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Evaluating fuel switching options in the Swedish iron and steel industry under increased competition for forest biomass

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HIGHLIGHTS

- Explore markets effects of biomass competition between steel and forest industries.
- Soft-linking technical energy system model and economic forest sector model.
- Regional competition disrupts biomass prices and allocation, and supply costs.
- Steel industry must consider market effects of new bio-production investment.
- Beneficial to co-locate bio-production plants with iron and steel industries.

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ABSTRACT

Significant use of forest biomass in the iron and steel industry (ISI) to mitigate fossil CO_2 emissions will affect the biomass availability for other users of the same resource. This paper explores the market effects of increased forest biomass competition when promoting the use of forest-based bio-products in the ISI, as well as the interactions between the ISI and the forest industries. We employ a soft-linking approach that combines a geographically explicit techno-economic energy system model and an economic partial equilibrium model of the forest industries and forestry sectors. This allows for iterative endogenous modelling of new equilibrium price developments for different biomass assortments, determining locational choice of bio-products and assessing optimal bio-products technology choices. The results indicate an upward pressure on biomass prices when bio-products are introduced in the ISI (up to 62%), which affects both forest industries and the ISI itself. Prudence is thus warranted not to render bio-production investments uneconomical ex-post by neglecting to include potential price effects in investment decisions. The estimated price effects can be mitigated by increased domestic biomass supply, adjustments of international trade or by revising relevant policies. Even though the results suggest that the price effects will affect the geographical preferences for individual bio-production plants, proximity to the ISI production facility and integration benefits are more important than the proximity to cheaper biomass feedstocks. Product gas production integrated at ISI sites emerges as particularly attractive, while charcoal production exhibits sensitivity to fluctuating markets, both regarding resulting cost for the ISI, and preferred production locations.

Abbreviations: BWS, BeWhere Sweden; BF, Blast Furnace; BOF, Basic Oxygen Furnace; CEPCI, Chemical Engineering Plant Cost Index; DH, District Heating; DR, Direct Reduction; EAF, Electric Arc Furnace; EU, European Union; EU-ETS, European Union Emissions Trading System; GAMS, General Algebraic Model System; HFO, Heavy Fuel Oil; ISI, Iron and Steel Industry; LFO, Light Fuel Oil; LHV, Lower Heating Value; LNG, Liquefied Natural Gas; LPG, Liquefied Petroleum Gas; L-SNG, Liquefied Synthetic Natural Gas; MILP, Mixed Integer Linear Programming; NG, Natural Gas; NCFSM, Norrbotten County Forest Sector Model; O&M, Operation and Maintenance; PoP, Pulp and Paper Industry; Saw, Sawmill Industry; SCFSM, Swedish County Forest Sector Model; SNG, Synthetic Natural Gas.

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1. Introduction

The Swedish iron and steel industry (ISI) sector is a noteworthy player in niche markets for specialised and advanced steel products. With its heavy dependency on fossil fuels and reductants, the ISI and mining industry combined account for 63% of Swedish industry's fossil energy use [1] and 46% of its greenhouse gas emissions (12% of the total territorial emissions) [2]. The ISI in Sweden thus faces similar challenges as the global ISI, namely, a need to decrease its fossil CO_2 emissions already in the short to medium term.

Currently, much focus, in Sweden as well as globally, is on replacing the CO_2 intensive blast furnace (BF) reduction pathway with renewable hydrogen based direct reduction [3,4]. This transition requires formidable commitment to long-term capital replacement, which can pose a major barrier, unless current industrial facilities are close to end-of-life [5]. As BF-based steel production represents over two-thirds of iron and steel produced globally [6], it is imperative to reduce the CO_2 emissions from this route not only in the longer perspective, represented by the hydrogen pathway, but also in a shorter time perspective. Full or partial replacement by biomass-based reductants and fuels can constitute a realistic short to medium term strategy both within the BF route and in other process routes, e.g., electric arc furnaces (EAF), direct reduction, secondary processing, etc., as it can be implemented with relative technical ease [4,7,8]. Although it is not technically possible to replace all the fossil reductants and energy carriers with biomass, various refined bio-products (e.g., charcoal, product gas, and synthetic natural gas, SNG) have all shown technical feasibility within different ISI processes [7,9-18].

Besides technical concerns, major issues related to utilising biomass in the ISI include the large biomass quantities required, and the increased competition for limited biomass resources that are also in demand by other industries as a primary raw material or as a means of achieving their CO_2 mitigation targets [19]. A large demand for biomass-derived fuels implies that the ISI will become a major actor within biomass markets [20]. Since biomass markets are often regional in character [21], local and regional market effects leading to feedstock prices changes can be expected. The market effects from increased biomass competition can create a ripple effect on the biomass supply costs for both existing and new biomass users, thus risking to affect the economic feasibility of the ISI to use biomass.

Previous studies that have analysed the economic feasibility of using biomass in the ISI have omitted the impacts of the increased competition for biomass on the practicability of the ISI switching to bio-products [22-24]. Similarly, broader economic impacts from allocating and supplying large quantities of forest biomass to the ISI have, to the best of our knowledge, been left unexplored. In this paper, we address this knowledge gap and explore the relationship between biomass markets and the options to use biomass in the ISI. As the study focuses on the Swedish ISI, the most suitable feedstocks from a Swedish perspective are considered, namely residual biomasses from forestry and forest industry.

Techno-economic assessments of using forest biomass in steel production have identified the costs for biomass feedstock and plant capital as the major contributors to the overall production cost (see e.g. [14]). Uncertainty in techno-economic parameters, such as biomass prices, is typically addressed by applying sensitivity analysis, which, however, ignores market dynamics resulting from competing uses of biomass. Interactions between the bioenergy sector and other sectors, in particular the forest sector, have instead largely been studied using partial equilibrium (PE) market models derived from the research field of economics [25,26]. Jåstad et al. [27,28] showed that biomass feedstock prices increase at different levels of production of biofuels for transportation, and industries affected by the resulting feedstock reallocation will lose market. Similarly, Bryngemark [29] concluded that part of the forest industry will be affected if forest biomass is used as main feedstock in large-scale biofuel production. However, she also indicates that there are synergy effects between the bioenergy and sawmill sectors that can be exploited. Mustapha et al. [30] investigated the dependencies between feedstock costs and emerging biomass conversion pathways. Their results indicated increased and conversion technology dependent feedstock costs, although technological learning can dampen the cost increase. While most PE modelling studies, including those mentioned, focus on either the stationary energy sector or biofuels for transportation, Olofsson [20] extended the scope to the ISI as a new biomass user. His analysis of the effects from an increased competition for forest biomass assortments on regional biomass markets in northern Finland and Sweden indicates that a partial transition to charcoal in the ISI will lead to price increases for the secondary biomass assortments.

A drawback of these forest sector model-based approaches is the lack of technology detail inherent in models derived from research fields of engineering, where detailed mass and energy balances can be used to describe the technology performance of the biomass conversion technologies. Similarly, spatial aspects of potentially significant impact for the bio-product supply chain are typically not considered; e.g., feedstock availability, available modes of transport, the prevalence of opportunities for integrated production, and local or regional biomass competition [31,32]. Geographically explicit optimisation for different bio-product systems has been widely dispatched as a method for identifying least cost bio-product supply chain options within a studied system (e.g. see [33-35]), being able to capture, e.g., beneficial options for logistics, supply chain design, facility location, and feedstock mixes. Several such supply chain studies have focused on bio-products for the ISI [19,23,24,36], applying exogenous biomass prices. Static representation of biomass prices in supply optimization models mask the true impact of bio-production since the effect of competition within biomass markets with the ISI being a new market entrant are excluded, thus diminishing the value of the economic results for the ISI.

By combining the strengths of a market model and a techno-economic supply chain model, the respective model capabilities can be leveraged, and additional insight gained. There is currently a growing trend in such cross-platform modelling integration to facilitate deeper investigation of complex issues related to energy system aspects and the energy transition [37,38]. For the case of biomass markets in relation to the energy transition, the detailed market description in a market model can thus be combined with the technology detail in the technical supply chain model, to enable the endogenization of disruptive biomass market changes. This type of approach has recently been used in several studies of large-scale forest-based biofuel production [39-41].

This paper aims to explore the economic effects of increased forest biomass competition when promoting the use of forest-based bio-products in the ISI. We address the knowledge gap outlined above by combining the economic impacts of biomass competition (price effects), supply costs of forest biomass, and technologies for biomass conversion. This is carried out by soft-linking two existing system models, neither of which can adequately address the issue independently: an economic partial equilibrium model of the forest industry and forestry sectors, and a geographically explicit techno-economic energy system model of the ISI and the bio-production options, respectively. We explore the interactions between the forest industry sector and the ISI sector by addressing the following questions:

1. How does the introduction of the ISI affect biomass feedstock prices?
2. How do biomass prices influence the localisation of bio-product plants?
3. How are the supply costs and feedstock allocation between competing sectors affected by different bio-production pathways for large-scale introduction of biomass to the ISI?
4. Which bio-production pathways are cost efficient for the ISI to adopt considering the effects of price dynamics from biomass competition?

Opportunities for biomass utilisation are included for the entire steel production chain, starting with production of iron ore pellets and across

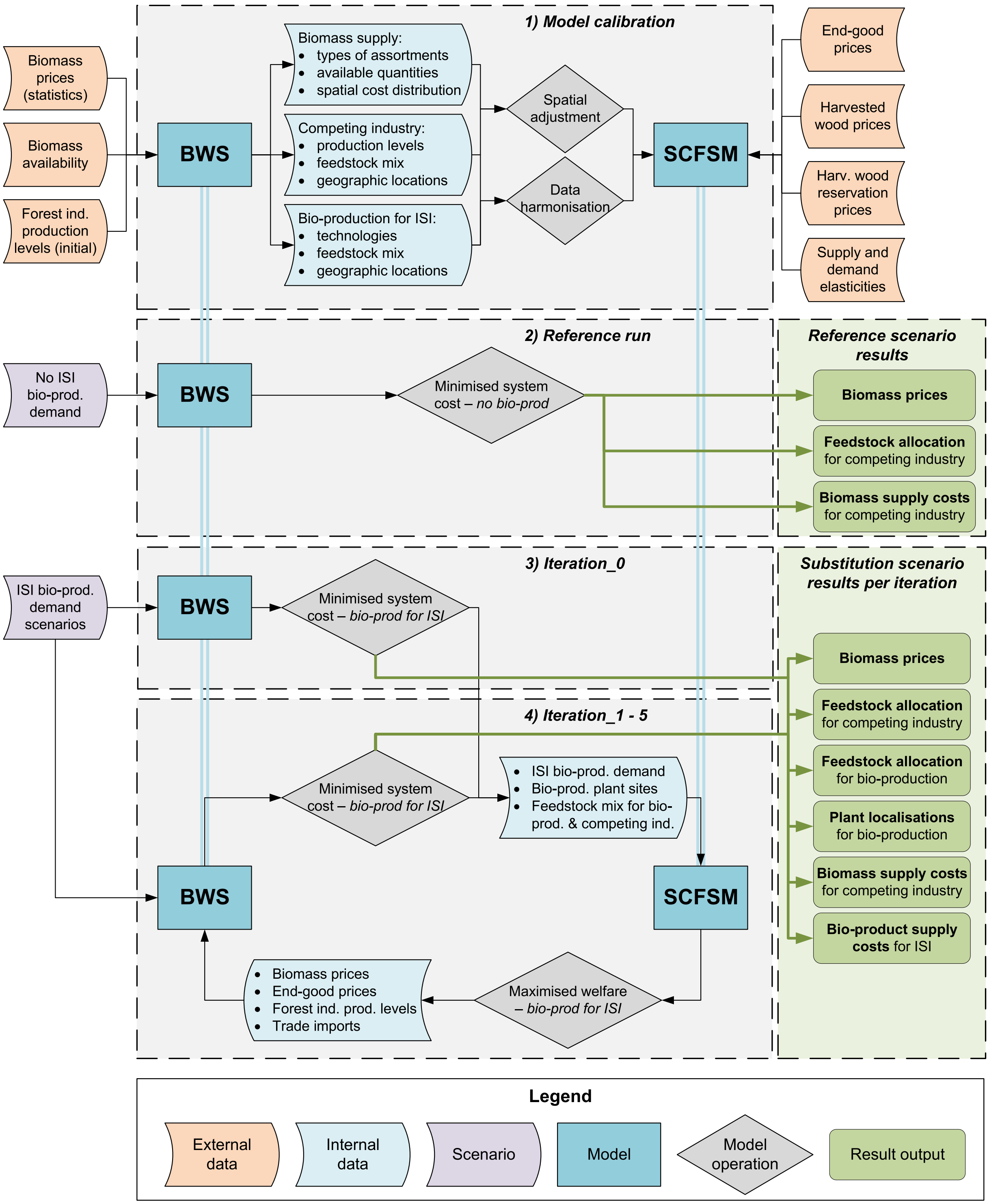

Fig. 1. Schematic overview of the soft-linking procedure between the BeWhere Sweden (BWS) model and the Swedish County Forest Sector Model (SCFSM).

the different production routes. With a focus on the ISI in Sweden, the relationship between the existing forest industry and the ISI is studied, together with how competition between the two industry sectors may impact feedstock prices, allocation of biomass resources, and options for the physical location of new bio-refineries. This inter-dependency between sectors is important for both industry and policy-makers to consider before proceeding with the restructuring of the ISI sector from fossil to biomass-based fuels and reductants.

