Economics of forest bioeconomy: new results

Jenni Miettinen and Markku Ollikainen

Abstract: We examine the emerging forest bioeconomy as an integrated, multi-product industrial ecosystem, where the traditional pulp mills allocate the use of side streams to independent biochemical companies manufacturing bioproducts in the vicinity of the pulp mills. Biochemical companies benefit from the proximity by receiving wood-based side streams at lower costs, and at the same time, pulp mills benefit from having a new source of revenue from selling side streams. We focus on the economic interaction between the pulp mill and the biochemical company, and we study the impacts on the use of wood and profits under perfect and imperfect competition. We demonstrate that the new industrial ecosystem uses more wood than traditional pulp mills, but depending on the side stream, it may promote cascading use of wood-based side streams.

Key words: biochemical companies, cascade use of wood, industrial ecosystem, pulp mills, tall oil.

Résumé : Nous examinons la bioéconomie forestière émergente comme un écosystème industriel intégré multiproduit, où les usines de pâte à papier traditionnelles attribuent l'utilisation des produits secondaires à des entreprises biochimiques indépendantes qui élaborent des bioproducts et sont situées à proximité de l'usine de pâte. Les entreprises biochimiques profitent de cette proximité en obtenant les résidus à base de bois à un coût moindre et, par la même occasion, les usines de pâte à papier bénéficient d'une nouvelle source de revenus grâce à la vente de produits secondaires. Nous mettons l'accent sur l'interaction économique entre l'usine de pâte à papier et l'entreprise biochimique, et nous étudions les impacts sur l'utilisation du bois et les bénéfices en situations de concurrence parfaite et imparfaite. Nous démontrons que le nouvel écosystème industriel utilise plus de bois que les usines de pâte à papier traditionnelles, mais selon le flux de produits secondaires cela peut promouvoir l'utilisation en cascade de produits secondaires à base de bois. [Traduit par la Rédaction]

Mots-clés : entreprises biochimiques, utilisation en cascade du bois, écosystème industriel, usine de pâte à papier, tallöl.

1. Introduction

New drivers, such as climate and energy policies, technological possibilities for generating new products, industrial globalization, and megatrends of services and digitalization, are changing the business environment in the forest sector (Nabuurs et al. 2015). This development provides new possibilities and challenges to promote the shift from the traditional forest industry towards a forest bioeconomy. The shift to bioeconomy is generally identified as manufacturing a large set of new and high-value-added products alongside old products and a consequential diversification of wood-based businesses (Ollikainen 2014). Furthermore, a forest bioeconomy is assigned to find solutions to several sustainability goals, such as replacing non-renewable resources, maintaining biodiversity, and increasing resource efficiency (e.g., Antikainen et al. 2017; Priefer et al. 2017; Winkel 2017).

In the literature, the notion of biorefinery is often used to provide a conceptual understanding of new ways of producing multiple goods from wood biomass (Christopher 2013). However, the economic content of the new forest bioeconomy concept is perhaps better understood and modelled as an integrated multi-product industrial ecosystem. The traditional pulp mills allocate other biomass-based production lines to separate companies, which sell their products directly to consumers or producers.

This trend is evident, especially in Finland and Sweden, where the most significant new softwood pulp investments have been made. The new plants are called “bioproduct mills” in Finland, as the business model is based on a network of companies utilizing side streams from pulp mills.¹ Alternatively, the traditional forest companies may add new production lines and produce the new value-added bioproducts by themselves. For example, Södra started biobased methanol production in Mönsterås (Sweden) in 2020, and UPM is constructing its new biochemicals facility in Leuna (Germany).

The recent emergence of integrated multi-product industrial ecosystems is based on the fact that the most efficient path towards new value-added products relies on the traditional forest companies. These companies buy and efficiently transfer wood from forests to pulp mills, providing wood waste and various side streams, such as biosludge, tall oil, or lignin, for biochemical and other companies. As a result, the biochemical companies benefit from reduced material costs, and the pulp mills, in turn, have a new revenue source from selling side streams as an alternative to using them for energy. However, while the literature on the material flows and production in the new industrial ecosystem is voluminous (e.g., Wenger and Stern 2019), treatises on the economic dimensions of this new system are scarce.

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¹Metsä Fibre Äänekoski bioproduct mill started its operations in 2017 and Metsä Fibre Kemi bioproduct mill was announced in 2021.

It is interesting to examine how the economic interaction between pulp mills and the new biochemical companies occurs in the emerging industrial ecosystem. For example, how does the possibility of producing energy from side streams impact a pulp mill's demand for pulpwood? How does the possibility of selling side streams to a biochemical company affect the pulp mill's production choices? Given the large pulp companies and new smaller companies manufacturing new bioproducts from side streams, is there a danger for imperfect competition, and how do these imperfections distort the use of side streams?

To address these topical issues of emerging bioeconomy solutions, we develop a formal economic model of the new industrial ecosystem and apply it numerically to the Finnish forest sector. The model's core is the interaction between a pulp mill and a biochemical company, basing their production on wood biomass and its side streams. The pulp mill brings the wood to the industrial ecosystem and receives revenue from pulp production and selling side streams of production, such as bark, lignin, and biosludge. The biochemical company then makes new and high-value-added products from the side streams. In addition, modern pulp mills produce more energy than they need in their production process, making them sellers of energy (both electricity and heat). Thus, the pulp mill can either use the side streams of wood in its energy production or provide part of the side streams to the biochemical company.

Our model consists of one pulp mill and one biochemical company to analyze the new industrial ecosystem sharply. We vary their interaction, assuming first perfect competition and then introduce market imperfections in two forms: the market power is given both upstream and downstream. Furthermore, we briefly focus on another type of imperfection, the risk concerning the adequacy of the raw material supplied to the biochemical company. Most of the analysis focuses on the behaviour of the pulp mill, around which the cascading use of wood-based side stream is built. Based on the theory, we build a numerical model to examine the magnitudes of impact and focus on detailed components of the model.

Literature on forest bioeconomy is developing rapidly. However, it has primarily focused on technical or material use issues and contained significantly fewer studies on economics, market implications, and policy designs (e.g., Söderholm and Lundmark 2009; Kangas et al. 2011; Gan 2013; Giurca and Späth 2017; Majumdar et al. 2017; Purkus 2017; Hurmekoski et al. 2018; Lundmark et al. 2021). Furthermore, most of the studies on forest bioeconomy focus on biofuels and bioenergy. Only a few examine the role of biochemicals, biomaterials, and bioproducts (Bauer et al. 2017; Dessbesell et al. 2017; Wenger and Stern 2019; Jonsson et al. 2021), even though the new high-value-added products will probably be invented for uses of wood biomass other than biofuels (Hurmekoski et al. 2018). This emphasis on biofuels contrasts with experts' position that only wood-based biomass that cannot be utilized for higher-value-added products should be used in bioenergy or biofuel production (Hämäläinen et al. 2011).

