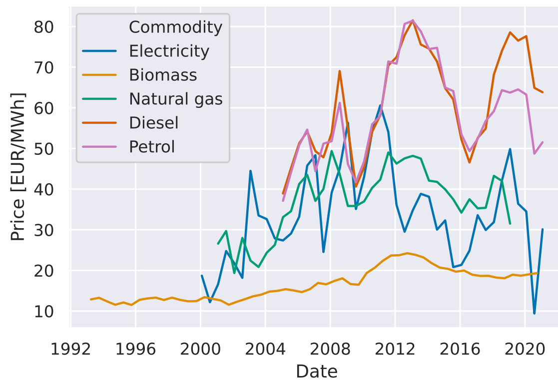

Figure 1: Historic price series based on the lower heating value.

3.2. Energy prices

Future energy prices were simulated assuming that they follow a Geometric Brownian motion, which has also previously been applied to simulate future energy prices (De Giovanni and Massabò, 2018; Li et al., 2015). The price in time-step t was calculated from:

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

where t is the current time-step, P the price, μ the drift, dt the size of the time-step, σ the volatility, and dW the increment of a standard Wiener process. At any specific time-step and scenario where the decision maker knows the current prices $P_{0,n}$, the expected future prices at time-step t, $E[P_t]$, can be calculated as described by Murto (2007):

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

3.2.1. Energy price data

The future energy prices were simulated using equation 2 which relies on the parameters describing the energy price drift (describing long-term price trends), and the price volatility (random price disturbances). The parameters used to simulate future energy prices are shown in table 2, and the historic prices used to estimate these parameters in figure 1.

3.3. Policy support

Two components of the policy support were considered; the risk of policy switching (*policy uncertainty*), and the future price for the GHG emission performance of the biofuel (*policy price*).

Table 2: Estimated parameters describing future commodity prices.

	Initial price[1]	Drift	Volatility	
Commodity	P_0	μ	σ	Source
Biomass	19.3	0.0166	0.00408	(Swedish Energy Agency, 2020)
Electricity[2]	30.1	0	0.147	(Nordpool, 2018)
Natural gas	36.7	0.0257	0.0155	(SCB, 2019)
Hydrogen[3]	58.8	0.0257	0.0155	–
Diesel	64.7	0.0498	0.0360	(European Commission, 2019)
Petrol	49.2	0.0305	0.0258	(European Commission, 2019)

[1]EUR/$\mathrm{MWh_{LHV}}$ [2]The drift for the electricity price was assumed to 0, as the price development has historically been governed by the volatility. [3]Initial price for hydrogen was calculated as a factor 1.6 larger than the price for natural gas (Jafri et al., 2019b) and the drift and volatility was assumed the same as for natural gas.

As the recently introduced reduction obligation has been implemented with a penalty if the fuel supplier fails to fulfil the reduction obligation, it is natural to assume that a market will develop which depends on the GHG emission reduction potential of the biofuel in comparison with the emissions of the corresponding fossil fuel. The price of the biofuel will thus be dependent on the simulated price of the fossil alternative, and the market price for GHG emission reduction, where the latter constitutes the *policy price*. The market price of the blend-in biofuel, $P_{blend-in}$, was calculated according to:

$$P_{blend-in} = P_{fossil} + P_{GHG-reduction} \cdot (GHG_{biofuel} - GHG_{fossil}) \tag{4}$$

where P_{fossil} is the simulated fossil fuel price, $P_{GHG-reduction}$ the policy price, $GHG_{biofuel}$ the GHG footprint of the biofuel, and GHG_{fossil} the GHG footprint of the fossil counterpart.

The risk of policy switching, the *policy uncertainty*, was simulated assuming a Poisson jump process, see for example (Hassett and Metcalf, 1999; Liu et al., 2018). This is in line with the actual tax policy behaviour, which gives an expected duration, but not the actual duration, of a tax policy (Hassett and Metcalf, 1999). For each time-step, there is a probability that policy switching will occur to the following time-step. Policy switching means that if the policy support exists, it can be removed, or, if the policy support is not in effect, it can be implemented.

In our framework, the policy scenarios are described by both the policy price, which is implemented as a fixed price for the GHG emission reduction compared with the fossil reference for each scenario, and the policy uncertainty, which is implemented as a probability (in percent) that there will be a policy switching in the following year.

3.3.1. *Policy price data*

It is to date unknown how the future market for biofuels will develop given the reduction obligation. However, the price for the GHG emission performance of the biofuels will not exceed that of the set penalty for failing to meet the blend-in requirements, which currently amounts to 660 EUR/ton CO_2-equivalent[3]. Given the option to purchase a biofuel with a GHG emission reduction cost lower than the penalty, that biofuel would likely be purchased. The result would be a market price for the GHG emission reduction potential which would be lower than the penalty.

The question is thus how the market for biofuels will develop in the future. Firstly, we can compare with the historic prices in the EU Emissions Trading System (EU ETS), which have been in the range of 5–30 EUR/ton CO_2-equivalent. Next, we can also compare with the current CO_2 tax in Sweden, which affects heat-generating facilities not included in the EU-ETS trading scheme, and which amounts to 105 EUR/ton CO_2-equivalent(World Bank, 2020).

Given the uncertainties of the future CO_2 price, we varied the policy price in the simulations with a CO_2 price of 0–700 EUR/ton CO_2-equivalent (using 50 EUR/ton increments). The higher end of the range thus represents a failure of the market to deliver biofuels with a lower price for the GHG emission reduction potential, compared with the set penalty for failing to meet the blend-in requirements.

3.3.2. *Policy uncertainty data*

The policy uncertainty, expressed as a probability of a policy switching in the following year, was varied from 0–45% in 5% increments. The 0% scenario means that there exists no uncertainty and that the policy support is active during the entire time horizon. In reality, it would not be possible to achieve a 0% uncertainty, as policy support is dependent on political support. The upper limit of 45% uncertainty was set based on observed policy switching for biofuel tax exemptions in the US, which amounted to 44% between 2005–2017 (Liu et al., 2018).