2. Methods and materials

To evaluate potential implications on both existing forest biomass-using industries and on the ISI using bio-products, in terms of feedstock prices and biomass supply for the bio-products, a soft-linking method between two existing models is used. Economic price impacts are endogenously modelled and identified using the PE forest sector model, and the resulting biomass prices are used as input in the geographically explicit supply chain model.

2.1. Modelling framework

This section describes the models used, as well as the soft-linking procedure. Additional details on the models used can be found in Appendix A.

2.1.1. Techno-economic supply chain model

The techno-economic supply chain model, BeWhere Sweden (BWS), is a geographically explicit optimisation model that has been developed for extensive system analysis of bioenergy systems, with a particular focus on forest biomass [33,36,42]. BWS is a mixed-integer linear programming problem, written in the commercial software General Algebraic Model System (GAMS) and solved using CPLEX. The model is solved for time-steps of one year, with the objective to minimise the total system cost to satisfy the demand for selected bio-products in the sector or sectors in focus for the analysis, while simultaneously meeting the demand for bioenergy in other, competing, sectors. The system cost includes the pertinent supply chain costs (procurement of biomass feedstock, biomass transportation, costs of bio-production plants, and transportation of bio-products), as well as costs for fossil fuels and materials and costs and revenues related to policy instruments, e.g., CO_2 price and green electricity certificates.

BWS was originally developed to analyse the production and use of advanced biofuels for transportation [33,42,43], but has recently been extended with a module that allows for analysis of biomass use in the ISI [24,36]. The new module includes the individual ISI plants' demand of fossil fuels and reductants, their replacement potential with bio-products, and the technologies for and potential locations of different bio-product production plants. The model considers the substitution of fossil fuels and its process application with the corresponding bio-product. The biomass demand of the existing forest biomass users is fixed and must be met, while the demand of new bio-production plants varies, depending on modelled demand from the ISI.

The geographical scope of the model encompasses the national boundaries of Sweden, with a large number of locations of importance for biomass supply and demand, as well as for potential integrated biofuel production, taken into account. The base grid consists of 334 grid cells with a half-degree spatial resolution and is used to represent biomass supply and demand. In addition, the coordinates of potential host industries for biomass conversion facilities are expressed explicitly. The model contains nine different biomass assortments, seven industry sectors with competing biomass demand, three bio-production (pathways) technologies, and 111 potential host sites for integrated bio-production.

Biomass prices in BWS are expressed with spatial differences depending on geographical variations and distances, see [33,44]. The prices are, however, static, which means that neither biomass prices nor production quantities in other industries are affected by the adaptation of a specific new demand of bio-products from the ISI.

2.1.2. Partial equilibrium economic model

The PE model used is the Swedish County Forest Sector Model (SCFSM). The model's objective is to maximise the economic wellbeing (i.e. welfare) for all agents, in all regions, given a number of constraints (see [45] for additional information regarding the SCFSM and its previous iteration, the Norrbotten County Forest Sector Model (NCFSM)). This is achieved by maximising the sum of all regional consumer and producer surpluses, net of the total cost of inter-regional trade [46,47]. The model is implemented in GAMS and solved using the CONOPT solver.

The modelling structure used by the SCFSM was first developed by Kallio et al. [48] and later refined by e.g. Bolkesjø [49]. The model utilizes a system of fixed input–output production functions, i.e., specific quantities of biomass are required for a given output. However, production flexibility is introduced for different industries by having diverse biomass bundles that can be used to produce one unit of output. In total, this iteration of the SCFSM contains 480 production activities, seven industry sectors, five woody inputs, 16 output products, and covers the 21 counties of Sweden and one aggregated region for the Rest of the World (ROW). The SCFSM is solved for one period (i.e., a static model).

When solving the objective function of the SCFSM, the model tries to satisfy a regional exogenous demand (i.e., production targets), which is here based on BWS production levels for the existing forest industry and estimated demand targets for bio-products. The model will continue to allocate woody input commodities to an industry if the feedstock is readily available, and/or if it is deemed economically to do so. The amount of harvested woody materials supplied to the market is selected by the model, but calibrated using estimates for biomass availability from BWS (based on [50], see [33,44] for detailed description), thereby introducing an upper regional limit for the biomass supply. Supply of woody by-products from sawmilling (defined as woodchips and industrial by-products) is limited by the production capacity of the regional sawmill sector.

In the SCFSM, total biomass demand and production output are treated statically, in that all sectors are trying to produce given quantities of output. Woody inputs will be allocated by the model to the sectors that produce the greatest social payoff (in economics usually defined as societal welfare).

Where possible, numerical estimates are collected from BWS and adjusted to fit the SCFSM's county spatial delineation. However, the PE model structure of the SCFSM entails that there are additional parameters that are required for the model to solve properly, when compared to BWS. These are prices for end-good and harvested woody materials, reservation prices for harvested woody materials, and supply and demand elasticities. The price parameters are used to calibrate the model, while the elasticities are used to determine the shape of the feedstock supply- and the end-good demand curves. For a detailed review of these and their sources, see [45].

In the SCFSM, woody biomass can be imported from foreign markets, as a way of alleviating any regional feedstock shortages. Imported quantity is endogenously determined by the model, but contingent on the estimated transport cost for the specific county. To avoid feedstock leakage, roundwood (i.e., sawlogs and pulpwood) is assumed to not be exportable from Sweden. Similarly, harvesting residues are by assumption not an importable or exportable good, primarily due to its low value-to-weight.

2.1.3. Soft-linking procedure

The soft-linking procedure is outlined schematically in Fig. 1, and performed according to the following steps:

1) **Model calibration and data harmonisation:** Exogenous data for biomass availability and prices and for forest industry production is collected and pre-processed for inclusion in BWS, after which it is adjusted to fit the SCFSM, and translated regarding, e.g., units. End-goods price, reservation price and elasticity data are collected and included in the SCFSM. The respective models are test-run individually to validate that they reproduce the current situation satisfactorily.
2) **Reference scenario:** BWS model is first run without any new bio-production in the system and applying the initial static exogenous biomass prices. This establishes the *Reference* scenario, i.e., a business-as-usual case where the ISI does not use biomass in any of its processes.
3) **Initial exogenous BWS run (Iteration_0):** BWS is run with new demand for bio-products from the ISI included, according to three different substitution scenarios (described in section 2.4). Optimal bio-production quantities and plant locations per bio-product and substitution scenario are obtained, based on the initial static exogenous biomass prices.

Table 1
Selected fossil energy substitution in the different process units across the entire iron and steel production chain. Production process in italics corresponds to nomenclature in Fig. 2.

Process unit	Fossil fuel used	Application	Bio-product as substitute	Maximum substitution potential	Ref.
Pelletising kilns *(iron ore production)*	Coal	Heating fuel	Charcoal	100%	[14,52]
	HFO, LFO		L-SNG or product gas	100%	
Coke ovens *(BF-BOF)*	Coking coal	Raw material for coke making	Charcoal	5%	[7,9]
Blast furnace *(BF-BOF)*	Pulverised coal	Fuel and reductant	Charcoal	100%	[10]
EAF	Coal	Slag former	Charcoal	100%	[11]
	Pet-coke	Fuel	Charcoal	100%	
DRI *(sponge iron)*	Coal	Heating fuel and reducing agent	Charcoal	100%	[14]
	Coke		Charcoal	100%	
Furnaces and secondary processing *(auxiliary processing)*	LNG, LPG, NG, LFO	Heating fuel	L-SNG or product gas	100%	[16,53]

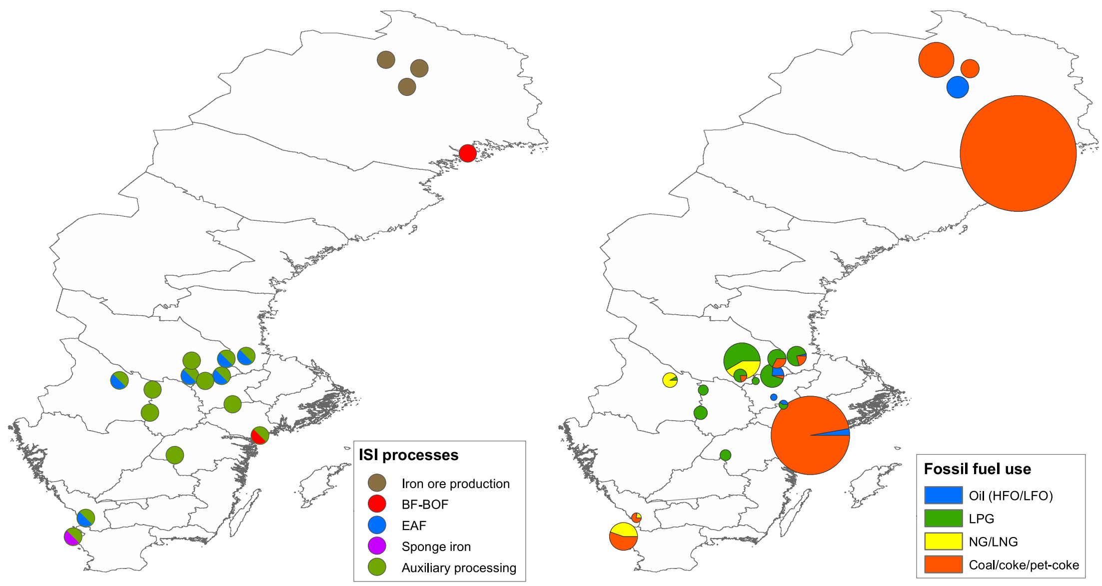

Fig. 2. Location and types of ISI plants included in this study (left), and relative fossil use (fuels, reducing agents, etc.) in 2018 (right). For more information on Swedish iron and steel industry, see [51].

4) **Iterative BSW-SCFSM runs:** The output from BWS Iteration_0, i.e., biomass quantities used for bio-production and competing industry and optimal plant localisations, is used as input to SCFSM, for each of the three substitution scenarios. SCFSM runs a market analysis based on the equilibrium results from BWS to obtain the resulting endogenous feedstock price implication. The new price estimates from SCFSM along with adjusted forest industry production volumes are then used as input in BWS in its next bio-production iteration. Observed import quantities from the SCFSM are used as upper import limits in BWS. A total of five iterations is done (*Iteration_1* to *Iteration_5*). The endogenous price estimates are used to determine the economic performance of bio-production in BWS.

As discussed by [38], while it may appear arbitrary to conduct a certain number of iterations, the step-wise analysis allows for insights into interactions between the industry sectors. The results produced are stable for the specific scenario assumptions and underpins the explorative approach of this study. Observation from each iteration provide information on the price stability, or lack thereof, for the biomass assortments. The iterations are evaluated in terms of:

i. **Biomass price changes:** Regional (county) biomass price changes derived by SCFSM are used as endogenous input to BWS, in an iterative manner. SCFSM solves for new equilibrium prices as a percentage increase or decrease from the subsequent iteration. In BWS, the percentage changes from SCFSM are multiplied by the price factors in each county to obtain an average national price per biomass assortment.
ii. **Plant localisations for bio-production:** Initial plant localisations resulting from the initial exogenous run (i.e., Iteration_0) in BWS serve as input to SCFSM, which then solves to determine endogenous regional prices for assortments. This interdependency results in plant localisations stabilising or varying during the iterative process.
iii. **Changes in allocation of biomass feedstock used for bio-production and for the competing industries:** Static feedstock composition in the *Reference* scenario serves as a basis to compare new feedstock shifts for the competing industries when bio-production is introduced in Iteration_0. Subsequent iterations solved with the endogenous inputs result in new allocation for assortments used for bio-production and in the competing industries.
iv. **Economic impacts on both the ISI and the competing industries based on their resulting supply costs for biomass and bio-products:** Supply costs for bio-products are computed in BWS and include the costs for supplying and transporting biomass

Table 2
Production capacity of forest industries and district heating sector.

	Production volume	Ref.
Sawmills	17.2 million m^3	[54,55]
Pulp mills (PoP)	11.6 million tonnes	[55]
Pellets production	1.80 million tonnes	[56]
District heating (DH)	47.2 TWh	[57]

feedstock, bio-production plant costs, and transport costs for distributing bio-products (see [24]). Supply costs for competing industries are also computed in BWS and comprise biomass feedstock cost and the corresponding transport costs.