An extensive set of previous quantitative modelling literature on forest biorefineries consists of supply chain design and optimization studies, which primarily focus on bioenergy and biofuels (e.g., Machani et al. 2014; Dessbesell et al. 2017; Daya and Nourelfath 2019). Higher-value-added production options, especially biochemicals, are less examined in supply chain and techno-economic assessment studies (e.g., Mansoornejad et al. 2010, 2013; Dessbesell et al. 2018; Elaradi et al. 2021). Dansereau et al. (2014) conclude in their review that it is vital for forest biorefineries' competitiveness to produce at least one differentiable added-value product and to assess the bioproduct portfolio according to supply chain design and management methodologies. As companies' future success will depend increasingly on environmental performance in addition to the economic profitability of the supply chain, green supply chain management provides a suitable tool for decision making. It combines the assessment of environmental impacts with economic and operational performance analysis (Daya and Nourelfath 2019).

Promoting the cascading use of wood is essential for the notion of bioeconomy as a provider of several environmental, social, and economic benefits (Jarre et al. 2020; Thonemann and Schumann 2018). In their review, Jarre et al. (2020) identify responses to policy, market, technical implementation, environmental effects, and stakeholder involvement as the main factors promoting cascading use of wood. Quantitative studies on the environmental impacts of cascading use of wood typically apply life cycle assessment (Jarre et al. 2020; Thonemann and Schumann 2018). A still somewhat limited number of life cycle studies have focused on alternative uses of pulp mill's side streams, such as tall oil, lignin, and biosludge (Cashman et al. 2015; Aryan et al. 2019; Bajwa et al. 2019; Culbertson et al. 2016; Mohammadi et al. 2019a, 2019b; Secchi et al. 2019; Hermansson et al. 2019, 2020). Studies on the tall oil industry have compared the use of tall oil either in biodiesel or in the pine chemicals industry (Cashman et al. 2015; Aryan et al. 2019). Bajwa et al. (2019) discuss the possibilities of lignin-derived products to improve both the profitability of the pulp and paper companies and their environmental performance compared to fossil-based products. Mohammadi et al. (2019a, 2019b) analyze the alternative uses of pulp and paper mill biosludge and their environmental impacts. These studies indicate that the cascading use of side streams may lead to better environmental performance (Cashman et al. 2015; Aryan et al. 2019; Bajwa et al. 2019; Culbertson et al. 2016; Mohammadi et al. 2019a, 2019b). However, as in the case of lignin, for example, the allocation method highly impacts the results of life cycle analyses (Secchi et al. 2019; Hermansson et al. 2020; Wenger et al. 2020). Furthermore, Jarre et al. (2020) point out that the economic competitiveness and environmental performance between energy and material uses of wood are uncertain, as they depend on several factors and on the chosen evaluation criteria.

Previous work indicates that biorefineries still have several challenges in answering the promise for new value-added products and improved sustainability (Temmes and Peck 2020). The new wood-based products have been estimated to increase the demand for wood (Hurmekoski et al. 2018). Thus, environmental concerns exist related to the forest sector's expected increase in wood use (Kumar et al. 2021). At the same time, many countries have increased biofuel and bioenergy production to replace fossil fuels in energy production (Kangas et al. 2011). The change to biofuel and bioenergy production will also increase demand for wood biomass. The increased use of forest biomass, especially in the energy sector, has been a significant factor in increasing competition for wood among buyers (Lundmark and Olsson 2015). Previously, at the European Union (EU) level, it has been estimated that the wood resources might not even satisfy the demand for wood in the future due to EU policies promoting renewable energy targets (Jonsson 2013).

Our work differs from previous literature in that we provide a comprehensive economic analysis of forest bioeconomy as an emerging industrial ecosystem. First, we characterize the new system, explore its properties, and develop a numerical model to assess the established properties of the model quantitatively. The rest of the study is organized as follows. In the next section, we present the theoretical framework applied in this study. Then, we develop the numerical application in section 3. Finally, the discussion and conclusions are presented in section 4.

2. Economics of forest bioeconomy

We now develop a forest bioeconomy model focusing on an industrial ecosystem consisting of a traditional pulp mill and a new biochemical company starting with perfect competition. The model is then extended to cover imperfect competition.

2.1. The setup: forest bioeconomy as an industrial ecosystem

Consider two companies, a pulp mill and a biochemical company, the latter manufacturing its products using wood-based side streams in the vicinity of the pulp mill. Choosing a location close to the pulp mill decreases the biochemical company's costs,

but fixing the location also makes it vulnerable to possible changes in the supply of wood-based side streams. Thus, benefits, on the one hand, and risks, on the other hand, characterize the forest bioeconomy as an industrial ecosystem — features identified in many other industries. To reduce these risks, the pulp mill and the biochemical company may enter a long-term contract securing delivery of side streams. Such a contract would dictate the amounts and prices of trade under some flexibility.²

We start downstream with the use of wood biomass by an independent biochemical company. It is an integral part of the new industrial ecosystem located in the vicinity of the pulp mill. To keep the analysis clear and without loss of generalization, we postulate that only one company produces biochemical products from each side stream. The company uses two inputs in its production: side streams from the pulp mill and energy. Let the amount of wood-based side stream from the pulp mill be $m = \eta x$, where η indicates the share of wood-based side stream sold to the biochemical company from the pulp mill, and x denotes the amount of pulpwood bought for pulp production. Let the production process be defined by a well-behaving concave production function $g(m, e_b)$, where e_b denotes energy used by the biochemical company. Finally, let the price of the biochemical product be P , the cost of the wood-based side stream c , and the price of energy φ .

The biochemical company maximizes its profits by choosing two inputs: the amount of side stream and energy:

$$(1) \quad J = Pg(m, e_b) - cm - \varphi e_b$$

We return later to the specific features of profit maximization. First, however, we note that solving the profit maximization problem results in the derived demand for side streams, $m^d = \eta x^d(P, c, \varphi)$. The demand function depends positively on the price of the biochemical product and negatively on input prices (details of the biochemical company will be scrutinized later). This demand enters the profit maximization problem of the pulp mill.

The pulp mill uses three inputs, pulpwood, energy, and chemicals, to produce pulp. Pulpwood is the main input in production. The amount of pulpwood bought from the timber market is x . Pulp production technology requires debarking the trees; also, a part of biomass (the so-called zero fibre) is unusable in pulp production. We denote the technologically fixed share of pulpwood usable in pulp production by εx with $0 < \varepsilon < 1$. The production process requires energy, denoted by e_p . The pulp production technology defines a concave production function $f(\varepsilon x, e_p)$. We assume that the production function is well-behaving and continuously differentiable with positive first derivatives ($f_x > 0$ and $f_{e_p} > 0$) and negative second derivatives ($f_{xx} < 0$ and $f_{e_p e_p} < 0$).

The share of wood fibre not usable in pulp production is $(1 - \varepsilon)x$. This amount can be used to produce renewable energy in the pulp mill or sold to biochemical companies as a raw material for biochemical production. To examine how the pulp mill allocates the side stream between these two alternatives, we denote the share of the side stream sold to the biochemical company by η with $0 \leq \eta \leq 1$, indicating the corner solutions are possible in principle. Thus, the share of pulpwood used in energy production in the pulp mill is $\hat{x} = (1 - \varepsilon)(1 - \eta)x$. We describe the amount of energy produced in the pulp mill by a production function $\hat{e}(\hat{x})$, which is concave. Typically, pulp mills produce more energy than they need in their pulp production, making them energy sellers. The company's energy sales are defined by the difference between produced and consumed energy: $\hat{e}(\hat{x}) - e_p$.