3.4. *GHG footprint evaluation*

We applied two different approaches for expressing the GHG footprint. Firstly, we applied a simplified approach based on the RED guidelines (European Commission, 2009). Secondly, we also applied an approach based on system expansion as described in ISO-14044 (ISO, 2006). The reason for complementing with the ISO-14044 approach (hereafter termed simply ISO) is that the RED guidelines prohibit the allocation of emissions to heat co-products, and thus fails to capture the benefits of heat integration, where heat replaces or reduces the need for another primary fuel.

[3] 7 SEK/kg CO_2-equivalent (Drivmedelslagen, (2011:319, 27 §), converted with 10.6 SEK/EUR (average of 2019) (European Central Bank, 2020)

The GHG footprints for the different technologies are shown together with the fossil fuel reference emissions in table 3. The fossil fuel references are based on the share of each biofuel produced, as they will replace different fossil alternatives; petrol, diesel, and natural gas[4], with reference emissions of 93.5, 95.5, and 67.0 g CO_2-equivalent/MJ, respectively.

Table 3: GHG footprint (g CO_2-equivalent/MJ fuel) for each biofuel production technology, according to the two applied approaches, and the reference emission for the corresponding replaced fossil fuel or fossil fuel mix.

	LSH	LSH-E	BLG	Pyr-HDO	Pyr-FCC	Hydropyr
RED	30.6	-28.9	8.9	31.0	14.7	6.7
ISO	7.0	-52.5	6.0	1.1	-33.7	6.7
Ref emission	95.5	95.5	90.8	94.6	94.9	94.1

3.5. TRL-adjusted investment costs

Projected investment costs are rarely the same as the final investment cost, once a project is completed. This was observed in the seminal work by the RAND-corporation which investigated the correlation between projected investment costs and final costs in various investments in industrial facilities (Merrow et al., 1981). In general, it was concluded that a larger share of commercially unproven technologies (e.g. a lower TRL), and a less inclusive initial cost estimate resulted in both a higher cost increase and a wider spread of the possible final investment cost, as illustrated in figure 2.

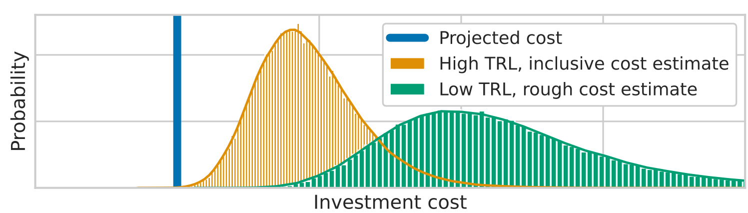

Figure 2: Generic illustration of the correlation between projected investment, and final investment cost depending on the technology readiness level.

To compensate for this effect, we employed the empirically derived equation from Merrow et al. (1981) to adjust the investment cost depending on the TRL of the technology. Equation 5 was used to obtain a value of the cost growth factor, which was in the next step multiplied with the technology investment

[4]the produced green LPG was assumed to replace fossil natural gas as they have historically been correlated prices

cost as assessed in the literature (see section 3.6), to get a likely estimation of the investment cost when implemented.

$$CostGrowth = Intercept - (b_1 PctNew - b_2 Impurities - b_3 Complexity \\ -b_4 Inclusiveness - b_5 ProjectDefinition) \tag{5}$$

where $Intercept$, b_1, b_2, b_3, b_4, and b_5 are empirically estimated parameters. $Intercept = 1.12196$, $b_1 = -0.00297$, $b_2 = -0.02125$, $b_3 = -0.01137$, $b_4 = 0.00111$, and $b_5 = -0.06361$, the standard deviation for the parameters were 0.083. The definition, range of values, and criteria for each parameter were determined as:

$PctNew$, **0-100** Defined as the percentage of the total investment cost that consists of technologies unproven in commercial scale. In this study, each process step with an estimated TRL < 8 was deemed unproven in commercial scale.

$Impurities$, **0-5** Estimate of the difficulties encountered with process impurities in the development process.

$Complexity$, **1+** The number of processing steps in the plant. Each major processing step contributed to the count, and both the integration with the pulp mill and the oil refinery were counted as separate steps.

$Inclusiveness$, **0-100** Defined against if the items; 1) land costs (property/ leases/ rentals), 2) initial plant inventory/warehouse parts/catalysts, 3) pre-operating personnel costs are included in the cost estimate.

$ProjectDefinition$, **2-8** The level of engineering and site-specific information included in the estimate.

The value for the level of engineering was determined from the list:

1. Design specification
2. Moderate or extensive study design
3. Limited study design
4. Screening study

Site-specific information was determined as the average value on a four-point scale assigned for each item in the list below:

- On-site and off-site unit configuration
- Soils and hydrology data
- Health and safety requirements,
- Environmental requirements

where the values were determined according to:

1. Definitive or completed work
2. Preliminary or limited work
3. Assumed or implicit analysis
4. Not used in the cost estimate at all

3.6. Techno-economic input data

For all technologies, the annual operation and maintenance costs were assumed to be 4% of the TRL-adjusted investment cost (as described in section 3.5), the annual operating time 8000 h, the discount rate 15%, and the economic lifetime 20 years. It was also assumed that all technologies, as described in this paper, would constitute feasible investments in the defined 10-year investment window. After those 10 years, the technologies would either have been supplanted by other technologies, or technology development or significant market changes would have occurred, which would make it necessary to alter the technology descriptions.