Although this work is done in a static time horizon, the iterative procedure is performed in a dynamic manner. However, one limitation here is that static fossil energy prices and CO_2 price are used throughout the model-linking. Nonetheless, the evaluated parameters can provide guidance when highlighting optimal bio-production sites for investors and policy-makers.

2.2. Description of systems studied

2.2.1. Iron and steel industry

We cover the entire iron and steel production in Sweden, including three iron ore production plants, two integrated steel plants (BF-BOF, blast furnace-basic oxygen furnace), one sponge iron plant, seven electric arc furnace plants (EAF), and fourteen secondary processing plants. We obtained data for iron and steel production and fossil energy requirements via questionnaires to the respective plants.

The production processes for each category are energy intensive and utilise a range of fossil fuels. Iron ore production requires coal, coke, and fuel oils to pelletise the mined iron ore. Primary steelmaking via BF-BOF from iron ore pellets and sponge iron produced via solid state direct reduction both require reductants in the form of coke and coal. Secondary steel production (EAF) also requires coal, while other steel processing plants (e.g., hot rolling, annealing) utilise fossil gaseous or liquid fuels. The total modelled fossil demand amounts to 20.6 TWh, which comprises fuels used for energy purposes, slag-formers, and reducing agents, as summarised in Table 1. Fig. 2 shows the geographical distribution of the included ISI plants, as well as the relative fossil demand per site (2018 data).

Representing the use of biomass, both as fuel and reducing material, at several stages of iron and steel production processes is complicated owing to multiple uses even within one process. Furthermore, the technical restrictions that limit biomass utilisation in some process applications contribute to the complexity even with varying substitution potentials. Table 1 presents a summary of the modelled substitution potentials as well as the fossil-based inputs considered for substitution with bio-products. Other bio-products could replace fossil fuels; however, we limit the possible substitute bio-products to charcoal, product gas and liquefied synthetic natural gas (L-SNG).

2.2.2. Competing industries

The Swedish forest industry sector is highly diversified and made up of different industries producing a wide array of products. These include, but are not limited to, lumber, cardboard, pulp and paper, white pellets and wood boards, with the pulp and paper (PoP) and sawmill industries being the economically most prominent. The forest industry sector is well-established with a large production capacity, reflecting the readily available feedstock supply in Sweden. This (historical) feedstock availability has meant that new industries (e.g., the ISI) are exploring the possibility of using woody materials as an alternative input to fossil fuels. However, such a structural development may have a negative impact on the existing forest industry's ability to produce at capacity.

District heating (DH) is the most common form of heating in Sweden, satisfying approximately a third of all heating needs in the residential and services sector [1]. Biomass (e.g., wood chips, waste wood, harvesting residues, etc.) and household waste constitute the main fuels for DH production. The DH networks also provide opportunities for electricity production through combined heat and power, which makes up approximately 5% of Sweden's electricity production.

Production quantities for the forest industries and energy sector are provided in Table 2.

2.2.3. Bio-production pathways

Production of charcoal, product gas and liquefied synthetic natural gas (L-SNG) is assumed to be integrated either directly with the ISI plants, or with sawmills, due to the availability of suitable feedstocks in the form of sawmill by-products [58]. A total number of 111 potential host sites in the form of sawmills and ISI plants are considered. Process modelling, via mass and energy balance, is carried out for each production or technology configuration (see section 2.3.4).

Production of product gas from forest biomass is carried out via a multi-stage gasification process, with mass and energy balance data

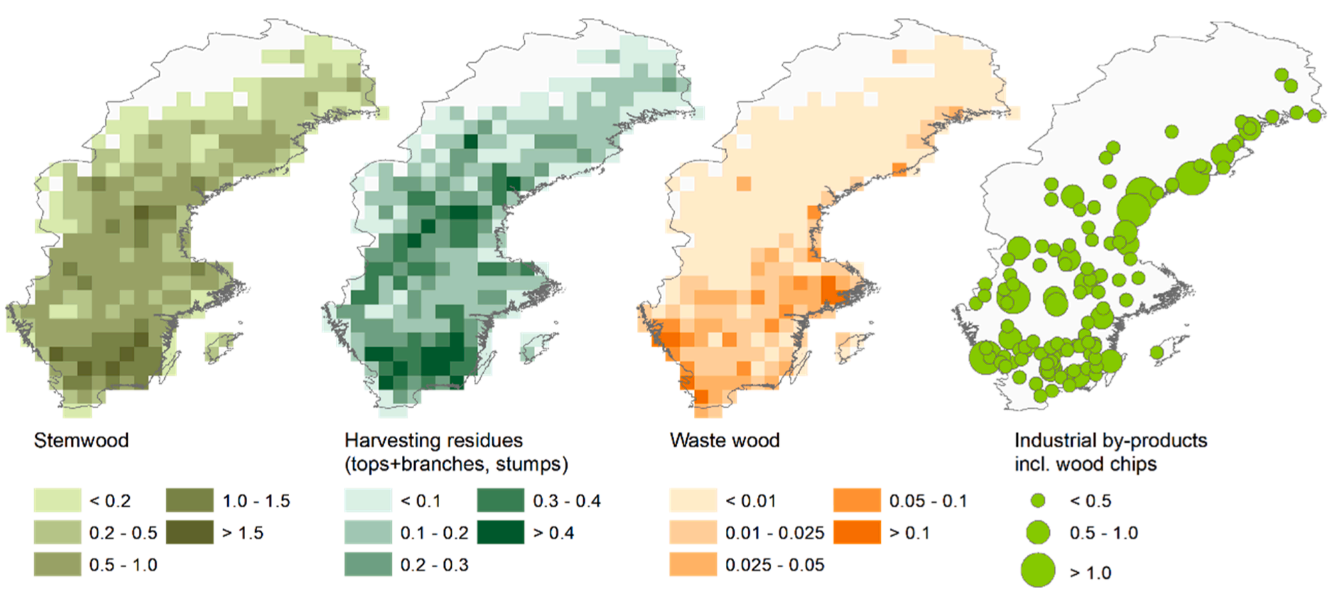

Fig. 3. Spatial distribution of biomass supply, as modelled in BeWhere Sweden (BWS). All values are in TWh/y. Stemwood includes both sawlogs and pulp wood.

Table 3
Aggregated available quantities in Sweden for the biomass assortments used in BeWhere Sweden (BWS).

Assortment	TWh/y
Sawlogs	89.3
Pulpwood	66.3
Waste wood	5.1
Wood pellets	8.1
Sawmill chips	18.7
Industrial by-products	19.6
Harvesting residues and stumps	52.6

obtained from [59,60]. Since product gas is not easily transported, plants within the ISI act as host sites for the integrated production. Steel plants acting as host sites for biomass gasification emphasise synergetic benefits from using excess process heat for biomass drying and treatment. The technology configuration also includes electricity generation via a steam turbine.

Integrated production of L-SNG is carried out via indirect dual fluidised bed gasification and hosted at a sawmill, based on the technology configuration studies carried out by Ahlström et al. [58]. As our previous investigation [60] showed that higher costs would be incurred if the production is carried out at the ISI, the configuration is here restricted to sawmill integration and dimensioned to use all available sawmill by-products for L-SNG production.

Charcoal production is carried out via slow pyrolysis of high-grade forest biomass assortments, in order to produce charcoal suitable for metallurgical purposes, with at least 80% fixed carbon content [61]. Mass and energy balances are calculated using studies from literature on standalone production systems e.g. [62,63]. To increase the energetic performance of the process, the option to generate electricity from the pyrolysis gases is included in the process configuration. Flexibility in the selection of host sites is allowed for this technology.

2.3. Input data

The models are calibrated using 2018 data as reference year unless otherwise stated. All costs and prices are given in Euro (€) using the average 2018 exchange rate of 1.18 $/€ [64]. The perspective used for the ISI sector is based on this reference year and this applies to all technologies included, and local and EU policies.

2.3.1. Biomass supply

The supply of biomass is expressed as the annual sustainable volumes that can be harvested or produced (industrial by-products). The supply of biomass is initially processed in BWS on a half-degree spatial resolution (Fig. 3) and, during the model iterations, aggregated to county level resolution for SCFSM. The biomass assortments included are sawlogs, pulpwood and harvesting residues from the forestry sector, and sawmill chips, industrial by-products and wood pellets from the forest industries. Data estimates in [33,65] were used to obtain supply potential for forest assortments based on data from the Swedish Forest Agency's "Today's forestry scenario" [50], while biomass quantities from industry operations were obtained based on data from [55-57,66].

All biomass volumes are converted to energy units on a lower heating value (LHV) basis, also including biomass demand not used for energy purposes, i.e., sawlogs and pulpwood demand from the forestry industry. For conversion between units, conversion factors of 0.42 odt/m^3 (oven dry tonnes of wood) and 4.9 MWh/odt (energy content of woody biomass) are applied. The annual aggregated availability of the biomass assortments is presented in Table 3. The available biomass quantities are assumed fixed in both BWS and SCFSM.

The supply elasticity used in SCFSM are assumed for sawlogs to 0.47, for pulpwood to 0.28, and for harvesting residues to 1.26 [67].

2.3.2. Biomass demand

Table 4 shows the annual demanded volumes of biomass as modelled in BWS, including which biomass assortments that can be used to fulfil each demand. Fig. 4 depicts the spatial distribution of the demand nodes. Demand for biomass from the forest industries and DH is considered explicitly based on a bottom-up estimation described in [33], while demand for biomass to substitute fossil fuels in the ISI is represented explicitly using a bottom-up estimation of the energy requirement at each ISI plant.

2.3.3. Biomass transportation and supply of bio-products

Transportation of biomass assortments and bio-products is assumed to be carried out via road, rail, and waterway. Transportation costs are expressed as functions of the distance between explicit geographic points according to the cost values from [65], which are reported in Table 5.

2.3.4. Bio-production technologies

Parameters for obtaining plant investment costs for the major equipment associated with the respective biomass conversion technology are summarised in Table 6. Assuming an economic lifetime of the equipment using an annuity factor of 0.1, the investments are discounted at an 8% rate and an economic lifetime of 20 years. Operation and maintenance costs (O&M) are calculated as a percentage of the investment costs depending on the bio-production technology. All

Table 4
Demand for biomass assortments as modelled in BeWhere Sweden (BWS) [24]. Material demands cover sawlogs for the sawmill industry, and fibre feedstock for the pulp and paper industry.

Demand	Aggregated demand (TWh/y)	Biomass assortments: Sawlogs	Pulpwood	Harvesting residues and stumps	Wood pellets	Industrial by-products	Waste wood
Material demands							
Sawmills	75	X					
Pulp and paper mills	96	X	X			X	
Energy demands							
Sawmill heat demand	4.8					X	
Pulp and paper mill external energy demand [a]	24		X	X		X	X
DH (unrefined wood)	24		X	X	X		X
DH (refined wood)	3.1				X		
Pellets production	8.1					X	
Charcoal production	Varying		X		X	X[b]	
Product gas production	Varying		X	X		X	
L-SNG production	Varying		X	X		X	

[a] Including internal fuels, excluding black liquor.
[b] Excluding lower grade by-products e.g., bark.

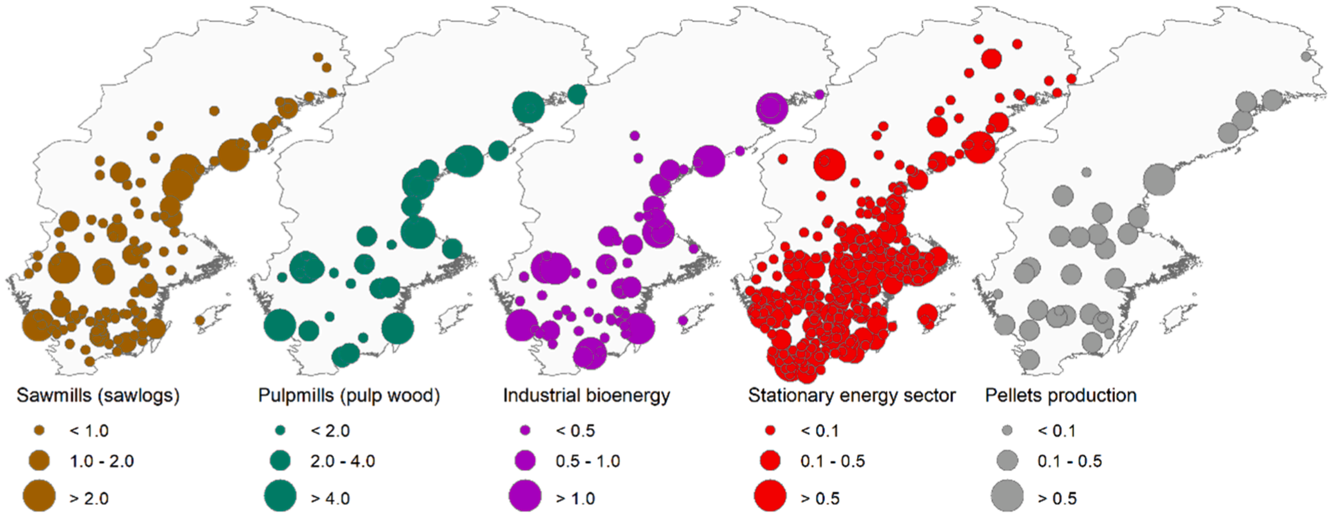

Fig. 4. Biomass demand as modelled in BeWhere Sweden (BWS). All values are in TWh/y.