For simplicity, we assume that chemical costs are proportional to the amount of pulpwood used in production, σx , and the unit price of chemicals is k . Let the price of pulp be p , price of pulpwood by w , price of energy by φ , and price of side stream sold to the biochemical company by c . The profit maximization problem of the pulp mill is then as follows:

$$(2) \quad \pi = pf(\varepsilon x, e_p) - wx + \varphi[\hat{e}(\hat{x}) - e_p] - k\sigma x + c\eta x$$

Equation 2 is seemingly simple, yet it allows an examination of the three key choices that the pulp mill typically does in real market conditions.³ We now turn to the formal analysis of both companies in the emerging industrial ecosystem of the forest bioeconomy.

2.2. A pulp mill in a perfect market: demand for wood, cascading use versus energy production

Even though the pulp mill faces a demand function for side streams and may have market power, we assume in this section that it operates as in a perfect market and takes the price of side streams as given. The price of pulp, determined in the international markets, is exogenous to the pulp mill. Under these assumptions, the economic problem of the pulp mill is to choose the use of pulpwood and energy inputs and allocate the wood-based side streams between energy production and sales to the biochemical company:

$$(3) \quad \pi = pf(\varepsilon x, e_p) - wx + \varphi[\hat{e}(\hat{x}) - e_p] - k\sigma x + c\eta x$$

The use of pulpwood, x , energy, e_p , and share of side stream sold to a biochemical company, η , are implicitly defined by

$$(4) \quad x: \quad pf_x \varepsilon - w + \varphi \hat{e}_x (1 - \varepsilon)(1 - \eta) - k\sigma + c\eta = 0$$

$$(5) \quad e_p: \quad pf_{e_p} - \varphi = 0$$

$$(6) \quad \eta: \quad -\varphi \hat{e}_\eta + c = 0$$

We start the interpretation with eqs. 5 and 6 as they are more straightforward to analyze. Equation 5 defines the use of energy in production by requiring that the value of marginal product equal the price of energy. Optimality condition (eq. 6) indicates that the pulp mill increases the share of the side stream sold to the biochemical company to the point where the lost value of marginal energy product equals the revenue (price) from selling that share to the biochemical company.

Equation 4 exhibits many interesting components and provides new insights into the forest bioeconomy. Therefore, we interpret this condition in subsequent steps. Suppose first that the pulp mill would neither produce energy from side streams nor sell side stream to the biochemical company. Setting $\hat{e}(\hat{x}) = 0$ and $c = 0$ gives as the optimality condition: $pf_x \varepsilon = w + k\sigma$. Interpretation is obvious — the use of pulpwood is increased to a point where the value of marginal product equals the price of wood and the marginal cost of chemicals. This condition reflects the conventional analysis of any company using inputs in production under the technologically fixed share of usable wood in production.⁴

We next add the possibility of producing energy from side streams of the chemical process. This addition leads to eq. 7, where we, for expositional purposes, shift the additional revenue to the cost side to reduce the costs:

²Please note that the pulp mill could start to manufacture biochemical products by itself, thus entering other markets than the pulp market. In this case, pricing between the production lines or divisions would be based on pricing under perfect market conditions.

³The analytical model omits labor and capital costs for simplicity, but we include labor and capital costs in the numerical analysis.

⁴This optimality condition implicitly assumes free disposal of waste streams, for instance, in landfills. While many companies traditionally have their own landfills, there is a long tradition of using the most valuable and important side streams. Nevertheless, the case of free disposal provides the theoretical baseline for our analysis.

$$(7) \quad pf_x \varepsilon = w + k\sigma - \varphi \hat{e}_x(1 - \varepsilon)$$

The right-hand side of eq. 7 contains the marginal revenue from energy production, which reduces the costs of the two inputs. For the given value of the marginal product, the decrease in the net costs of the wood input boosts the use of wood to take full advantage of the possibility of earning some additional revenue from selling renewable energy. Thus, we find that the production of renewable energy from side streams tends to increase the use of wood.

In the spirit of circular economy, we now introduce the possibility that the pulp mill sells side streams to the biochemical company and receives a constant price c for each unit sold. Given that a concave function characterizes the pulp mill's energy production, an interior solution emerges where the pulp mill produces energy and sells side streams simultaneously. The interior solution leads to the following re-expression of eq. 4 for the choice of pulpwood:

$$(8) \quad pf_x \varepsilon = w + k\sigma - \varphi \hat{e}_x(1 - \varepsilon)(1 - \eta) - c\eta$$

The right-hand side now contains a term, $c\eta$, tending to reduce further the costs of using pulpwood in production, but this share slightly reduces marginal revenue from energy production. By eq. 6 and concavity of energy production, the net result is, however, increased use of pulpwood relative to the previous cases. This outcome provides our second new finding for a forest bioeconomy.

Figure 1 illustrates the impacts of input prices, net of marginal revenue from energy, and sales of side streams on the use of pulpwood in the pulp mill. It assumes an interior solution for all decision variables introducing them in a row, starting with the case of no side streams and introducing then energy use of side stream followed by saleable side stream. The value of marginal product function of pulpwood is downward-sloping in the use of pulpwood, x . The vertical axis describes the input prices ($w + k\sigma$) from which the marginal revenue from energy and sales of side streams are subtracted. The determination of pulpwood use can be read on the horizontal axis as gradually increasing amounts of pulpwood use.

We will assess the quantitative effects relating to the use of side streams using a numerical model in section 3. We now turn to other properties of the model.

Given that the second-order conditions hold due to concavity assumptions, the first-order conditions implicitly define the optimal use of pulpwood and energy and the allocation of wood-based side streams between energy production and sales to the biochemical company. The dependence of this choice on exogenous variables can be examined using comparative statics. We are especially interested in determining how prices of pulp, energy, and side stream, as well as input prices, impact the optimal choices of the pulp mill. We compile the results in Table 1.

As expected, the price of pulp has a positive impact on the use of wood, as it increases the profitability of pulp production. Its impact on energy production is generally ambiguous, as is well known from production theory. In the usual case, assuming that the inputs are complements, the sign would be positive. The effect of pulp price on the share of sold side stream is positive, because the mill uses more pulpwood to increase pulp production.

An increase in the energy price affects all decision variables ambiguously. However, the impact is natural, as energy plays a double role as a production factor and a source of revenue. When the energy price increases, for complements, the use of energy decreases, but at the same time, the profitability of energy production from side streams increases. Depending on which one of these opposing effects dominates, the effects are either positive or negative. A higher price of side streams has a positive effect on the use of wood, use of energy, and the share of sold side stream, as it increases the profits of the pulp mill by boosting pulp production.

The price of pulpwood has a negative effect on the use of wood and energy, and the share of sold side stream. Energy and pulpwood are complements in pulp production, which explains the negative

Fig. 1. Impact of input prices and additional revenue from energy and side stream selling on the use of pulpwood in the pulp mill. [Colour online.]

Table 1. Comparative statics of the model.

Exogenous variable	Use of pulpwood	Use of energy	Share of sold side stream
Pulp price	+	?	+
Energy price	?	?	?
Price of side stream	+	+	+
Price of pulpwood	—	—	—
Price of chemicals	—	—	—

impact on energy use: the higher price of pulpwood decreases production and energy use. As production decreases, the amount of side streams decreases, and the pulp mill sells less side stream to the biochemical company and uses more in its own energy production. An increase in the price of chemicals decreases the use of all endogenous variables similarly to the price of pulpwood.

We condense the most important implications of the findings of the model in proposition 1.