The total investment costs, as assessed in the literature, at both the pulp mill and oil refinery are shown in table 4 together with the estimated parameters for TRL-adjustment of the investment costs according to equation 5. The investment costs were updated to the monetary value year of 2019 using the Chemical engineering plant cost index (CEPCI, 2020) and represent first-of-a-kind investments. A note on the difference between the cost-structure of LSH and LSH-E The difference between these options is that the hydrogen production cost is included in the operational costs for LSH, while it is mainly included in the investment cost for LSH-E (apart from the increased electricity usage). Additionally, LSH will require investment in additional hydrogen production capacity at the refinery if the current production capacity is insufficient, however, this cost is not considered.

The summary of the main energy inputs and outputs for all technologies, as integrated with a state-of-the-art market pulp mill are displayed in table 5. The numbers are the summary of net changes in energy flows for both the pulp mill and oil refinery, including energy carriers replaced by excess heat from the biorefinery process, where applicable.

3.7. Scenario summary and key performance indicators

The framework was applied for a number of scenarios, defined by a specific combination of the varied exogenous parameters for the policy price, policy uncertainty, and method used to calculate the GHG footprint, as described in the previous sections. In summary, the scenario parameters were defined as and varied according to:

- Policy price - the price for the GHG emission reduction compared to the fossil alternative; 0–700 EUR/ton CO_2-equivalent in 50 EUR/ton increments

Table 4: Investment costs from literature and estimated parameters for TRL adjusting the estimated investment costs, according to section 3.5 and TRL-data in Appendix A. Investment costs were converted to 2019 monetary value using the Chemical Engineering Plant Cost Index (CEPCI, 2020).

	LSH[1]	LSH-E[1]	BLG[1]	Pyr-HDO[2]	Pyr-FCC[2]	Hydropyr[2]
Spec. inv. cost[3]	1.8	5.0	2.6	2.3	3.0	2.8
PctNew	80	100	77	90	85	88
Impurities	5	5	1	5	5	5
Complexity	7	7	6	5	4	5
Inclusiveness	100	100	100	100	100	100
ProjectDefinition	6.5	6.5	3.75	6.5	6.5	6.5
CostGrowth[4]	2.52	2.97	1.48	2.57	2.41	2.53

[1]Investment cost from Jafri et al. (2020). [2]Investment cost from Jafri et al. (2019b). [3]Specific investment cost as assessed in the literature. [4]Result from equation 5 without standard deviation. Used as multiplying factor with literature assessed investment cost.

Table 5: Main energy inputs and outputs, MW_{LHV}, derived from (Jafri et al., 2019a, 2020). Negative are inputs, and positive are outputs. [1]

	LSH	LSH-E	BLG	Pyr-HDO	Pyr-FCC	Hydropyr
Electricity	-34.8	-129.8	-33.8	1.5	1.5	0.1
Biomass	-36.7	-36.7		-65.8	-65.8	-65.9
Hydrogen	-71.3			-6.0	-1.8	-0.6
Natural gas[2]	112.4	112.4	1.7	10.1	-18.2	
Biofuel product						
Green Diesel	78.8	78.8		7.3	9.0	4.7
Green Petrol	1.4	1.4	40.0	5.9	3.9	12.1
Green LPG			4.6			
Additional fossil product						
Fossil Petrol					11.8	
Fossil Diesel					5.5	

[1]The numbers reflect integration with a state-of-the-art market pulp mill with an energy surplus. [2]Excess heat at the refinery was assumed to replace natural gas, and is included in the energy balance for natural gas. For more information, see Jafri et al. (2019a) where excess heat was assumed to replace heavy fuel oil.

- Policy uncertainty - the risk of policy switching; 0–45% in 5% increments.
- GHG footprint approach - the GHG footprint was expressed both in accor-

dance with the Renewable Energy Directive, and with ISO-14044; labelled RED and ISO, respectively.

The key performance indicators used to assess the results for the scenarios, and technologies were:

Investment share: The share of the simulations in a specific scenario where an investment occurred. This should be interpreted as the share of simulated scenarios in that specific scenario where investment will be economically rational for the 10-year investment window.

Average investment year: The average investment year for all simulations within a scenario that resulted in an investment, meaning that all simulations where no investment occurred are ignored. An early average investment year should be interpreted that there is a high likeliness that the technology is favourable for early investment for the given scenario.

Early emissions reduction: The total GHG emissions reduction compared with the fossil reference within the investment window. The early emissions were calculated according to ISO-14044 regardless of the method used to calculate the policy support received (RED or ISO). This was chosen as it represents a more "true" description of the changes of CO_2 emissions in the system as it accounts for the benefits from the heat integration, which can be substantial for heat integrated technologies. The value was calculated as the average of all early emission reductions in all simulations for each scenario, including scenarios without investment (which consequently has a GHG emission reduction of zero).

Early emissions reduction cost: The difference between the exogenous policy price in the scenario and the policy support cost for the total early emissions reduction. This accounts for the difference between the GHG footprint calculations according to either RED or ISO, and also for the policy uncertainty as it includes data where no policy support is in effect (due to policy switching).

Investment costs resulting in investments: The distributions of the investment costs for the simulations resulting in investments is compared with the entire simulated investment cost distribution. This will show if the investment cost uncertainty is a governing factor for making the technology an economically rational investment.

4. Results and discussion

The results are presented in four sections. First, section 4.1 provides a summary of the simulated TRL-adjusted investment costs and energy prices. Next, the impact of uncertainty on the decision of whether to invest or not is presented in section 4.2, followed by an analysis of the influence of the investment cost in section 4.3. Results regarding how the promotion of early investments impacts early emission reduction and the corresponding cost for the early emission reduction are presented in section 4.4. The chapter is concluded with a summarising discussion that also includes the study's limitations, in section 4.5.

4.1. TRL-adjusted investment costs and future energy prices

Figure 3 shows the resulting distributions for the simulated specific investment costs according to equation 5, compared with the original investment cost estimations from the literature. This outlines how the investment costs of the different technologies are systematically underestimated, concerning their respective TRL.