Table 5
Transportation costs in €/MWh for forest biomass assortments and bio-products. Transport distance, *d*, is in kilometres (km) and applies to the three modes of transportation. Cost values are based on [65,68] and CO_2 emissions are adapted from [69,70].

	Transport cost (€/MWh)			CO_2 emissions (tCO_2/TWh, km)	
	Truck	Train	Boat	Truck	Train
Sawlogs, pulpwood	0.33 + 0.026·*d*	1.32 + 0.0021·*d*	1.06 + 0.0010·*d*	20.2	0.15
Harvesting residues, stumps	1.10 + 0.035·*d*	1.92 + 0.0028·*d*	1.05 + 0.0013·*d*	25.1	0.18
Ind. by-prods, pellets, waste wood	0.55 + 0.033·*d*	1.83 + 0.0027·*d*	1.33 + 0.0012·*d*	12.2	6.2
Charcoal	0.28 + 0.017·*d*	0.91 + 0.0013·*d*	0.66 + 0.0006·*d*	5.5	2.8
Product gas	–	–	–		
L-SNG	0 + 0.0079·*d*	0.16 + 0.0004·*d*	0.58 + 0.0004·*d*	3.5	1.8

Table 6
Investment cost function for main equipment relevant to the bio-production and electricity co-generation. The investment cost is calculated as $A \cdot S^n$ (M€$_{2018}$).

	A	*S* (MW)	*n*	O&M (%)	Ref.
Charcoal	1.97	Biomass input	0.72	8.0	[71]
Product gas	3.54	Biomass input	0.67	6.3	[60]
L-SNG	0.02	Sawmill prod. capacity (m^3)	0.73	4.0	[58]
Steam cycle	1.82	Electricity produced	0.67	4.0	[72]

Table 7
Energy output of biomass conversion technologies scaled against one unit of biomass input.

	Product gas [a]	Charcoal [b]	L-SNG [c]
Bio-product output	0.78	0.53	0.69
Electricity output	0.09	0.065	0.057

[a] Based on data from [59,60].
[b] Calculated based on [62,63].
[c] Based on data from [58]. The electricity requirement for liquefaction is 0.104 per unit of biomass input.

Table 8
Energy prices based on average values in Sweden and the EU and their corresponding CO_2 emission factors.

	Fuel price (€$_{2018}$/MWh)	Emission factor (kg CO_2/MWh)	Ref.
Heavy fuel oil (HFO)	71.0	270	[1,74]
LNG	42.0	198	[74,75]
LPG	42.0	234	[74,75]
NG	42.5	202	[1,74]
Coal	9.6	344	[1,74]
Light fuel oil (LFO)	85.0	267	[1,74]
Coke & pet-coke	19.4	400	[74]
Coking coal	14.3	335	[74]
Electricity	46.0	47 [a]	[76,77]
Sawlogs [c]	25.0	1.5 [b]	[78,79]
Pulpwood [c]	15.0	1.5 [b]	[78,79]
Harvesting residues and stumps [c]	15.0	1.5 [b]	[78,80]
Waste wood	4.2		[80]
Wood pellets	24.0		[80]
Industrial by-products	24.0		[80]

[a] Emission factor for electricity is given in CO_2-eq.
[b] Biomass harvest emissions.
[c] Thinning assortments have a higher price factor not shown in the table. See instead [44].

investment costs related to the plant and equipment are adjusted to the year 2018 currency value using the Chemical Engineering Plant Cost Index (CEPCI). Table 7 presents the energy output for each biomass conversion technology.

2.3.5. *Prices and policy instruments*

All biomass flows, including the bio-products and other energy carriers, are presented in energy units (LHV). Table 8 presents average energy prices and CO_2 emission factors of the fossil fuels used in ISI and those of untreated biomass assortments. The EU-ETS CO_2 price was set to 25 €/ton CO_2 [73]. Additional support instruments in the form of green certificates from the Swedish electricity certificate system is included for co-generated electricity during bio-production.

The initial biomass prices are exogenously collected from the Swedish Forest Agency [79] and are average 2018 prices on delivered logs in northern, middle and southern Sweden. The initial price of harvesting residues is collected from the Swedish Energy Agency [80] and is based on average 2018 prices on forest wood chips used by the

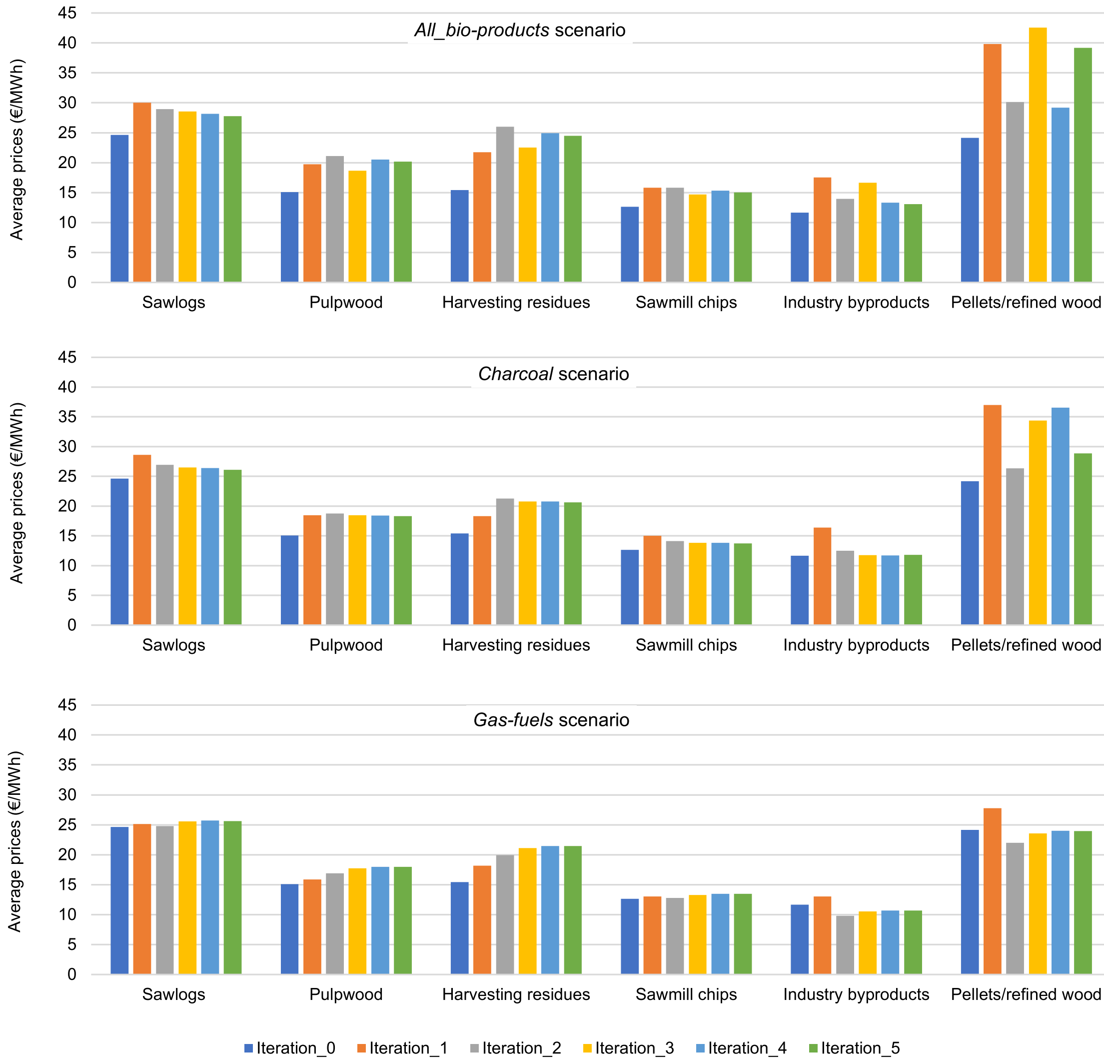

Fig. 5. Average price effects for the biomass assortments in the three fossil substitution scenarios, over all iterations. Waste wood is excluded since no price changes are observed as the assortment is not used for any bio-production.

district heating sector. All biomass prices are converted to €/MWh, as reported in Table 8. The collected biomass prices are used in the initial BWS runs (*Reference* scenario and Iteration_0), as described in section 2.1.3. The price dynamics are captured by the model integration. The available supply of biomass is assumed constant in the simulations, but demand changes are derived by BWS, triggered by the scenario descriptions. These demand changes are subsequently implemented in SCFSM to derive the implied price changes. Thus, the iteration between the models accounts for changes in biomass prices derived by changing biomass demand.

2.4. Scenario descriptions

As discussed in the introduction, full or partial replacement of fossil reductants and fuels by by-products can constitute a realistic short to medium term strategy for decarbonising a number of ISI processes, as it can be implemented with relative technical ease. To study the competition effects from biomass utilisation in the ISI, three substitution scenarios are thus constructed to reflect full or partial substitution of fossil energy and reductants with biomass:

i. **All_bio-products:** this scenario represents maximum possible substitution of all fossil fuels and reductants with charcoal, product gas and L-SNG in all ISI processes is assumed (see Table 1).
ii. **Charcoal:** this scenario reflects a situation whereby the ISI seeks to reduce reliance on fossil coal and coking coal in BFs by partially substituting with charcoal.
iii. **Gas-fuels:** this scenario reflects the relatively low-hanging fruit of full replacement of fossil gas-fuels in the ISI with alternatives derived from biomass.

The constructed scenarios consider maximum (100%) substitution with the bio-products according to technical limits and replacement ratios outlined in section 2.2.1.

In addition to the substitution scenarios, the *Reference* scenario is considered, where biomass is not yet introduced in the ISI. Since this scenario corresponds to no new bio-production, it is used to compare changes in supply costs and feedstock use for the competing industries..

All three scenarios undergo iterations based on the soft-linking procedure described in section 2.1.3. These ‘iterated’ scenarios represent a dynamic biomass market due to the changes in feedstock prices because of biomass use in the ISI. Initial exogenous prices of the biomass assortments are the same in all scenarios.

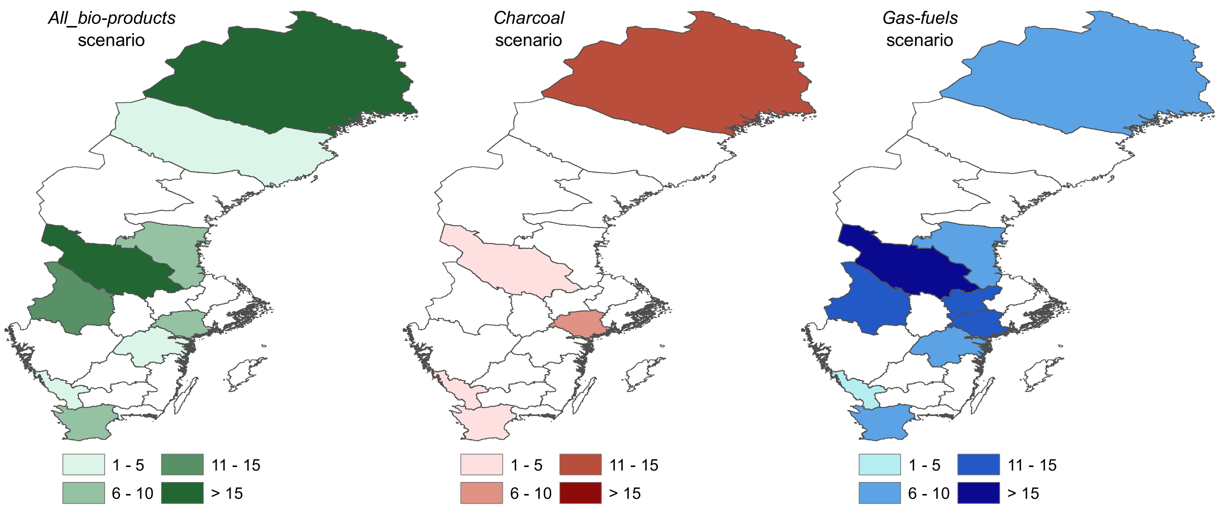

Fig. 6. Plant localisations on a county level for the three fossil substitution scenarios, over all iterations. Legend refers to frequency of plants occurring within each region throughout the iterative process.