Proposition 1. A forest bioeconomy as an industrial ecosystem, comprising pulp mills and biochemical companies, supplies new biochemical products and renewable energy from wood residuals and side streams in addition to the main product, pulp. Under perfect competition, this industrial ecosystem uses more pulpwood than it would use without the utilization of side streams. At the same time, it promotes a more efficient cascading use of side streams.

How does proposition 1 relate to the postulated goals and promises of a forest bioeconomy? Incentives for using more wood are stronger than in the traditional forest industry. Increasing demand for pulpwood creates additional pressure on the use of forests. The impacts on biodiversity are not, however, evident. The pulp mill buys most of the pulpwood from thinnings and final fellings. Thus, the overall effect of increased demand for pulpwood on biodiversity depends on multiple issues, such as how significant the increase in pulpwood demand is, what the relative shares of pulpwood from thinnings and final fellings are, how increasing timber prices affect the levels of final fellings, and most of all, what is the forest management regime (such as continuous cover or even-aged forest management with clearcuts). Furthermore, measures and instruments used to promote biodiversity modify all forest management regimes (Hetemäki et al. 2017). Furthermore, increasing demand for pulpwood reduces the forest carbon sink on the one hand, but on the other hand, channelling biomass to a further cascading use instead of burning it is beneficial climate-wise and also promotes a circular economy. All in all, the previous discussion shows that while promoting cascading use of wood and reducing fossil fuels in energy production, a forest bioeconomy may face trade-offs

between increased use of wood and biodiversity, and between energy and biochemical production based on side streams.

The economic functioning of the industrial ecosystem may not even be as harmonious as the previous analysis suggests. The questions of market power and shortages of raw material for the biochemical company may seriously hinder the development of the industrial ecosystem. We next focus on these issues.

2.3. Market imperfections in the forest bioeconomy

The industrial ecosystem may not be perfect. Market imperfections may exist either upstream or downstream, and more probably so upstream. In addition, the amount of wood-based side stream may be volatile due to changes in market prices of pulp, wood, and energy. Furthermore, the wood-based side stream may not be sufficient for the biochemical company's production if the demand for its product increases. The only way of expanding production in such circumstances will be to import raw material from elsewhere if that option is feasible. This section provides a brief analysis of these imperfections.

2.3.1. Pulp mill as a monopoly in side stream markets

A large pulp mill may easily have market power in the side stream markets, making it a monopoly in that market while it remains competitive in the pulp markets. In this case, the pulp mill faces the demand for its wood-based side stream and can choose either its price or quantity but not both. The inverse demand function for the side stream, ηx , by the biochemical company can be defined as $c(\eta x)$. We re-write the profit function of the pulp mill to reflect the demand function:

$$(9) \quad \pi = pf(\varepsilon x, e_p) - wx + \varphi[\hat{e}(\hat{x}) - e_p] - k\sigma x + c(\eta x)\eta x$$

The optimal choice of the monopolist pulp mill is characterized by

$$(10) \quad x: \quad pf_x \varepsilon - w + \varphi \hat{e}_x (1 - \varepsilon)(1 - \eta) - k\sigma + c(\eta x)\eta + c_{\eta x}(\eta x)\eta^2 x = 0$$

$$(11) \quad e_p: \quad pf_{e_p} - \varphi = 0$$

$$(12) \quad \eta x: \quad -\varphi \hat{e}_x + c_{\eta x}(\eta x)\eta x + c(\eta x) = 0$$

Energy use in eq. 11 remains qualitatively similar to that under perfect competition, but the two other optimality conditions exhibit new features. We start interpreting the optimality conditions by looking at eq. 12, the decisions to sell side stream to the biochemical company. Relative to eq. 6, the optimality condition contains an additional term $c_{\eta x}(\eta x)\eta x$ implying that eq. 12 contains marginal revenue (MR) from selling side streams to the biochemical company defined by $MR = c_{\eta x}(\eta x)\eta x + c(\eta x)$. Thus, the pulp mill sells side streams up to the point where the marginal revenue from the last unit sold equals the lost value of the marginal product of side stream in its energy production, that is, marginal cost defined by $\varphi \hat{e}_x$. Relative to the perfect competition, the pulp mill reduces the supply of side streams to the biochemical company and shifts a higher share to its energy production to increase the selling price.

The use of pulpwood in eq. 10 differs from that under perfect competition, and we re-express it in a similar way as before:

$$(13) \quad pf_x \varepsilon = w + k\sigma - \varphi \hat{e}_x (1 - \varepsilon)(1 - \eta) - \eta[c(\eta x) + c_{\eta x}(\eta x)\eta x]$$

The last bracket term in eq. 13 is simply ηMR , indicating that the marginal revenue from the side stream impacts the use of

pulpwood as a marginal opportunity cost. As other terms in eq. 13 are the same as in perfect competition, the use of pulpwood is lower than under perfect competition. As the pulp mill reduces the supply of side stream to the biochemical company to increase the selling price, it also reduces demand for pulpwood.

2.3.2. Biochemical company: material shortages and market power

Consider next the biochemical company. We keep the notation provided in section 2.1 but include a possibility of buying similar raw material (as a wood-based side stream) from other sources. In this case, the biochemical company must pay the price and transport cost for this item, denoted by $\hat{c}$ (if no import is needed, costs are c). We denote the amount of wood-based side stream from the pulp mill by ηx and additional raw material from another source by z . Thus, to allow for importing wood-based side stream, the total amount of side stream used is $m = \eta x + z$. The profits of the biochemical company, denoted by J , are given by

$$(14) \quad J = Pg(m, e_b) - \hat{c}m - \varphi e_b$$

leading to the first-order conditions:

$$(15) \quad m: \quad Pg_m - \hat{c} = 0$$

$$(16) \quad e: \quad Pg_{e_b} - \varphi = 0$$

Interpretation of both conditions is conventional: the value of marginal product equals the input price.

Two twists of eqs. 15 and 16 are worth looking at in this problem. First, a shortage in the supply of side streams, and second, the unlikely but still possible case wherein the biochemical company has market power. We start with the case of shortage by looking more closely at the properties of eq. 15. Consider the case in which importing raw material elsewhere would not be possible and evaluate eq. 15 by setting $z = 0$. Given concavity of production function, this would lead to

$$(17) \quad Pg_m|_{z=0} - \hat{c} > 0$$

Thus, the biochemical company is not producing at the optimal level and would increase its profits by increasing the use of side streams in its production. There are many reasons why this possibility would emerge. First, pulp production has historically been sensitive to business cycles with periods of booms and recessions, which are potential conditions for shortages. Second, demand for the produced biochemical product may expand beyond the expected. Third, both high transport costs and legislation governing the possibilities of transporting side streams may prevent the use of the planned additional raw material. Fourth, policies might also create incentives for the pulp mill to utilize side streams for other uses, such as biodiesel production, creating a shortage of raw material and need for imports (Cashman et al. 2015). Figure 2 illustrates these possibilities. If the biochemical company can buy enough raw material from the pulp mill at price c , it would use an amount of $m^{***} = \bar{\eta x}$. If there is a shortage of raw material, the company imports some material from outside at higher costs. Under a higher cost $\hat{c}$, the optimal amount of side stream $m^{**} = \eta x + z$, with $m^{**} < m^{***}$. But if $z = 0$, the amount of side stream that the biochemical company buys only $m^* = \eta x$, and the excess demand (Ed) caused by material shortage is shown in Fig. 2.