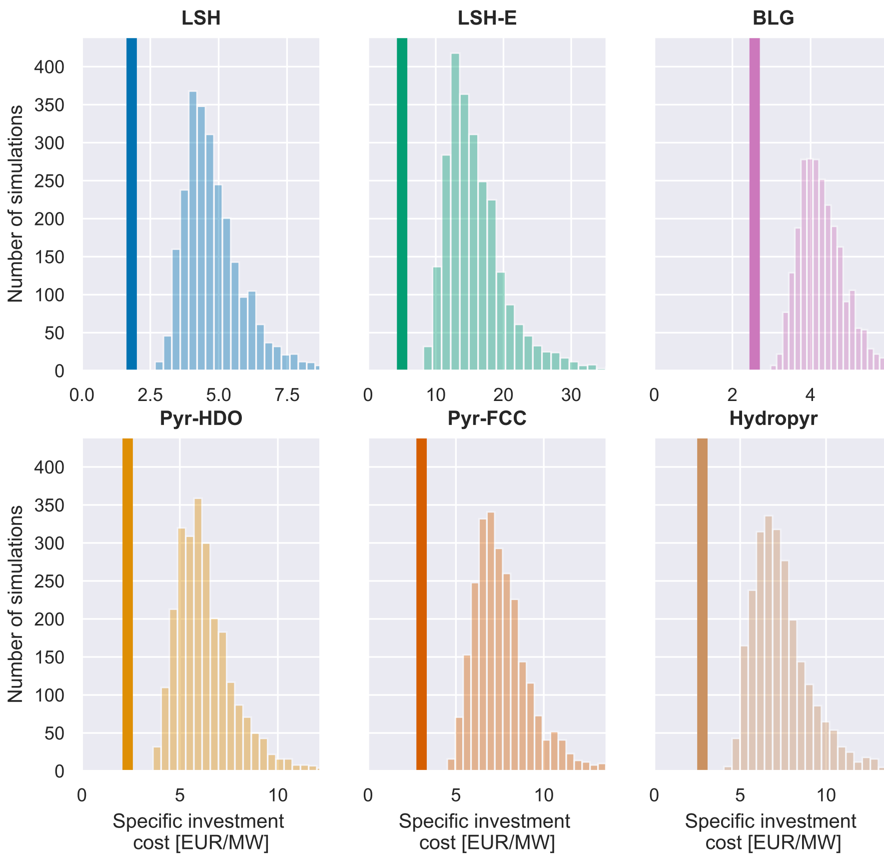

Figure 3: The specific investment cost from the literature (dark vertical line) compared to the resulting simulated TRL-adjusted specific investment costs.

The results from the simulations show that the resulting specific investments costs are the lowest for LSH and BLG, with the most probable specific investment cost located at 4.5 and 3.8 EUR/MW, respectively. Both technologies have a relatively high TRL (affecting $PctNew$ in equation 5). In addition, LSH has a low specific investment cost from the literature, while BLG has both a low problem with impurities (affecting $Impurities$ in equation 5) and a high level of engineering detail in the cost assessments (affecting $ProjectDefinition$ in equation 5).

For the forest residues-based technologies, the resulting specific investment costs with the highest probabilities were 5.9, 7.2, and 7.1 EUR/MW, for Pyr-HDO, Pyr-FCC, and Hydropyr, respectively. The technologies are of similar TRL and level of detail in the cost assessments as LSH, however, they suffer from a higher estimated specific investment cost from the literature.

The outlier in terms of resulting specific investment cost is LSH-E, with a most probable specific investment cost amounting to 15 EUR/MW. This is explained by a combination of high specific investment cost from the literature due to the need to invest in an electrolyser, and that a majority of the investment cost is related to process equipment not tested in commercial-scale (affecting $PctNew$ in equation 5). This is again mainly related to the investment in the electrolyser, as the same is not true for LSH, which is basically the same technology but without the electrolyser. Here, it should be noted that for LSH, the natural gas-based hydrogen has been assumed to be imported, and thus the investment in methane reforming capacity is not included in the investment cost, meaning that a part of the cost component is shifted from capital to operating expenses. As a consequence, the absolute specific investment costs of LSH and LSH-E are not fully comparable.

The future simulated energy prices are shown in figure 4, with the average, 10^{th} and 90^{th} percentile of the simulated future prices plotted, together with the price path of one specific scenario as illustration.

With the simulated future prices some implications from the assumptions regarding the future prices should be noted. Diesel and petrol prices have historically been correlated (see figure 1) with the prices starting to diverge around 2017. In this work, no future correlations were considered, and while the estimated drift and volatility are similar, the future prices are independent of each other.

No drift was assumed in the future electricity prices, but it has historically been subject to very large price volatility. This resulted in a wide distribution in the simulated future prices, meaning that the future market as observed by the investor in the real options framework is subject to very high uncertainties. Similarly, the simulated future prices for the other energy carriers (except biomass due to the low historic volatility), display a relatively wide range of outcomes, and particularly diesel and petrol show not only a wide distribution of future prices but also a high expected price increase compared with current prices. It should be remembered that the prices are shown for a 30-year time horizon and the final price point is here shown for the year 2050. Conversely, the investment horizon considered for the analysis was 10 years.