3. Results and discussions

3.1. Biomass prices

The estimated price effects are undeniable a result from an increasing biomass demand by the ISI sector as stipulated by the scenarios. In monetary terms, the price effect on roundwood (sawlogs and pulpwood) after all iterations ranges between 1.0 €/MWh (sawlogs in *Gas-fuels* scenario) and 5.1 €/MWh (pulpwood in *All_bio-products* scenario). The price effect for harvesting residues ranges between 5.2 and 9.1 €/MWh, for sawmills chips between 0.80 and 2.4 €/MWh and for industrial by-products between −0.95 and 1.4 €/MWh.

Fig. 5 disaggregates the estimate average price effects by biomass assortments, scenario and model iteration. In general, subsequent model iterations indicate a positive price effect but to varying degreesm depending on biomass assortment and scenario. The volatility (or non-volatility) of the price effect can be explained by the internal mechanism of the models. For instance, in the *All_bio-products* scenario, sawlogs have an initial increasing price effect, followed by a decreasing price effect in subsequent iterations. This suggests that after the initial price effect, biomass demand patterns change accordingly (both by the ISI and by other sectors), which will have a mitigating impact on the price effect in subsequent iterations. Price effects exhibiting an erratic behaviour across the iterations, i.e., increase and decrease interchangeably, suggest that the biomass effect is not converging. Methodologically this suggests that the iterations are switching between corner solutions. This pattern is mostly visible for pellets/refined wood in the *All_bio-products* scenario. However, most interesting are the results indicating stable price effects over the iterations, especially for the latter iterations. This suggests that the prices are converging to a new equilibrium. That is, the demand change driven by the scenarios cause an initial increasing price effect (in general) but after the corresponding demand adjustment, the prices remain stable. In an equilibrium, there is no need for any sector to further adjust their biomass demand.

The price effects after the first iteration indicate the initial price impact directly after the scenario-imposed demand changes. The *All_bio-products* scenario, where both fossil fuels and reductants are replaced with bio-products, exhibits the largest initial price effect. For instance, industrial by-products and pellets/refined wood experience an increasing price effect close to 50% and 65%, respectively. These price changes are linked to the high demand of specific biomass assortments used in the transformation of the ISI sector, in particular in the production of charcoal. On the other end of the spectrum is the *Gas-fuels* scenario, where only fossil gaseous and liquid fuels are replaced by biomass, with more moderate price effects in Iteration_1. The largest price effect is observed for harvesting residues that will increase by 18% followed by pellets/refined wood (15%) and industrial by-products (12%). Finally, the results for the *Charcoal* scenario, where coal is partially replaced with charcoal, indicate that the highest price effect is for pellets/refined wood that would increase by 53% in Iteration_1. Furthermore, industrial by-products have a price effect of 41% and the remaining biomass assortments between 16% and 22%. A continuing adjustment to price and demand changes, i.e., later iterations, suggest that harvesting residues will have the highest final price effect over the scenarios. The difference in price effects between Iteration_0 and Iteration_5 for harvesting residues is 59% in the *All_bio-products* scenario, and 34% and 39% in the *Charcoal* and *Gas-fuels* scenarios, respectively. The single largest price effect of 62% can be observed for pellets/refined wood in the *All_bio-products* scenario. However, together with industrial by-products, pellets/refined wood will have a negative price effect in the *Gas-fuels* scenario.

The results suggest that the price effects, caused by an increasing biomass demand by the ISI sector, will also affect the forest industries. The price effects do not differentiate between users. The forest industries might be forced to adjust their business models or decrease their demand for certain biomass assortments, which might also affect their production level. Similar effects have been found by e.g., Olofsson [20]. Sawlogs are not directly used for bio-products to the ISI sector, but their price is nevertheless affected by a substitution chain-effect. Since pulpwood and sawmill chips will, given a favourable relative price, be allocated to the charcoal and gas production, this forces the pulp and paper industry to start using sawlogs (reclassifying sawlogs as pulpwood). This will increase the demand for sawlogs and consequently also its price. This type of chain-substitutions also occurs when demand for other biomass assortments change. It has been shown that the relative price between biomass feedstock options determines their allocation and demand [81]. However, the marginal effects will eventually erode any price difference rendering the sectors indifferent to which biomass assortment it uses, assuming they are technically possible to substitute [82-84]. This price effect derived from the scenario descriptions can also revert the relative price so that previously uneconomical biomass assortments become economically to use. The price-adjustment process, i.e., the iterations, suggests that the relative price between pulpwood and harvesting residues tend to decrease, making pulpwood relatively more expensive compared to harvesting residues. In the ISI sector's gas production both biomass assortments can be used, but the relative price indicate that ISI sector will prefer to use more harvesting residues if the production needs to increase, rather than pulpwood.

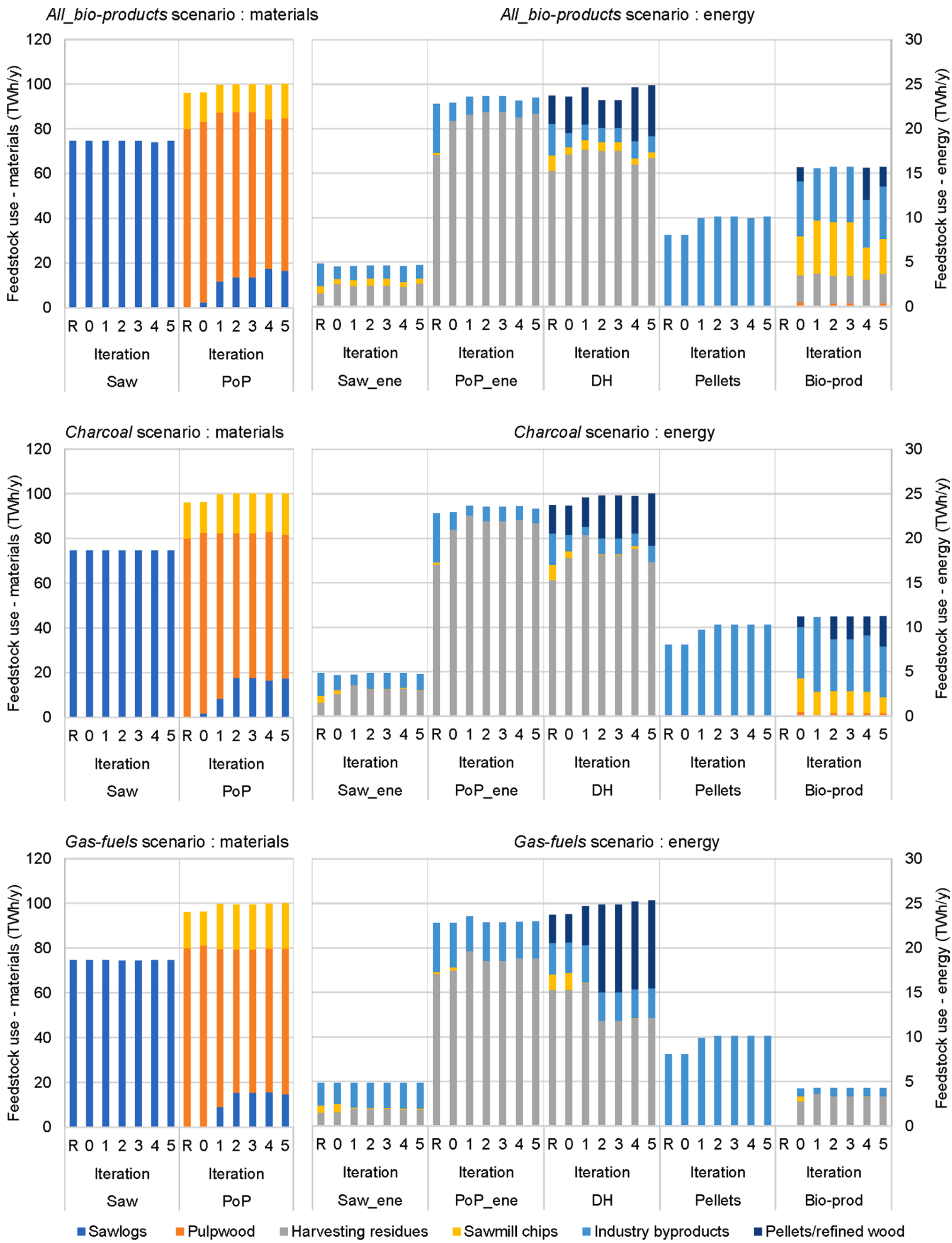

Fig. 7. Biomass use in competing industries in the Reference scenario (labelled 'R'), and in competing industries and bio-production for all iterations (0–5), for the three substitution scenarios. Material demands (left y-axis): Saw = sawmills, PoP = pulp mills. Energy demands (right y-axis): Saw_ene = sawmills energy demand, PoP_ene = pulp and paper mill external energy demand, DH = unrefined plus refined biomass demand for district heating (excl. waste wood), Pellets = pellets industry demand, Bio-prod = feedstock demand for bio-products for ISI.

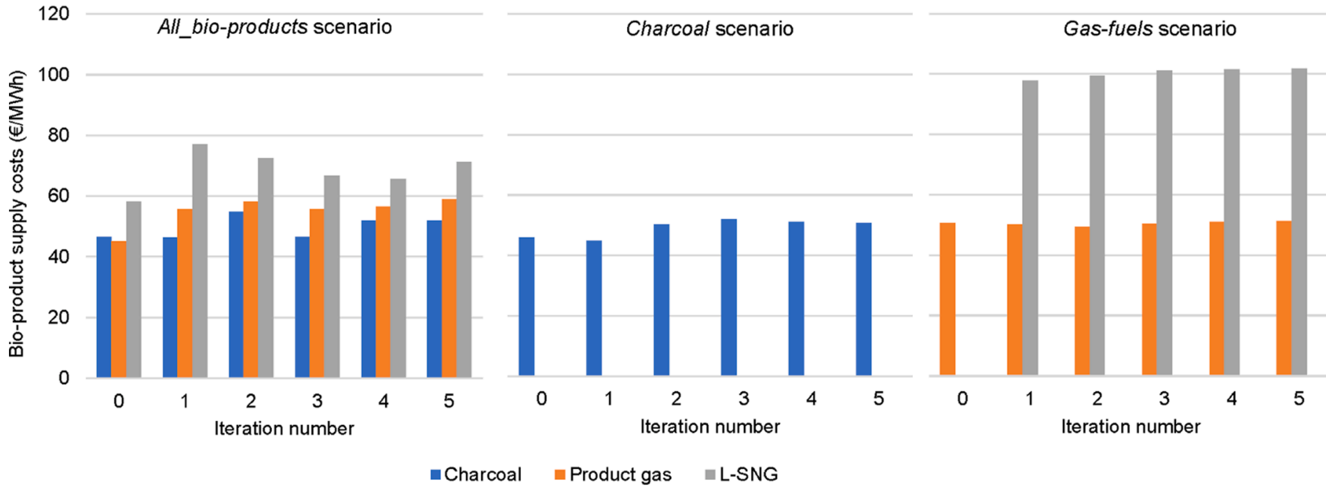

Fig. 8. Supply costs for bio-products to the ISI produced in the three substitution scenarios.