If the biochemical company had market power concerning buying the wood-based side stream, it would face the (inverse) supply function, expressed as $c(\eta x)$ with $c_{\eta x}(\eta x)x > 0$, indicating that if the biochemical company wants to buy more, it should

Fig. 2. The impact of the shortage of raw material on the choice of the profit-maximizing biochemical company. [Colour online.]

pay a higher price for side streams. The target function of the biochemical company reads

$$(18) \quad J = Pg(\eta x, e_b) - c(\eta x)\eta x - \varphi e_b$$

While the optimality condition for energy use remains qualitatively the same as before, the demand for side stream is determined by

$$(19) \quad \eta x: \quad Pg_{\eta x} - [c(\eta x) + c_{\eta x}(\eta x)\eta x] = 0$$

This condition is the classical monopsony choice: the value of the marginal product of the side stream is set equal to its marginal buyer cost (MBC) defined by $MBC = c(\eta x) + c_{\eta x}(\eta x)\eta x$. Thus, the monopsonistic biochemical company reduces its demand for side streams to reduce the price it has to pay to the pulp mill for the side stream. As the demand for side streams is reduced by Table 1, the pulp mill reduces the use of pulpwood, energy, and side stream sales to the biochemical company, as the biochemical company used market power to reduce the price below the competitive price.

We collect the main findings concerning imperfect competition to Proposition 2.

Proposition 2. Market imperfections of the industrial ecosystem of forest bioeconomy showing up either in monopoly or monopsony behaviour lead to a lower cascading use of wood-based side streams and increase their use in energy production. At the same time, both cases decrease the demand for pulpwood.

Proposition 2 shows that the previously identified trade-offs also prevail under imperfectness: while the use of pulpwood decreases, which may improve biodiversity (under the qualification presented above), the forest bioeconomy fails to fully promote cascading use of timber, which would be beneficial for the climate. In more general terms, there is a loss of welfare, measured by the sum of producers' (pulp mill) and buyers'/consumers' (biochemical company) surplus and environmental impacts due to imperfectness relative to the case of perfect competition in the forest bioeconomy. How significant the welfare loss is, is an empirical question. Nevertheless, our analysis suggests that even imperfect markets in a forest bioeconomy provides a welfare improvement compared to the case where all wood-based side streams are either placed on landfills or used for energy only.

We next turn to examine how the features outlined by the theory appear between a pulp mill and biochemical company for some selected examples of wood-based side streams.

3. A numerical analysis of forest bioeconomy

We build our numerical model using some typical side streams from the pulp mills in the Finnish forest industry. They include lignin, biosludge, and tall oil, which the pulp mill may use in energy production or sell to a biochemical company. Many intermediate products (e.g., detergents, resins, and preservatives) can be made from lignin. However, it is currently most often used for energy in pulp mills (Hurmekoski et al. 2018; Volama 2012). Biosludge is used mainly as an energy source in Finland, even though it is not well suited to energy production due to its moisture content (Moring et al. 2013; Pöykio et al. 2018). One alternative is to place it in a landfill (Mohammadi et al. 2019a). However, biosludge from the pulp mill can be utilized as a fertilizer or a material for soil amendment (Pöykio et al. 2018). Tall oil has been used for decades as an input in the production of bio-based chemicals. It also illustrates alternative and competing use of side streams. European Union policies promote biofuel production, providing the possibility of using tall oil for biodiesel (EU Directive 2015/1513; European Parliament and of the Council 2015). This competing use may create a shortage of tall oil material for the tall oil industry that produces higher-value-added products from tall oil, according to the cascading use of side streams.

Since data are too limited for a comprehensive analysis, we are obliged to restrict the analysis to the case of perfect competition on both sides of the forest bioeconomy. We focus on both the short-term and long-term profits of the pulp mill. The former case helps us to identify the differences concerning profits when side streams are either used in the pulp mill's energy production or sold as a side stream. The latter case shows how pulp mills perform in the forest bioeconomy outlined by the theory. Finally, we focus especially on tall oil and its use in the pine chemical industry.

3.1. Cascading use of side streams: the pulp mill

3.1.1. Data and parameters

The key variables of the theoretical model are the prices of pulp and productive inputs and the side streams. Furthermore, we need information on input use and production of pulp and side streams. The parameter values are given in Table 2. Data on the costs and profitability of the pulp mills are scarce (Korpunen et al. 2012), and we have collected data from multiple sources. Thus, some inconsistency is possible in the way parameter values are determined in each source. This does not, however, distort the comparison of alternative solutions. All parameter values are converted to 2018 price levels (Official Statistics of Finland 2020).

We use the price from bleached sulfate pulp export prices from 2018 as the pulp prices (Natural Resources Institute Finland 2021). The price of electricity is the average wholesale baseload electricity price from 2018 (European Commission 2019a, 2019b, 2019c, 2019d). The price of heat energy, annual chemical costs, annual capital costs, and total labour costs are based on Korpunen (2012, 2015). The price of biosludge is estimated as a share of the Soilfood soil amendment prices (J. Joona, Soilfood Oy, personal communication, 13 November 2018). The amounts of pulp, lignin, biosludge, tall oil, and excess electricity and steam (sold outside) produced and pulpwood used are taken from the environmental impact assessment report of the Metsä Fibre Äänekoski pulp mill. This source allows us to describe the levels of the most important inputs and produced intermediate and final products (Metsä Fibre 2014; alternative plan VE1).⁵ If lignin is used in

⁵Lignin, tall oil, and biosludge are the main side streams of the pulp mill (Metsä Fibre 2014) that entail the trade-off we are focusing on: the use either for energy or biochemical products (cascading use). The environmental impact assessment report of the Metsä Fibre Äänekoski pulp mill (Metsä Fibre 2014, alternative plan VE1) states as other side streams: turpentine, product gas, and bark and dust. In alternative plan VE1 bark and dust are used to produce product gas, and turpentine is sold to companies that use it only for biochemical products.

Table 2. Data and parameter values used in the profit maximization of a pulp mill.

Description	Unit	Value	Source
Production inputs			
Wood raw material (pulpwood and wood chips)	m ³	6 780 000	Metsä Fibre 2014
Electricity use	GWh	750	Metsä Fibre 2014
Capital costs	€/year	193 991 334	Korpunen et al. 2012
Total labour costs	€/year	18 649 673	Korpunen 2015; Metsä Fibre 2014
Chemical costs	€/year	34 564 830	Korpunen et al. 2012
Prices of production inputs			
Price of pine pulpwood	€/m ³	17.9	Natural Resources Institute Finland 2021
Price of spruce pulpwood	€/m ³	20.3	Natural Resources Institute Finland 2021
Price of birch pulpwood	€/m ³	17.0	Natural Resources Institute Finland 2021
Price of wood chips	€/m ³	29.5	Korpunen 2010
Unit cost in mechanized harvesting (pulpwood)	€/m ³	13.4	Natural Resources Institute Finland 2021
Overhead costs in harvesting and transportation	€/m ³	2.7	Natural Resources Institute Finland 2021
Unit costs of long-distance transportation of industrial roundwood (rail transportation)	€/m ³	10.8	Natural Resources Institute Finland 2021
Price of electricity	€/MWh	47	European Commission 2019a, 2019b, 2019c, 2019d
Price of heat energy	€/MWh	33	Korpunen 2015
Production amounts			
Pulp	t	1 300 000	Metsä Fibre 2014
Lignin	t	75 000	Metsä Fibre 2014
Biosludge	t	11 000	Metsä Fibre 2014
Tall oil	t	60 000	Metsä Fibre 2014
Excess steam sold	GWh	650	Metsä Fibre 2014
Excess electricity	GWh	750	Metsä Fibre 2014
Prices of final product and side streams			
Price of pulp	€/t	669	Natural Resources Institute Finland 2021
Price of lignin	€/t	462	Gosselink 2011
Price of biosludge	€/t	0.60	Estimated using Soilfood prices ^a
Price of tall oil	€/t	441	Eurostat 2018a