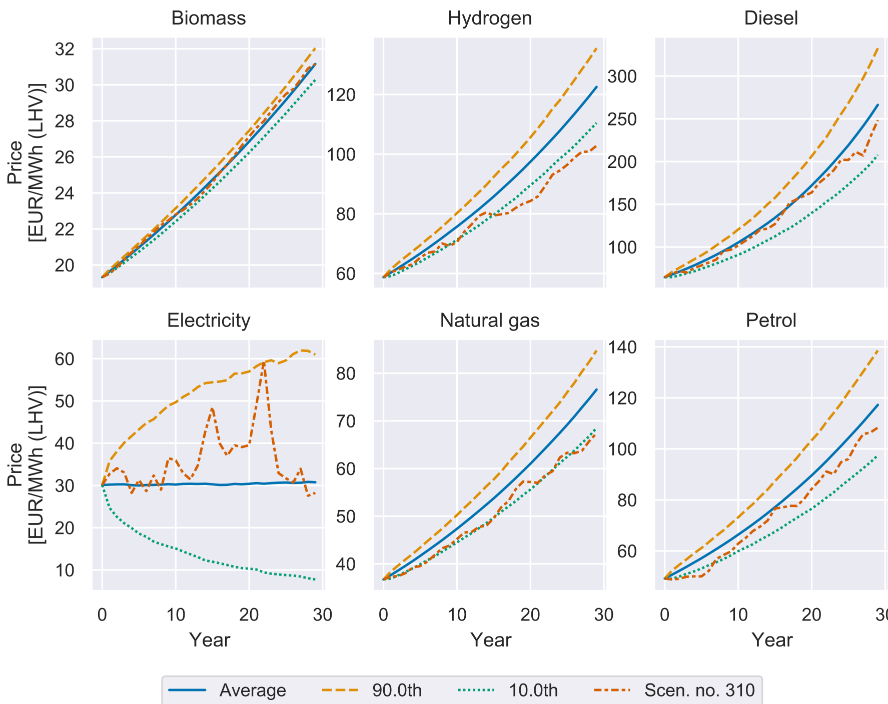

Figure 4: Average, 10$^{\text{th}}$ percentile and 90$^{\text{th}}$ percentile of all simulated future energy prices together with the price path of one specific simulated scenario (randomly selected and shown for illustrative purposes).

4.2. Investment share and investment timing

Figure 5 shows the share of the simulations that result in investment, and the average investment year for all simulated scenarios (policy uncertainty, policy price, and method to calculate GHG footprint). To note is that the result includes investments for the entire investment horizon, which also includes the investments occurring in year 10, where the investor no longer has the option of postponing the investment decision.

With the current market development, the results show that LSH is a technology where it is a high likeliness that the future market conditions will make it an economically rational investment choice. This is especially true since it is not reliant on any policy support to reach a 60% investment share. Also, BLG is a technology of particular interest, albeit reliant on relatively high policy prices to achieve economically favourable conditions. If the market, however, achieves sufficiently high policy prices, BLG shows both high investment shares and favourable results in terms of early investments. For the technologies with a low likeliness to achieve favourable economic conditions (LSH-E, Pyr-HDO, Pyr-FCC, and Hydropyr), a higher uncertainty leads to a need for very high policy prices for investments to occur at all.

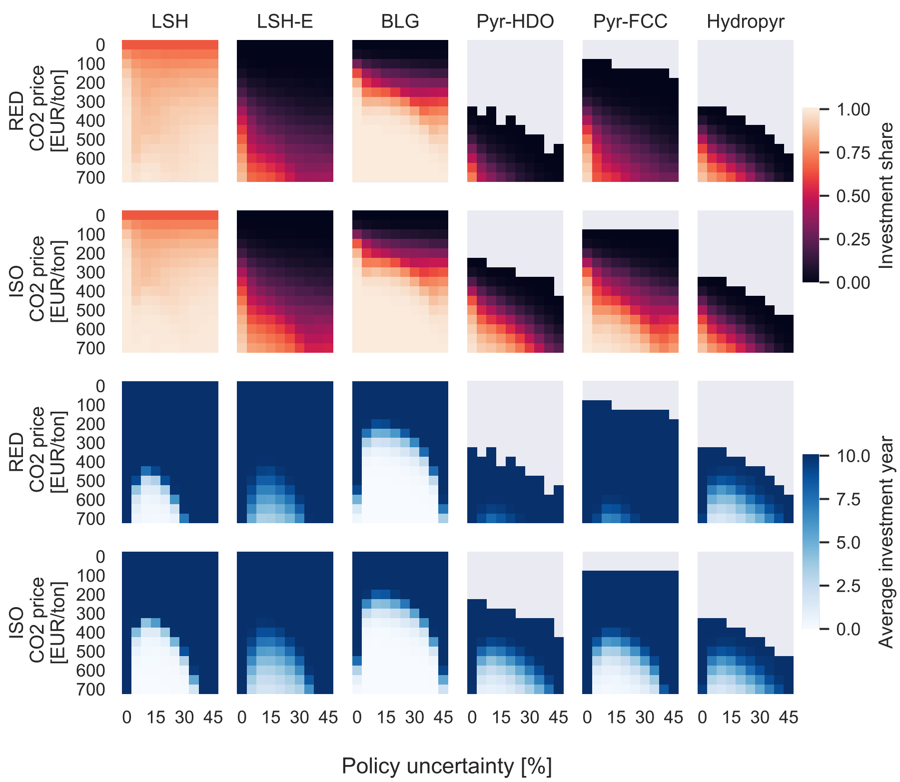

Figure 5: Share of simulations resulting in investment (top) and the average investment year (bottom), per scenario (policy uncertainty, policy price, and method to calculate GHG performance). Grey = no investment for that particular scenario.

While LSH reaches a high investment share regardless of the policy price, it is reliant on very high policy prices for investments to occur early in the investment horizon. Conversely, while BLG is reliant on the policy price to achieve significant investment share, once sufficient policy support is in place it is likely to achieve early investments.

Pyr-HDO and Hydropyr would seem to be technologies that are of no interest due to their low probability of achieving favourable investment conditions. However, if the policy price reaches levels where investments are favourable, they are likely to achieve investments earlier in the investment horizon. Compared with the other technologies, they have characteristics that make it less favourable to wait for better market conditions, i.e., they have a relatively low share of scenarios where investments occur late in the investment window.

For all technologies, an absence of policy uncertainty (0%) is favourable for investments occurring. However, it would be unreasonable to reach a political support system with stable, guaranteed support for a 30-year time horizon. While the absence of policy uncertainty (0%) has a positive influence on the share of simulations resulting in investments, it consistently results in investments occurring later in terms of the average investment year. This can be explained by that the investor is guaranteed to receive the policy support, and it becomes economically favourable to postpone the investment to wait for better market conditions. It is, however, not guaranteed that the specific simulations result in better market conditions in the future, it is only more likely.