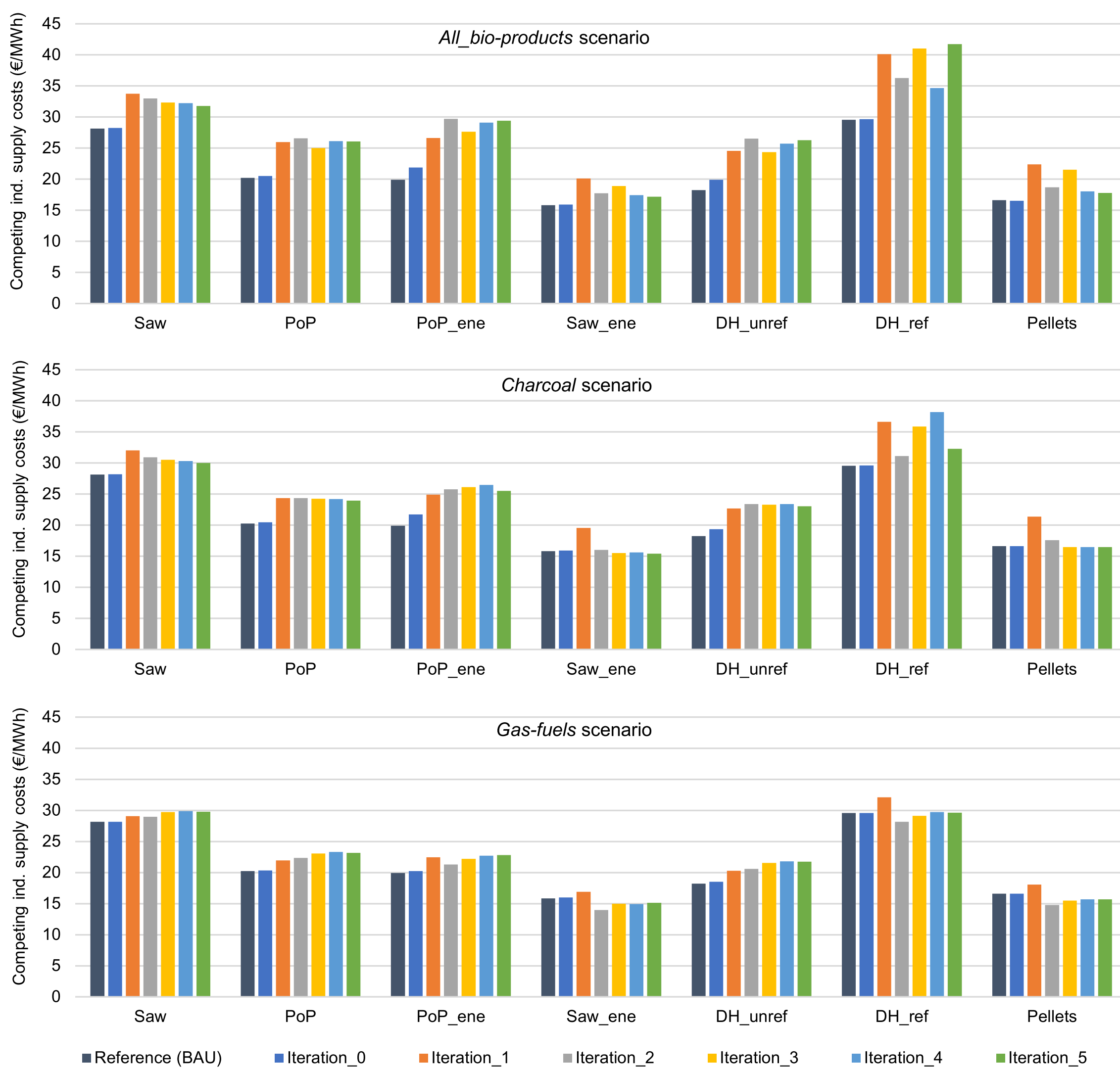

Fig. 9. Supply costs for competing industries in the Reference scenario and in all three substitution scenarios. Material: Saw = sawmills, PoP = pulp mills. Energy: Saw_ene = sawmills energy, PoP_ene = pulp and paper mill external energy, DH_unref = unrefined biomass for district heating, DH_ref = refined biomass for district heating, Pellets = pellets industry demand.

Few studies have analysed price effects on forest biomass from an increasing demand of biomass by the ISI industry. A notable contribution is Wetterlund et al. [85] who report similar results to this study. They report price effects ranging from 50 to above 100% for harvesting residues and industrial by-products depending on the ISI biomass use. However, they also report significant spatial variations in the price effects. Additionally, there are studies analysing price effect on forest biomass from changing demand patterns by other sectors. Bryngemark [29] assesses the price impact of an expansion by 5–30 TWh of second-generation biofuel production in Sweden using forest biomass as feedstock. This is within the same range of demand changes estimated for the ISI industry in this study. She concludes that harvesting residues will experience a price effect of more than 100%, while wood pellets will experience a price effect of approximately 40%. Similarly, Ouraich et al. [86] estimate price effects from an increased demand of forest biomass corresponding to the equivalent to (at most) 30 TWh but using a different method. They find more moderate price effects around 2% depending on biomass assortment, type of harvest operation and level of biomass competition. The difference between the estimated price effects in the studies, especially by Ouraich et al. [86], can partly be explained by the number of biomass assortments included and by the disaggregation of harvesting operations. By including addition biomass assortment available from different harvesting operations, the price effects are distributed over more options.

3.2. Plant localisations

Regional biomass prices influence preferred localisation of bio-production plants. Using results from the iterations, regions with frequently occurring plants localisations are highlighted in Fig. 6 as possible locations for bio-production for the ISI. Details of all selected locations are given in Appendix B.

Production of bio-based gas-fuels occurs at significantly more dispersed locations (20 unique plant locations in nine regions), compared to charcoal production (10 unique locations in seven regions). The two main regions identified as having more occurrences of plant localisation are home to the two integrated steel facilities where the demand for charcoal to (partially) replace coking coal and pulverised coal in the BFs is very high compared to the charcoal demand in other regions, where it is only used in the EAFs (see Fig. 2). Charcoal production on-site the steel industry reoccurs more frequently than at the one sawmill industry. Co-production of charcoal at sawmills is seen to occur in Iteration_1 and Iteration_5 in two different regions, suggesting that localisation is affected by the regional price difference.

For the *Gas-fuels* scenario, plants are mostly located at the ISI industry due to the lower investment costs of producing product gas compared to L-SNG. A majority of the ISI's gas-fuel demand is covered by product gas produced on-site, while industries with smaller gas demands, to a greater extent, purchase L-SNG produced off-site. The majority of plant localisations are found at auxiliary processing plants, where large volumes of fossil gases such as NG, LNG, LPG for heating purposes are required. The occurrence of one sawmill-integrated L-SNG production is driven by the lower prices for sawmill by-products (sawdust and bark) used as feedstock, when costs for harvesting residues (branches and tops) increase with the introduction of endogenous prices in Iteration_1.

In the *All_bio-products* scenario, when charcoal and gas-fuels are produced simultaneously in the system, the plant localisations vary slightly for charcoal and product gas compared to the individual plant locations in the *Charcoal* and *Gas-fuels* scenarios. Plant localisation for L-SNG varies even more across different sawmills, and does not exhibit any robust plant localisation. This observation can be interpreted as that several sawmill locations exhibit similar economic performance for integrated L-SNG, and that the bio-production technology is relatively site independent. This confirms the findings by Ahlström et al. [36].

The volatile price developments for all assortments in the *All_bio-products* scenario explains the visible but slight fluctuations in individual plant localisation for bio-production. Overall, the regions (counties) with high reoccurrence of plants for bio-production localisation do not deviate from the trend observed for charcoal production and gas-fuel production in the *Charcoal* and *Gas-fuels* scenarios, respectively.

The results highlight several bio-production plants that exhibit a constant plant localisation independent of changing biomass prices or changes to the woody biomass feedstock bundle that is used. Overall, the results indicate specific counties as particularly well-situated for bio-production plants. Plant localisation for charcoal production is in general more sensitive to changing feedstock prices compared to that for gas-fuels, as the localisation of gas-fuels is relatively unaffected by changing feedstock prices or changes in the type of feedstock assortment used. Plant localisations found to occur in all three scenarios constitute bio-production plants that could attract potential investment regardless of the substitution strategy.

3.3. Biomass use

Biomass demand by the forest industries is static when executing BWS in the *Reference* scenario (as described in section 2.1.3). During the iterative process, forest production levels and import quantities obtained from SCFSM and contingent on the regional biomass price development, serve as input to BWS. Thus, with each iteration, the biomass availability varies according to the new equilibrium solved in SCFSM.

The resulting original feedstock allocation in the *Reference* scenario is presented in Fig. 7 together with the feedstock re-allocations from the soft-linking procedure for the three substitution scenarios. From the results, competition for certain assortments, in particular industrial by-products and wood chips, is noticeable since bio-production relies on feedstock otherwise used in pulp mills, DH and pellet production. When bio-production for the ISI is first introduced in Iteration_0, the pulp industry starts to use sawlogs because of the competition with bio-production for sawmill chips and pulpwood assortments. The extent of competition is contingent on the scenario. For instance, in the *Gas-fuels* scenario, initial use of sawlogs by the pulp industry is almost negligible since pulpwood is not used for gas-fuel production, unlike for charcoal. However, in subsequent iterations (i.e., Iterations_1-5) and for all three substitution scenarios, the pulp industry increases its use of sawlogs and sawmill chips to satisfy its fibre demand as the pulpwood price increases. In pulp industries, use of sawmill chips is connected to the regional price impacts seen in Fig. 5 where pulpwood prices are higher. However, despite the higher prices for sawlogs, the pulp industries utilise this assortment because of reduced availability of domestic pulpwood during the iterations. The pulp industry is affected by the decreased imports of pulpwood after Iteration_0, which leads to an increased reliance on domestically supplied biomass assortments. Although increased domestic demand for biomass assortments is likely to be partially met by imports, the results observed are driven by the import levels observed from the results of SCFSM. As such, the total amount of biomass assortments available in BWS is reduced compared to when the model can freely select imports of biomass assortments. This development in turn means that domestically available biomass assortments, e.g., sawlogs, will be utilised more extensively.

Pellets are also increasingly allocated to the DH sector that otherwise typically uses more of unrefined than refined wood. This re-allocation is a result not only of increasing heat production levels in SCFSM but also of increased prices for harvesting residues due to the competition from gas-fuel bio-production. Furthermore, the more expensive pellets assortments are utilised increasingly in the DH plants due to lower transportation costs compared to harvesting residues, which would otherwise have to be sourced at farther distances.

In the *Charcoal* scenario, initial introduction of charcoal production for the ISI is carried out using sawmill by-products and chips, pellets, and pulpwood. However, with the endogenous prices for pulpwood becoming more expensive, use of pulpwood as a feedstock slightly reduces in the subsequent iterations. As mentioned already, use of sawlogs and chips appear increasingly in the pulp industries across the iterations. The use of pellets as a feedstock for bio-production follows the price development for the assortment, as shown in Fig. 5. Price volatility for pellets, which results from competing uses in bio-production, discourages very high use of the assortment in the DH sector (unlike in the *Gas-fuels* scenario). Rather, the use of harvesting residues for DH and heat demand for pulp industries remains high. This observation thus suggests that competition for harvesting residues in the *Gas-fuels* scenario is a likely factor for increased pellet utilisation in the DH sector. The patterns observed in the *Gas-fuels* and *Charcoal* scenarios are repeated in the *All_bio-products* scenario. Regional price developments result in feedstock re-allocation since the cost of using a particular assortment depends not only on competing uses but also on the industry's proximity to biomass supply.

3.4. Supply costs

3.4.1. ISI bio-product supply costs

Production of single or combined bio-products in each of the three scenarios in the BWS model is constrained to maximum capacity as explained in section 2.4. Therefore, the initial quantities of bio-products produced in Iteration_0 do not significantly differ in the subsequent iterations. A main deviation is however observed in Iterations_1-5 of the *Gas-fuels* scenario, where small quantities of L-SNG are produced in addition to product gas, as discussed in section 3.2. Maximum bio-production in the *All_bio-products* scenario is approximately 9.3 TWh, although total fossil use in the ISI is 20.6 TWh. Replacement of fossil gas fuels (3.3 TWh) is fully met in the *All_bio-products* and *Gas-fuels* scenarios, while substitution with charcoal is at a maximum of 6 TWh in the *All_bio-products* and *Charcoal* scenarios.

The supply costs for bio-products differ to some extent due to the endogenous biomass prices used during the iterations in the model soft-linking. From Fig. 8, supply costs in the *Gas-fuels* scenario appears nearly stable across all iterations performed due to the relatively stable feedstock use highlighted in the previous section. Comparing with the *All_bio-products* scenario, supply costs for product gas and L-SNG fluctuates, which can be explained by the equally volatile biomass prices (see Fig. 5) for the *All_bio-products* scenario. A significant difference in the two scenarios can be discerned in the supply costs for L-SNG, where higher costs are observed in the *Gas-fuels* scenario compared to the *All_bio-products* scenario. Higher supply costs correspond to lower quantities of L-SNG produced in the *Gas-fuels* scenario, while relatively lower supply costs in the *All_bio-products* scenario tally with more significant L-SNG production. The general increase in the price of the major feedstock used for gas-fuels (i.e., harvesting residues) results in the production of L-SNG to boost replacement of fossil fuels in more ISI plants, compared to when only product gas is used. Flexibility of bio-product choice in the model solutions when endogenous biomass prices are used indicates that although more ISI plants switch to product gas and L-SNG, lower system costs are incurred regardless of individual bio-product supply costs.

Supply costs for charcoal follow the same pattern in the relevant scenarios. Again, the supply costs can be linked to the instability in feedstock use corresponding to regional price developments for the biomass assortments. However, the supply cost for charcoal in Iteration_1 is slightly lowered compared to Iteration_0, where the exogenous biomass prices are lower than the endogenous prices used in the latter iteration. Looking at the cost component in BWS, revenues from green certificates for electricity co-produced as well as low investment costs dampen the higher biomass cost components. Even with increasing biomass prices, cost-efficiency of bio-products thus also depends on the technology pathways employed and policy or support incentives present. Looking across the scenarios explored in Fig. 8, charcoal turns out economically appealing as a bio-product for the ISI at supply costs in the range of 45–55 €/MWh. Supply costs for L-SNG and product gas fall in the ranges of 66–102 €/MWh and 49–59 €/MWh, respectively.