^aSoilfood is a company selling soil amendment material containing side streams from pulp mills.

energy production, its heat value is 7.22 MWh/tonne (1 metric ton (t) = 1000 kg) (Tomani et al. 2011), the heat value of biosludge is 0.69 MWh/t, and the heat value of tall oil is 10.28 MWh/t (Statistics Finland 2018). The bioenergy sold outside is assumed to be produced at an efficiency ratio of 80% (Metsä Fibre 2014). The used wood raw material of the pulp mill consists of both pulpwood and wood chips, which is transported to the mill either by road or rail transport (Metsä Fibre 2014).⁶ The price of wood raw material is calculated as the weighted average price of pulpwood and wood chips (Korpunen 2010; Natural Resources Institute Finland 2021). The price of pulpwood (pine, spruce, and birch) and wood chips, the unit cost in mechanized harvesting of pulpwood, and the unit costs in harvesting and transportation of industrial roundwood are constant per cubic metre (Natural Resources Institute Finland 2021). However, both pulpwood (x_p) and wood chips (x_w) have increasing unit road transportation costs (Fjeld et al. 2021; Laitila et al. 2016). For pulpwood transported by rail, we assumed a constant unit transportation cost (Natural Resources Institute Finland 2021). Thus, we define the function for wood input costs as follows:

(20) $C_{\text{pulpwood(road)}} : 34.34 \times x_p + 0.0204 \times x_p^{1.3903}$

(21) $C_{\text{pulpwood(rail)}} : 45.16 \times x_p$

(22) $C_{\text{wood chips}} : 29.5 \times x_w + 0.0522 \times x_w^{1.3558}$

⁶According to alternative plan VE1 in the environmental impact assessment report of the Metsä Fibre Äänekoski pulpmill, we assume that 59% of wood raw material is pulpwood transported by road, 21% of wood raw material is pulpwood transported by rail, and 20% of wood raw material is wood chips transported by road (Metsä Fibre 2014).

⁷We acknowledge that it might not be feasible to use the same amount of side stream both in energy production or to sell it as a side stream in practice. However, this simplification allows us to compare these two alternative uses of side streams.

3.1.2. Use of inputs and profits from pulp production

We start the analysis by simply calculating the profits of the pulp mill according to eq. 2 for a given level of inputs and production, reflecting the short-term choice of the mill. We assume that all lignin, biosludge, and tall oil are either sold as a side stream or used to produce energy in the pulp mill.⁷ Because the pulp mill produces more energy than it needs, the energy produced from lignin, biosludge, and tall oil can be sold.

Outcomes are reported in Table 3, including sensitivity analysis with respect to the side stream and energy prices when 6 780 000 m³ of wood raw material is used annually in the production process. Profits are higher when lignin and tall oil are sold as a side stream, even when we let the prices of side stream or sold heat energy vary. Given that both the price of biosludge sold as a side stream and the heat value of biosludge are low, the difference in profits between these alternative uses for this side stream is relatively small.

In the long term, the pulp mill can optimize the use of all inputs. We employ the Cobb–Douglas production function to describe the production technology of the pulp mill. The Cobb–Douglas production function is given by $(x, e_p) = Ax^\alpha e_p^\beta$, where parameters α and β describe the shares of production factors (wood raw material and energy) in the production of pulp. We calibrate the parameters A , α , and β using Matlab and the data reported in Table 2. We calibrate the production function assuming the pulp mill neither produces energy from side streams nor sells it to a biochemical company. This produces the benchmark

Table 3. The short-term profits of the pulp mill when side streams are either sold to the biochemical company or used as energy.

Side stream	Profits of the pulp mill (million €/year)					
	Sold as a side stream			Used as an energy source		
	Basic run	Price of side stream		Basic run	Price of energy	
		–10%	+10%		–10%	+10%
Tall oil	419.6	416.9	422.2	409.4	407.8	411.0
Biosludge	393.1	393.1	393.1	393.3	393.3	393.4
Lignin	427.8	424.3	431.2	407.4	406.0	408.9

of free disposal of waste in the firm's landfill as our benchmark.⁸ We compare the benchmark to two cases. First, the pulp mill produces energy from side streams and sells the produced extra energy. Second, we add the possibility of selling all side streams to the biochemical company. In both cases, the pulp mill freely chooses the use of inputs to optimize its profits. Pulp production produces steam as a side product, and the mill sells the excess steam, which is considered additional revenue similarly in all three cases.

Table 4 reports the results when the side stream to be allocated is tall oil. Under the postulated prices, allocating tall oil from the benchmark for energy or bio-products increases profits and the use of wood. The possibility to produce energy from tall oil increases profits by 4.3% relative to the benchmark. Allowing the possibility of selling tall oil to a biochemical company increases the profits even by 7.1%. Looking at the sensitivity analysis, when the pulp price increases, the use of both wood and electricity increases as the profitability of the pulp production is higher. This is according to our analytical results (Table 1), suggesting that the impact of energy price on the use of wood and energy is ambiguous due to two opposing effects. The numerical model shows that the price effect on the use of wood is positive and on the use of energy negative. Increased profitability of wood in energy production increases the use of wood. As expected, the price of the side stream has a positive effect on both the use of wood and electricity. Similarly, the price of wood has a negative effect on the use of wood and electricity.⁹

Table 5 reports the results for lignin as the side stream. The possibility to produce energy from lignin increases profits by 3.8% relative to the benchmark. The possibility to sell lignin to a biochemical company increases the profits by 9.5% relative to the benchmark. The sensitivity analysis shows similar results as in the case of tall oil.

Table 6 reports the results for the case of biosludge. In this case, producing energy from biosludge increases profits by only 0.05% relative to the baseline. Furthermore, the possibility to sell biosludge to a biochemical company does not change the profits relative to the baseline because the price of biosludge as a sold side stream is low. It should also be noted that the amount of biosludge produced in the pulp mill is relatively low compared to the produced amounts of tall oil and lignin. These two features also explain our finding that the price of the side stream does not affect the use of wood and electricity. Sensitivity analysis provides similar effects as in the cases of tall oil and lignin.

Finally, Tables 4 and 5 show that relative to the baseline, the possibility of producing energy or selling tall oil and lignin to the bioproduct company increases the use of wood. In the case of biosludge, the use of wood does not significantly change. Both the long-run and short-run profits indicate that the profitability of

side streams differs. First, the profits of the pulp mill are higher when tall oil and lignin are sold as side streams than when they are used in energy production. Second, the difference in profits of the pulp mill is relatively small between alternative uses of biosludge. Third, the long-run sensitivity results also indicate that changes with respect to the pulp price have the most significant effects on the optimal input use and profits. This result holds for all three products: tall oil, lignin, and biosludge.