When comparing the two approaches for estimating the GHG performance, all technologies except Hydropyr were found to benefit from being able to account for heat integration benefits in accordance with ISO-14044, regarding the required policy price for investments to occur. However, the differences in terms of both investment share and investment timing were relatively small. The forest residue-based technologies (Pyr-FCC and Pyr-HDO) were the only technologies majorly impacted by accounting for their GHG performance using ISO-14440. Although the GHG performance is improved in the same magnitude for the lignin separation technologies (LSH and LSH-E, see table 3), those technologies were not impacted nearly as heavily. For LSH, this is explained by that the technology does not rely on the income from the GHG performance to be an economically viable alternative, and it is thus only marginally affected by the increased income. LSH-E is, conversely, reliant to some extent on the income from GHG emission reductions to be economically viable. The simulations resulting in investment are, however, more sensitive to the investment cost of that particular simulation than to the GHG performance.

4.3. Impact of investment cost on investment decision

Naturally, not only the policy price and policy uncertainty impact the decision whether to invest or not, but also the investment cost and related uncertainty. This section explores the impact of the investment cost on the investment decision. Figure 6 illustrates the specific investment cost distributions over the entire simulated range (blue boxes), versus over the simulations that result in a positive decision to invest (orange and green boxes, respectively).

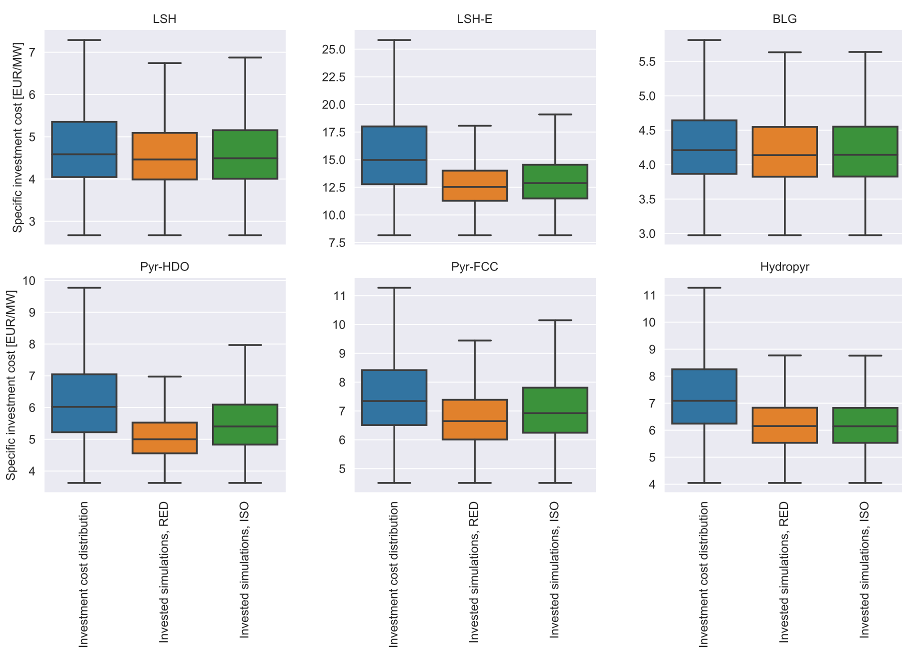

Figure 6: Simulated specific investment cost distributions, for all simulations, and only simulations where investment has occurred for the RED and ISO GHG-footprint scenario, respectively.

Examining the figure, the differences between the entire simulated investment cost distributions, and the distributions of the simulations resulting in investments are significant for all technologies, except for BLG and LSH. This small difference in the investment cost distribution further highlights why BLG and LSH have significant advantages regarding the probability of investment, compared to the other technologies, as they have lower sensitivity to the investment cost uncertainties. Since the future actual investment costs can develop both towards the lower and the upper ends of the TRL-adjusted investment cost ranges, the results show that both BLG and LSH can be viable technologies, as they are robust investments even if the future actual investment costs would develop towards the higher end of the range.

The difference in the results depending on the chosen method to calculate the GHG footprint had only a major impact on the fast pyrolysis-based technologies. They, together with LSH-E were the technologies that were heavily impacted in the assessed GHG footprint, depending on the chose method. That LSH-E was not impacted in the relation between the specific investment costs depending on chosen GHG footprint calculation method shows that the investment costs plays have a much larger impact on the economic performance, compared to the income from the policy support. Contrasting this result with the results in figure 5, which shows that a high CO_2-price favours investment, these results show that unless the CO_2-price is close to the penalty, the investment cost for LSH-E must be in the lower range of the simulated investment costs.

4.4. Avoided early emissions and costs for early emission reduction

Figure 7 shows the avoided early GHG emissions, (i.e., the total avoided emissions within the investment window), as well as the early emissions reduction cost (i.e., the difference between the implemented policy price, and the resulting policy cost for the avoided early emissions). The resulting early emissions policy support cost is consequently a measure of the difference between the cost of the policy support if it was in effect for the entire investment window, and the actual simulated cost of the policy support. This accounts for the simulated scenarios where policy switching occurs and the policy support is not in effect for the entire investment window.

Although higher policy support is received when the GHG footprint is calculated according to ISO instead of RED, the difference in the resulting early emissions reduction cost was found to be negligible. This was true irrespective if there was a large difference between the GHG performance depending on the method used, as for LSH-E, or no difference, as for Hydropyr.

While a low policy uncertainty (excluding the total absence of uncertainty) resulted in a larger share of early investments, a higher policy uncertainty resulted in a lower cost for early emission reduction. This is mainly due to the number of scenarios where investments occur early while the policy support is in effect and the policy support disappears at a later date, increases for the scenarios with higher policy uncertainty.