3.4.2. Supply costs for competing industries

Based on exogenous biomass prices used in the *Reference* scenario and in Iteration_0, supply costs for the competing industries are calculated for both the *Reference* scenario and for the substitution scenarios with bio-production for the ISI, with endogenous biomass prices in Iteration_1-5. Fig. 9 shows the resulting supply costs for each substitution scenario.

The introduction of ISI as a user of biomass bears little to no effect on the supply costs for the different competing industries in the *Gas-fuels* scenario, even though supply costs for product gas for the ISI are on average 4 €/MWh higher than for charcoal. When endogenous biomass prices are introduced in Iteration_1, very high supply costs are observed for DH plants using refined assortments such as pellets. This occurs in connection with the price increase seen in Fig. 5 and the increased use of pellets (discussed in section 3.3). Increased supply costs for the pellets industry, as well as for the pulp industry, are similarly a result of the increase in assortment price. However, compared to when exogenous biomass prices are used, relatively higher supply costs are found for the pulp industry and DH sector using unrefined woody assortments.

As a general trend in the three scenarios, supply costs for all competing industries increase in Iteration_1 compared to the *Reference* scenario and Iteration_0. The supply costs in Iteration_1-5 follow a similar pattern as the endogenous price development for biomass assortments (Fig. 5) matching the specific industry as detailed in Table 5. Initial introduction of charcoal production results in rising supply costs for heat demand in sawmills and pulp industries, as well as in DH plants using unrefined woody assortments. In the *Charcoal* scenario, rising supply costs are incurred for district heating sector, pulp industry, and sawmills when endogenous biomass prices are applied in Iteration_1-5. Similar pattern is followed in the *All_bio-products* scenario, although with more severity due to the increased competition when more bio-production is carried out. Even as regional biomass prices determine supply costs for a particular industry, the type of bio-production carried out also influences the extent to which the industries are economically impacted.

4. Conclusions

This study has explored technical and economic implications of introducing the iron and steel industry (ISI) as a user of bio-products from forest biomass. Specifically, price effects, localisation of bio-product plants, feedstock allocation, and supply costs have been analysed. An integrated assessment of these issues was conducted by soft-linking a geographically explicit techno-economic energy system model (BeWhere Sweden, BWS) and a partial equilibrium forest model (Swedish County Forest Sector Model, SCFSM).

With the transformation of the ISI sector towards an increasing reliance on renewable energy sources, and where forest biomass is an option, large increases in biomass demand can be expected, which will affect biomass allocation all over the biomass system. The results presented in this study demonstrate how economic effects from forest biomass competition are intertwined with technology pathways for bio-production. Large-scale use of bio-products (e.g., charcoal, product gas, L-SNG), as substitutes to fossil fuel and reductants by the ISI industry, will impact the markets and entail price effects on the forest biomass assortments. In the choice of location of bio-products plants, spatial trade-offs are necessary. The locational decisions are based on the proximity to the biomass feedstocks contra the proximity to the ISI plants, and the suitability of the bio-product production location. Changing biomass prices were found to affect these trade-offs. We conclude that:

- The upward pressure on biomass price levels when bio-products are introduced in the ISI will affect both competing industries and the ISI itself. Prudence is thus warranted not to render bio-production investments uneconomical ex-post by neglecting to include potential price effects in the investment calculations.
- The estimated price effects can be mitigated by increasing domestic biomass supply, increasing international trade, or by revising policies.
- While regional price disruptions caused by the ISI's new biomass demand affect the geographical preferences for individual bio-production plants, in particular charcoal plants, proximity to the ISI production facility and integration benefits are more important than the proximity to cheaper biomass feedstocks. This suggests that local biomass price increases are of less importance compared to the production synergies achieved, and that several locations exhibit similar economic performance for bio-production.
- Product gas production integrated at ISI sites emerges is a particularly attractive option to replace gaseous and liquid fossil fuels in the industry, due to relatively low bio-product supply costs and robust site selection. Conversely, charcoal production exhibits sensitivity to fluctuating markets, both regarding supply costs and preferred production locations.

Overall, our findings accentuate that if the ISI sector is considering"the biomass option", they and their alliance partners within the bio-production sector need to take into account the market effects of new bio-production investments, and, preferably, locate new plants in proximity to the current ISI production facilities to utilise all the synergy effects.

CRediT authorship contribution statement

Chinedu Maureen Nwachukwu: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration. **Elias Olofsson:** Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Robert Lundmark:** Supervision, Writing – review & editing, Funding acquisition. **Elisabeth Wetterlund:** Methodology, Software, Validation, Writing – review & editing, Supervision, Visualization, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. – Model descriptions

A.1. BeWhere Sweden (BWS)

Model formulation.

BWS is based on mixed integer linear programming (MILP) and is written in the commercial software GAMS, and solved using CPLEX as a solver. On a general form, a minimising MILP problem can be described as:

$$\min_{x,y}\left[\sum_{n=1}^{N}c_nx_n+\sum_{k=1}^{K}e_ky_k\right]$$

$$\text{s.t.}\sum_{n=1}^{N}a_{n,m}x_n+\sum_{k=1}^{K}d_{k,m}y_k=b_m, m=1,\cdots,M \tag{A1}$$

$$y_k\in Z, k=1,\cdots,K$$

where *N* is the number of continuous variables, *K* is the number of integer variables, and *M* is the number of constraints. × are the continuous variables and *y* are the integer variables. *a, b, c, d,* and *e* are parameters and *Z* is the set of all integers.

BWS minimises the system cost of the entire studied system. The costs of emitting CO_2 is included in the objective function, thus internalising the impact of fossil CO_2 emissions in the studied supply chain. The total system cost thus consists of the supply chain cost and the supply chain CO_2 emission cost.

The supply chain cost, as implemented in this study, includes:

- Feedstock cost
- Cost for transportation of biomass to bio-production plants and other biomass users
- Setup and operation and maintenance costs for new bio-production plants
- Cost for bio-product transport to ISI plants
- Cost of imported biomass
- Revenue from co-produced energy carriers
- Revenue or cost related to policy instruments
- Cost of fossil fuels and reducing agents used in the system

The supply chain CO_2 emissions include:

- Emissions from transportation of biomass and bio-products
- Emissions from used or produced energy carriers (including offset emissions from displaced fossil energy carriers)
- Emissions related to the procurement of biomass

The total cost is minimised subject to a number of constraints regarding biomass supply, biomass demand, biomass trade, bio-production plant operation (efficiencies, capacity etc.) and bio-product demand. The model will choose the least costly pathways from one set of feedstock supply points to a specific bio-production plant and further to a set of bio-product demand points, while meeting the demand for biomass in other sectors, over the time period chosen (in this study, 1 year).

Model architecture and workflow.

The BWS model consists of the following main parts:

1. Database containing all input data
2. Input data pre-processor
3. MILP optimisation model
4. Results output post-processor

Before running the model, input data has to be treated to be expressed in the correct format and units, as well as on the appropriate geographical form. The data is stored in a database for access by the pre-processor, which reads the data and creates input files for the optimisation model. After optimisation, the results are obtained in the form of a list of selected variables. The results are treated by a post-processor to attain the results in a more accessible form. Selected results can further be plotted geographically explicitly. Fig. A1 shows an overview of the model architecture and workflow, as well as the software used for each step.

Swedish county forest sector model (SCFSM)

Model structure.

Fig. A2 illustrates the model structure and main material flows of the SCFSM.

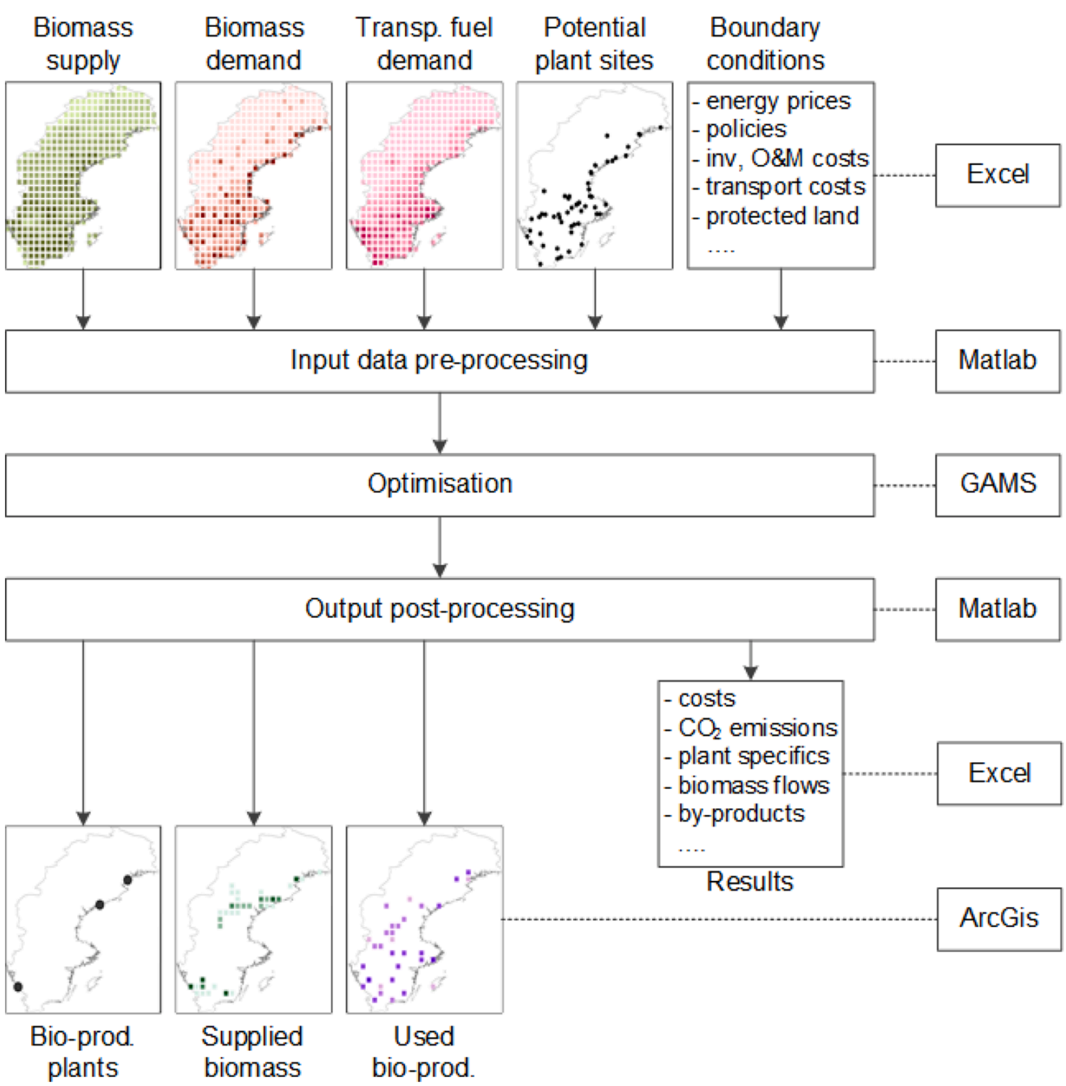

Fig. A1. Overview of the BeWhere Sweden (BWS) model architecture and workflow, as well as the software used for each step.