Next, we focus on the biochemical company's optimal production decisions in the pine chemical industry, which represents the traditional use of pulp mill's side streams into high-value-added chemical products.

3.2. The cascading use of side streams: biochemical company

Biochemical companies play an essential role in the forest bioeconomy. They produce high-quality products from side streams, thereby giving pulp mills a chance to get rid of their side streams profitably. However, data from biochemical production and prices from side streams are even scarcer than in the case of pulp mills. In this section, we focus on the pine chemical industry and examine the properties of the model numerically. We also employ them to illustrate the welfare effects of material shortages on the production of the biochemical company. This exemplifies the extreme impact the promotion of biodiesel might have on the production of higher-value chemical products via increasing raw material prices (Cashman et al. 2015).

3.2.1. Data and parameters

The biochemical company using tall oil produces tall oil rosin and tall oil fatty acids as the final products. We assume that the biochemical company buys tall oil and steam from the pulp mill. Suppose we assume that biochemical company uses 60 000 t of crude tall oil annually, based on Cashman et al. (2015). In that case, we can estimate the amount of tall oil used for tall oil rosin and tall oil fatty acids, produced amounts of final products, and the energy needed in the production process. Transportation and light fuel oil costs and steam provided to the pulp and paper mill are omitted here. The main production inputs and their prices, production amounts, and final products are presented in Table 7.

3.2.2. The use of inputs and profits of the biochemical company

We again use the Cobb–Douglas production function to characterize the production technology of the biochemical company. In the long term, the biochemical company can optimize the use of inputs in its production process. The Cobb–Douglas production function is given by $y = Ax^a e_p^b$, where the factors a and b describe the shares of production factors (tall oil and energy) in the production of tall oil rosin and tall oil fatty acids. First, Table 8 reports the optimal production under the basic price of 441 €/t of crude tall oil. Then, these figures are compared to choices under higher input prices. It is, however, difficult to estimate how much the price increases due to decreased supply of raw material if the tall oil is increasingly used to produce biodiesel. Therefore, we postulate 10% and 20% increases in the input price of crude tall oil, mainly due to the assumption of increased transportation costs. Appendix Table A1 presents the sensitivity analysis with respect to changes in energy prices and the price of the final product.

From Table 8, if the price of crude tall oil increases by either 10% or 20%, the reduction in the use of tall oil is significant. The use of energy inputs, production, and the profits also decrease. In light of these calculations, a biofuel policy that creates demand

⁸Using landfills is, in practice, an option for low-value waste. However, assuming free disposal is a simplification, as using the firm's own landfills entails some costs.

⁹In the sensitivity analysis, the change in wood prices is modelled as the change in the weighted average of pulpwood (birch, pine, and spruce) and wood chips.

Table 4. Tall oil as a side stream and the profits and use of pulpwood for the pulp mill: baseline, the use for energy, or sale to a biochemical company.

	Benchmark: no use of tall oil			Tall oil for energy production			Tall oil sold to the biochemical company		
	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)
Basic run	6 780	750	393.1	7 284	778	410.0	7 627	796	421.2
Energy prices (electricity/heat), €/MWh									
42/30 (−10%)	6 567	830	387.8	7 001	857	402.6	7 372	880	414.9
52/36 (+10%)	7 011	687	399.2	7 594	715	418.3	7 904	729	428.2
Side stream price, €/t									
397 (−10%)	—	—	—	—	—	—	7 536	791	418.2
485 (+10%)	—	—	—	—	—	—	7 719	801	424.2
Pulp price, €/t									
602 (−10%)	5 538	606	310.4	5 957	629	324.2	6 242	644	333.4
736 (+10%)	8 133	908	484.6	8 728	941	504.9	9 131	963	518.3
Price of wood raw material, €/m ³									
−10%	7 207	774	407.5	7 757	803	425.4	8 132	822	437.3
+10%	6 388	728	379.6	6 851	754	395.5	7 164	771	406.0

Table 5. Lignin as a side stream and the profits and use of pulpwood for the pulp mill: baseline, the use for energy, or sale to a biochemical company.

	Benchmark: no use of lignin			Lignin for energy production			Lignin sold to the biochemical company		
	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)
Basic run	6 780	750	393.1	7 220	774	407.9	7 918	811	430.6
Energy prices (electricity/heat), €/MWh									
42/30 (−10%)	6 567	830	387.8	6 946	854	400.7	7 648	896	424.0
52/36 (+10%)	7 011	687	399.2	7 519	711	415.9	8 212	744	437.9
Side stream price, €/t									
416 (−10%)	—	—	—	—	—	—	7 793	805	426.6
508 (+10%)	—	—	—	—	—	—	8 047	818	434.7
Pulp price, €/t									
602 (−10%)	5 538	606	310.4	5 903	626	322.5	6 485	657	341.1
736 (+10%)	8 133	908	484.6	8 652	937	502.3	9 474	981	529.5
Price of wood raw material, €/m ³									
−10%	7 207	774	407.5	7 687	799	423.2	8 451	839	447.3
+10%	6 388	728	379.6	6 792	751	393.5	7 431	786	414.8

Table 6. Biosludge as a side stream and the profits and use of pulpwood for the pulp mill: baseline, the use for energy, or sale to a biochemical company.

	Benchmark: no use of biosludge			Biosludge for energy production			Biosludge sold to the biochemical company		
	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)	The wood raw material used (1000 m ³)	Electricity used in pulp production (GWh)	Profits, million (€/year)
Basic run	6 780	750	393.1	6 786	750	393.3	6 780	750	393.1
Energy prices (electricity/heat), €/MWh									
42/30 (–10%)	6 567	830	387.8	6 572	830	387.9	6 562	829	387.6
52/36 (+10%)	7 011	687	399.2	7 018	687	399.4	7 018	687	399.4
Side stream price, €/t									
0.54 (–10%)	—	—	—	—	—	—	6 780	750	393.1
0.66 (+10%)	—	—	—	—	—	—	6 780	750	393.1
Pulp price, €/t									
602 (–10%)	5 538	606	310.4	5 545	607	310.7	5 540	607	310.6
736 (+10%)	8 133	908	484.6	8 138	909	484.7	8 131	908	484.5
Price of wood raw material, €/m ³									
–10%	7 207	774	407.5	7 214	774	407.7	7 549	792	418.7
+10%	6 388	728	379.6	6 393	728	379.8	6 117	712	370.1

for tall oil via blending mandates provides a true challenge to biochemical companies in the tall-oil-using industry. Drawing on the results of Table 8, we can estimate the welfare loss due to material shortage at the production and the need to import raw material at a higher price as illustrated in Fig. 2 (recall, the difference between m^* and m^{**}). Suppose that biochemical company receives side streams from the pulp mill 30%–40% less than the optimal production would require. The welfare loss estimate is considerable, ranging from 555 300 € to 877 300 €.

4. Conclusions

We examined the economic features of the forest bioeconomy as an industrial ecosystem consisting of traditional pulp mills and biochemical companies using side streams from pulp production in the vicinity of the pulp mill. Our analysis is unique in the literature. It focuses on the economic interaction between the companies and traces out the impacts of relative prices on the allocation of wood-based side streams between energy production and cascading use for biochemical products.