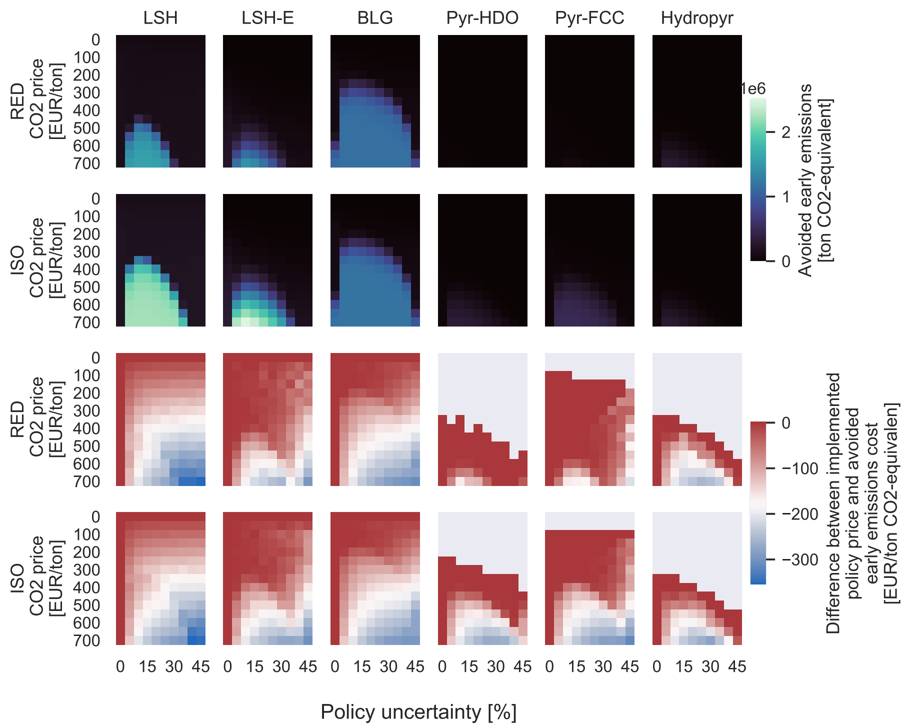

Figure 7: Average avoided early emissions (emissions occurring in the investment window), and the difference between implemented policy price and resulting cost for the avoided early emissions (bottom), per scenario (policy uncertainty, policy price, and method to calculate GHG performance). Grey = no investment for that particular scenario.

4.5. Summary and study limitations

While the results lend some credence to the claim that policy uncertainty is a major hindrance to investments in biorefinery technology, this was shown to primarily be true for technologies that are unlikely to reach favourable investment conditions at all (see figure 5). If excluding the scenario devoid of policy uncertainty, which is unlikely to be achievable, the validity of the claim is weakened further.

Further, while policy uncertainty indeed was shown to negatively impact the total share of investments achieved under the different scenarios, it increases the chance for investments to occur early. Generally, the earliest investments for the lowest policy prices were achieved at a policy uncertainty of 10–15% (meaning that, on average, a policy switch is expected every 6–10$^{\text{th}}$ year). Due to the mechanisms of the real options framework, the uncertainty contributes positively to earlier investments by the virtue of the investor having to invest due to a likeliness that the policy support might disappear in the future. For higher policy uncertainties, this effect disappears as the likeliness of disappearing policy support is negated by a lower total expected policy support over the entire lifetime of the investment.

Under a reduction obligation mandate which creates a market with a price premium for the GHG performance of the biofuel, as investigated here, it was shown that it is not necessarily the specific GHG performance that has the highest impact on investments occurring. This was made evident by the high investment share achieved by the technology with the lowest GHG performance (LSH). Rather, the results showed a preference for technologies with low specific actual investment cost, as BLG and LSH, the technologies with the lowest TRL-adjusted investment costs, were the most favoured technologies.

The type of policy switching which this study has considered was limited to the appearance and disappearance, respectively, of policy support. The results do therefore not consider policy switching where the type of policy support is replaced with a new policy support regime, or where the switch occurs between different levels of policy support. Hence, the simulated policy switching regime represents a worst-case scenario. If the uncertainties reflect switching between different policy regimes, the results should see a lower impact from policy uncertainty.

The policy price in the higher range of 650–700 EUR/ton GHG equivalent emission reduction was based on the current penalty for not complying with the reduction obligation mandate. It is however unlikely that the market for GHG emission reduction from blend-in biofuels would attain those levels, as it is possible to import other biofuels at lower prices.

The policy support tool which was examined here was a time-based fixed level of policy support. As has been mentioned, it would be impossible to create a framework reaching a 0% policy uncertainty with these time-based policy support mechanisms, as the investments are likely to be operational for 20 years. If the policy support instead were to be given as one-time investment support, the same conditions as for a 0% policy uncertainty would be achieved.

The product price is of major importance in deciding if the simulation results in investment or not. Compared to the price of biomass - petrol and diesel prices are subject to higher uncertainties due to their high historic price volatilities, and the resulting simulated future prices provide a wide range of prices. For example, the petrol price at the end of the investment horizon provides a range of 90–120 EUR/MWh between the 10^{th} and 90^{th} percentiles (see figure 4). This wide range can flip a particular scenario with a specific investment cost from being very profitable, to very unprofitable. However, it should be noted that future simulated scenarios rely on parameters estimated from historic price data. If a significant new capacity of biorefinery technologies are deployed, it can significantly increase biomass prices (Zetterholm et al., 2020).

5. Conclusions

We have here used a real options framework to investigate the economic rationale behind the argument that policy uncertainty leads to deferred investments in biorefinery technologies. The real options framework was implemented for Swedish market conditions with emerging forest-based biorefinery technologies at different stages of their technological development with a policy price depending on the GHG performance of the produced biofuel.