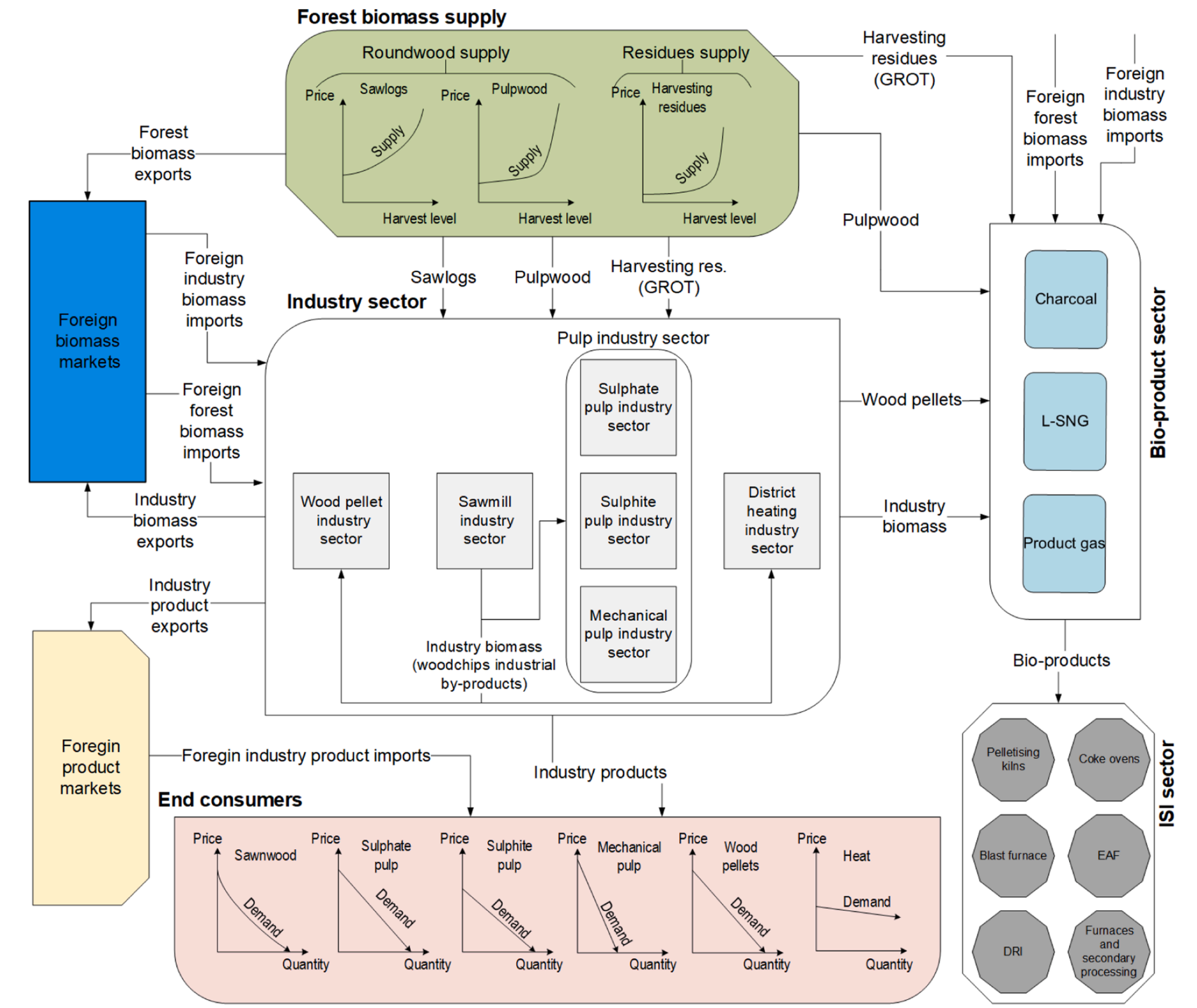

Fig. A2. Schematic overview of the Swedish County Forest Sector Model (SCFSM), as implemented for forest biomass use for the ISI.

Model formulation.

The SCFSM tries to satisfy a regional exogenous demand (i.e., production targets), based on BWS production levels for the established forest industry and bio-product targets. The model will continue to trade in woody materials as long as the feedstock is readily available, and/or as long as it is deemed economically to do so. The amount of harvested woody materials supplied to the market is selected by the SCFSM, using calibrated BWS data. The model is expressed as follows, with sets, variables and parameters presented in Table A1:.

$$Max\ Welfare = \sum_{i,o}\int_{l}^{Q}\left(p_{i,o}\left(\frac{Q_{i,o}}{q_{i,o}}\right)^{1/\xi_{i,o}}\right)dQ_{i,o} - \sum_{i,RW}\int_{0}^{H}\left(a_{i,RW}+\omega_{i,RW}H_{i,RW}^{\epsilon_{i,RW}}\right)dH_{i,RW} - \sum_{i,HR}\int_{0}^{R}\left(b_{i,HR}+\frac{\sum_{RW}h_{i,RW}}{\sum_{i,RW}H_{i,RW}}\rho_{i,HR}R_{i,HR}^{\mu_{i,HR}}\right)dR_{i,HR} - \sum_{IM,EX,T}\left(tc_{IM,EX,T}TR_{IM,EX,T}\right) \tag{A2}$$

s.t.

$$Q_{i,o} - \sum_{AC}\left(\theta_{i,AC,o}X_{i,AC}\right) + \sum_{IM}TR_{i,IM,o} - \sum_{EX}TR_{i,EX,o} = 0 \tag{A3}$$

$$-\sum_{AC}\left(\theta_{i,AC,RW}X_{i,AC}\right) - H_{i,RW} + \sum_{IM}TR_{i,IM,RW} - \sum_{EX}TR_{i,EX,RW} = 0 \tag{A4}$$

$$-\sum_{AC}\left(\theta_{i,AC,HR}X_{i,AC}\right) - R_{i,HR} + \sum_{IM}TR_{i,IM,HR} - \sum_{EX}TR_{i,EX,HR} = 0 \tag{A5}$$

Table A1
Set, variable and parameter descriptions.

Sets	Description
i	County
o	End-products
RW	Roundwood assortment
HR	Harvesting residues
BP	Industrial by-products
T	Tradable goods
IM	Importing county (subset of i)
EX	Exporting county (subset of i)
AC	Activity set
ByC	By-product consumer (subset of AC)
ByP	By-product producer (subset of AC)
Variables	Description
H	Roundwood harvesting rate
Q	Consumption quantity of end-product
R	Harvesting rate residues
TR	Tradable quantities
X	Utilization of woody input
Parameters	Description
a	Reservation price roundwood
b	Reservation price harvesting residues
h	Observed harvesting rate of roundwood
k	Capacity constraint for the forest industry
l	Lower integral value
p	Observed price
q	Observed end-product consumption
r	Observed extraction rate of harvesting residues
tc	Unit transport cost
ε	Inverse elasticity of roundwood supply
Θ	Leontief production function (industry specific input–output coefficients)
μ	Inverse elasticity of harvesting residue supply
ξ	Own-price elasticity of end-products
φ	Shift parameter harvesting residues
ω	Shift parameter roundwood
η	Roundwood supply elasticity
ν	Harvesting residues supply elasticity

$$-\sum_{ByC}\left(\theta_{i,ByC}X_{i,ByC}\right)+\sum_{IM}TR_{i,IM,BP}-\sum_{EX}TR_{i,EX,BP}\geq\sum_{ByP}\left(\theta_{i,ByP,BP}X_{i,ByP}\right) \tag{A6}$$

$$Q_{i,o}\leq q_{i,o} \tag{A.7a}$$

$$H_{i,RW}\leq h_{i,RW} \tag{A.7b}$$

$$R_{i,RW}\leq r_{i,RW} \tag{A.7c}$$

$$X_{i,AC}\leq k_{i,AC} \tag{A.7d}$$

In Equation (A.2), the first term denotes the sum of consumer surpluses from end-products and the second term expresses the sum of producer surpluses from all roundwood assortments (i.e., sawlogs, pulpwood and fuelwood). The third term is the sum of producer surpluses from harvesting residues, and the fourth term captures the reduction in welfare from the cost of inter-regional trade. Equations (A.3) to (A.7) are constrains. Equation (A.3) states that consumption in each county must equal production net of trade. This constraint also ensure that all produced products will be consumed. Equation (A.4) states that roundwood demand is satisfied through county roundwood harvest or trade. Equation (A.5) states the same but for harvesting residues. Equation (A.6) states that by-product demand is less or equal to its supply, thus allowing for a surplus in supply but not a surplus in demand. Trade in harvesting residues is prohibited in the model, as is export of Swedish roundwood. These restrictions are imposed to better align the SCFSM with BWS. Finally, Equations (A.7a-d) state that there exists an upper constraint for end-product demand, roundwood harvest, extraction of harvesting residues, and an upper production capacity, respectively. Furthermore, from the balance constraints for roundwood (A.3), harvesting residues (A.4) and industrial residues (A.5) it is possible to obtain a regional shadow price for each feedstock [87].

Appendix B. – Detailed results

In the *All_bio-products* scenario (Table B1.), charcoal production is shown to primarily be concentrated around the largest steel mills (i.e., charcoal consuming industry sector), situated in the counties of Norrbotten and Södermanland, while bio-gasfuel production is mainly localised to the counties of Dalarna, Gävleborg and Värmland, areas with auxiliary processing and EAF plants. This suggests that contingent on the increased demand for refined bio-products from the ISI sector, it is economically advantageous to concentrate charcoal production close to the large ISI plants and transport the charcoal bio-product to smaller ISI plants, while product gas is primarily located at the auxiliary processing and EAF plants. However, approximately 16% (0.52 TWh) of the gas-fuel demand is satisfied by L-SNG, which is transportable.

Table B1
Resulting plant locations in the All_bio-products scenario.

Charcoal production								
			Iteration					
Plant location	**Plant ID**	**Host industry**	**0**	**1**	**2**	**3**	**4**	**5**
Södermanland	31	ISI (integrated steelmaking)	X	X	X	X	X	X
Norrbotten	102	ISI (iron ore prod.)	X					
Norrbotten	173	ISI (iron ore prod.)			X	X		X
Norrbotten	261	ISI (integrated steelmaking)	X	X	X	X	X	X
Norrbotten	779	sawmill			X	X	X	X
Västerbotten	801	sawmill					X	
Halland	903	sawmill	X	X				
Östergötland	905	sawmill	X					
Product gas production								
			Iteration					
Plant location	**Plant ID**	**Host industry**	**0**	**1**	**2**	**3**	**4**	**5**
Dalarna	34	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Gävleborg	39	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Dalarna	95	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Östergötland	136	ISI (auxiliary proc.)				X		
Skåne	141	ISI (sponge iron + auxiliary)	X	X	X	X	X	X
Norrbotten	198	ISI (iron ore prod.)	X	X	X	X	X	X
Dalarna	215	ISI (EAF + auxiliary proc.)	X		X		X	X
Dalarna	273	ISI (auxiliary proc.)	X	X	X	X	X	X
Värmland	590	ISI (auxiliary proc.)	X	X	X	X	X	X
Värmland	689	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
L-SNG production								
			Iteration					
Plant location	**Plant ID**	**Host industry**	**0**	**1**	**2**	**3**	**4**	**5**
Norrbotten	779	sawmill		X				
Dalarna	783	sawmill	X		X	X	X	X

The *Charcoal* scenario (Table B2) indicate a similar result to charcoal production in the *All_bio-products* scenario, i.e., primarily concentrated around the steel mills in Norrbotten and Södermanland. However, as the general competitive state in the *Charcoal* scenario is less severe (11.2 TWh of forest biomass demand compared to 15.7 TWh in the *All_bio-products* scenario), charcoal production is, depending on the iteration, also located in e.g., Skåne.

Table B2
Resulting plant locations in the Charcoal scenario.

Charcoal production								
			Iteration					
Plant location	**Plant ID**	**Host industry**	**0**	**1**	**2**	**3**	**4**	**5**
Södermanland	31	ISI (integrated steelmaking)	X	X	X	X	X	X
Norrbotten	102	ISI (iron ore prod.)	X					
Skåne	141	ISI (sponge iron + auxiliary)			X	X	X	
Norrbotten	173	ISI (iron ore prod.)			X	X	X	X
Norrbotten	261	ISI (integrated steelmaking)	X	X	X	X	X	X
Dalarna	783	sawmill	X					X
Halland	903	sawmill	X	X				

While the results for the *Gas-fuels* scenario (Table B3) indicate that 14 bio-production plant (product gas) are consistently selected across all iteration, and that one plant (L-SNG) is selected for Iteration_1-5, but not in Iteration_0 (exogenous prices). Compared to the *All_bio-products* scenario, production of product gas is spread over a larger number of sites, and plant localisation is, after Iteration_0, shown to be unconditional to changing feedstock prices. However, L-SNG production in the scenario only covers approximately 2% (0.08 TWh) of the ISI gas fuel demand.

Table B3
Resulting plant locations in the Gas-fuels scenario.

Product gas production								
			Iteration					
Plant location	**Plant ID**	**Host industry**	**0**	**1**	**2**	**3**	**4**	**5**
Södermanland	31	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Dalarna	34	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Gävleborg	39	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Västmanland	53	ISI (auxiliary proc.)	X	X	X	X	X	X
Värmland	73	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Dalarna	95	ISI (auxiliary proc.)	X	X	X	X	X	X
Östergötland	136	ISI (sponge iron + auxiliary)	X	X	X	X	X	X
Skåne	141	ISI (iron ore prod.)	X	X	X	X	X	X
Norrbotten	198	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Dalarna	215	ISI (EAF + auxiliary proc.)	X	X	X	X	X	X
Norrbotten	261	ISI (integrated steelmaking)	X					
Södermanland	263	ISI (auxiliary proc.)	X	X	X	X	X	X
Halland	269	ISI (auxiliary proc.)	X					
Dalarna	273	ISI (auxiliary proc.)	X	X	X	X	X	X
Värmland	590	ISI (auxiliary proc.)	X	X	X	X	X	X
Västmanland	681	ISI (EAF + auxiliary proc.)	X					
L-SNG production								
			Iteration					
Plant location	**Plant ID**	**Host industry**	**0**	**1**	**2**	**3**	**4**	**5**
Västmanland	876	sawmill		X	X	X	X	X

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