Analytically, we found that under perfect competition, the emerging industrial ecosystem uses more pulpwood than the traditional forest industry. Second, market imperfections showing up either in monopoly or monopsony behaviour lead to a lower cascading use of wood-based side streams and increased use of side streams in energy production. On the other side of the coin, imperfect competition decreases demand for pulpwood. Third, in the presence of a shortage in the supply of side streams or market power of the biochemical company, the production of bio-products remains at a sub-optimal level.

The numerical forest bioeconomy model confirms that for the main side streams analyzed in this study, tall oil and lignin, bioeconomy with cascading use of wood promotes higher use of wood, implying higher harvesting levels of forests. By lowering forest sink, this would pose a challenge to climate change mitigation, which the transition to forest bioeconomy is expected to promote (Kalliokoski et al. 2020; Seppälä et al. 2019; Soimakallio et al. 2016). However, the effect of increased harvesting on biodiversity is less clear. It depends on multiple issues, such as the relative shares of thinnings versus final felling, the forest management regimes, and biodiversity policy.

We show that selling side streams is more profitable than energy production for the pulp mill, promoting the more efficient use of side streams in the case of tall oil and lignin. In contrast, profits from biosludge did not significantly differ between alternative uses due to low prices and produced amounts. These results align with previous studies as they find value-added biochemical products based on lignin and tall oil economically feasible and providing significant future potential (Aryan et al. 2019; Bajwa et al. 2019; Xu et al. 2021). Hassan et al. (2019) defined biosludge as a low-value side stream and estimated that only a small share of biosludge is used for economic purposes in Finland.

Our results have implications for the debate on EU policies promoting renewable energy targets (EU Directive 2015/1513). The pine chemicals industry has highly criticized these policies for favouring biodiesel production and increasing competition on crude tall oil. Aryan and Kraft (2020) estimate that the supply deficit of crude tall oil may be as high as 8% globally by 2030. This material shortage would increase tall oil prices and decrease the pine chemical industry's profits and production levels. This does not follow the cascading principle of side stream use. The life cycle assessment studies by Cashman et al. (2015) and Aryan et al. (2019) did not find any additional climate benefits if crude tall oil is used in biodiesel production instead of current chemical production. Bauer et al. (2017) note that the EU has set clear targets for biofuels but has not set any targets for other bioproducts, such as biochemical and biomaterials.

Table 7. Data and parameter values used in the profit maximization of a biochemical company.

Description	Unit	Value	Source
Production inputs			
Crude tall oil	t	36 600	Cashman et al. 2015; Metsä Fibre 2014
Purchased electricity	MWh	6528	Estimated based on Cashman et al. 2015
Purchased steam	MWh	6121	Estimated based on Cashman et al. 2015
Natural gas	MWh	2528	Estimated based on Cashman et al. 2015
Heavy fuel oil	MWh	1520	Estimated based on Cashman et al. 2015
Prices of production inputs			
Price of tall oil	€/t	441	Eurostat 2018a
Price of electricity	€/MWh	47	European Commission 2019a, 2019b, 2019c, 2019d
Price of heat energy	€/MWh	33	Korpunen 2015
Price of natural gas	€/MWh	39	Eurostat 2018b
Price of heavy fuel oil	€/MWh	44	Statistics Finland 2019
Production amounts			
Tall oil rosin	t	16 701	Estimated based on Cashman et al. 2015
Tall oil fatty acids	t	21 031	Estimated based on Cashman et al. 2015
Prices of final products			
Price of tall oil rosin	€/t	1520	Spekreijse et al. 2019
Price of tall oil fatty acids	€/t	1162	Eurostat 2018a

Table 8. Profits, produced amounts, and use of production inputs of the biochemical company in the long-run optimum when the price of crude tall oil increases.

	Profits, million (€/year)	Production amount (t)	Use of tall oil (t)	Use of energy (MWh)
Basic run	33.00	37 732	36 600	16 698
Crude tall oil price, €/t				
485 (+10%)	31.5 (−5%)	36 013 (−5%)	31 757 (−13%)	15 937 (−5%)
529 (+20%)	30.2 (−9%)	34 513 (−9%)	27 898 (−24%)	15 273 (−9%)

Our analysis sheds new light on the slow development towards utilizing all side streams from pulp production, despite keen interest in ‘biorefineries’ (see, e.g., Bauer et al. 2017). We demonstrated that competitive input prices and a secure supply of raw material are crucial for biochemical company’s profits – and indirectly also for the decision to invest in new bioproducts. This also includes a company’s assessment of the potential market power of pulp mills. From the pulp mill’s viewpoint, in turn, the profitability of different side streams, whether sold as a side stream or used in energy production, differs. Anticipating future demand and profits from bioproduct markets thus affect pulp mills’ decisions. Finally, an additional source of uncertainty is provided by energy and climate policies, which are not always consistent, as the case of biofuel policy suggests.

The data used in the numerical application was gathered from different sources. Similarly, as in many quantitative studies on wood cascading, there are uncertainties concerning how detailed the data are (Jarre et al. 2020). Interestingly, though, our results concerning net profits (302–331 €/t) are very close to Korpunen et al. (2012), who found that the net profits were 312 €/t to 334 €/t (2018 price level). Nevertheless, more and better data are needed for an analysis of all possible side streams. Also, more detailed technical data related to the pulp mill’s processes would be highly valuable to develop the numerical model further. More information is also needed on the environmental and climate impacts of alternative uses of different side streams.

The most important contribution of this study is to offer a genuinely economic analysis of the forest bioeconomy as an industrial ecosystem. It complements the existing and more technically

oriented models and provides a framework for incentive analysis.¹⁰ Our formal economic framework facilitates both analytical and numerical analysis of climate and other policy instruments. It can be flexibly made more complex and detailed either technologically, economically, or policy-wise. Therefore, it opens many avenues for future research. The role of market imperfections and policies correcting them shows up as an essential issue. Regarding the sustainability challenges, examination of the impacts of climate and circular economy instruments is urgently needed. The broader aspects of the forest bioeconomy, such as biodiversity or the role of sinks, were only shortly discussed in this study. Interesting questions for future work include broadening the established framework to forest biodiversity and land use, land-use change, and forestry (LULUCF) policies, as it is clear that the sustainability aspects of the forest bioeconomy need to be secured (see e.g., recent IPBES 2018; and IPCC 2019 reports) in order for the forest sector to fulfil its promise of being the renewable alternative to the fossil-based industry in a sustainable way.

Competing interests

The authors declare there are no competing interests.

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¹⁰Recall, these models cover the supply chain design and optimization models (e.g., Mansoornejad et al. 2010; Elaradi et al. 2021; Machani et al. 2014) and techno-economical assessment models and process models (e.g., Mansoornejad et al. 2010; Dessbesell et al. 2018), process modelling and economic analysis (e.g., Huang et al. 2009, 2010).

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Appendix A

Table A1. Profits and use of production inputs of the biochemical company in the long-run optimum when the prices of energy and final product vary.

	Profits, million (€/year)	Use of tall oil (t)	Use of energy (MWh)
Basic run	33.00	36 600	16 698
Energy price, €/MWh			
36 (–10%)	33.07	36 679	18 593
44 (+10%)	32.93	36 530	15 150
Price of the final product, €/t			
1188 (–10%)	28.15	31 219	14 243
1452 (+10%)	38.10	42 263	19 281