While the results partly confirm that increased policy uncertainty can lead to a need for higher policy support in order to reach the same investment rates, this was, however, found to mainly be true for technologies that require very high policy support to reach any significant investment rates at all. Technologies that resulted in significant investment rates at lower policy support levels, conversely, showed low to no reduction in investment rates with increased policy uncertainty. The presence of some policy uncertainty improves the economic argument for earlier investments, as it becomes favourable to invest while the policy support is in effect rather than waiting for other market conditions to be improved.

Among the set of investigated technologies, the study showed that there is a strong preference for technologies with a low specific investment cost and with a lower investment cost uncertainty. This was highlighted by that the technologies with relatively low investment costs reported in the literature showed unexpectedly unfavourable results in this study. The explanation behind this is the relatively low technological maturity, which makes it likely that those investment costs are severely underestimated.

Policy support mechanisms where the support is linked to the GHG performance of a biofuel or a technology are intended to favour concepts with high GHG performance. However, the results reflected no major advantage for those technologies since they had disadvantages in terms of their investment and operational costs, thus requiring a very high policy price to become economically viable. If the policy support is intended to promote investments in emerging technologies with high GHG performance, the results thus stress that such support must be directed specifically to those technologies. Otherwise, under the same policy support scenario, it would be economically favourable to invest in technologies with lower GHG performance but more beneficial investment and operational cost performance.

Overall, we conclude that we find little support for the claim that policy uncertainties is a major source for the failure of commercial deployment of advanced forest-based biorefinery technologies. The uncertainties surrounding investment costs, and future energy prices play a larger role in that investment in these technologies can not be justified from an economically rational point of view.

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Appendix A. Technology TRL assessment

The technology readiness level (TRL) of each individual processing step for each technology is summarised from references (Jafri et al., 2019b, 2020) in tables A.1–A.5.

Table A.1: Process steps and TRL for lignin separation-hydrotreatment with natural gas derived hydrogen (LSH) and electrolysis derived hydrogen (LSH-E). Source: (Jafri et al., 2020).

Process step	TRL	Comment
Membrane filtration	6	Pilot operating in pulp mill environment.
Heat treatment and lignin separation	5	Shorter bench/small pilot
Purification and formulation	4	
Hydrodeoxygenation and cracking	4	Work is being performed in lab scale on lignin oil. Concept demonstrated in lab scale for other bio-oils
Integration with pulp mill, permeate and lignin lean liquor	4	Difficult to mature when working on small slip-streams, but partly demonstrated on similar effluents streams
Hydrogen production	9 / 7	Natural gas reforming (LSH)/ PEM electrolysis (LSH-E)
Integration with refinery	7	Concept formulated. Relatively easy integration with heat being supplied through steam and hot water generation, NCG combustion in refinery boiler, proven in other applications

Table A.2: Process steps and TRL for black liquor gasification-catalytic synthesis (BLG). Source: (Jafri et al., 2020).

Process step	TRL	Comment
Black liquor gasification	7	Gasifier upscaling factor 25
Gas cleaning and conditioning	8	Commercial technology (rectisol and WGS), -1 fro biosyngas
Methanol synthesis and purification	8	Commercial technology (BWR), -1 for biosyngas
Methanol-to-gasoline	7.5	1G tech: 600 kt/y in NZ 1985-1997 2G tech: 100 kt/y on coal derived syngas in China 2009, -1 for biosyngas
Integration with pulp mill, green liquor and steam	4.5	Not demonstrated since GL flow from gasifier is negligible in pilot. Green liquor analysed and upgrading tio white liquor demonstrated in bench scale.
Refinery integration of MTG	4.5	Not demonstrated but fairly straightforward and non-complex

Table A.3: Process steps and TRL for fast pyrolysis with upgrading via hydrodeoxygenation (Pyr-HDO). Source: (Jafri et al., 2019b).

Process step	TRL	Comment
Fast pyrolysis of forest residues	7.5	Commercial operation 30 MW on pellets/sawdust, -(1-2) for forest residue feedstock
Hydrodeoxygenation	3	SOTA: 2-step HDO in lab scale <400 mL, -1 for forest residue FPO (alkali)
Final upgrading to transportation fuel	8.5	Commercial process, -(0-1) for product from new process
Integration in pulp mill	9	Only integrated through steam supply
Integration in refinery	7.5	Only integrated through use of non-condensable gases in refinery boiler and heat recovery in form of hot water and steam

Table A.4: Process steps and TRL for fast pyrolysis with upgrading via fluidised catalytic cracking (Pyr-FCC). Source: (Jafri et al., 2019b).

Process step	TRL	Comment
Fast pyrolysis of forest residues	7.5	Commercial operation 30 MW on pellets/sawdust, -(1-2) for forest residue feedstock
FCC co-feeding	4.5	Petrobras pilot 200 kg/h (<5% of commercial scale) with approx. 250 h acc. op. time. UOP claims that commercial trials are underway but no results available. Not demonstrated with forest residue pyrolysis liquids (alkali).
Final upgrading to transportation fuel	8	Commercial process, -1 for product from new process
Integration in pulp mill	9	Only integrated through use of non-condensable gases in refinery boiler and heat recovery in form of hot water and steam

Table A.5: Process steps and TRL for catalytic hydropyrolysis-hydroconversion (Hydropyr). Source: (Jafri et al., 2019b).

Process step	TRL	Comment
Catalytic hydropyrolysis, incl. feeding	3.5	GTI pilot 50 kg/d, -(1-2) for forest residue
HDO	4.5	GTI pilot 50 kg/d, -(0-1) for forest residue based vapours
NCG reforming to hydrogen	7.5	Integrated NCG reforming not demonstrated but very similar to commercial process, -(1-2) for gas from hydropyrolysis
Final upgrading to transportation fuel	8	Commercial process, -1 for product from new process
Integration with refinery	7.5	Relatively easy integration with steam and hot water generation, proven in other applications