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

Chinedu Maureen Nwachukwu [a,*], Elias Olofsson [b], Robert Lundmark [b], and Elisabeth Wetterlund [a,c]

[a] *Department of Engineering and Mathematical Sciences, Luleå University of Technology, 97187 Luleå, Sweden*

[b] *Department of Business Administration, Technology, and Social Sciences, Luleå University of Technology, 97187 Luleå, Sweden*

[c] *International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria*

**Corresponding author: Email: chinedu.nwachukwu@ltu.se*

Abstract

Significant use of forest biomass in the iron and steel industry (ISI) to mitigate fossil CO_2 emissions may impact biomass availability for other users of the same resource. Increased competition for biomass will likely have an effect on both the price of forest biomass assortments and on the economic feasibility of the ISI's investments in biomass utilisation. This paper explores the market effects of increased biomass competition and the interactions between the ISI and the forest industry sectors. A soft-linking approach is employed that combines a spatially explicit techno-economic energy system model and a partial equilibrium model. This allows for new equilibrium price developments for different feedstock assortments to be endogenously modelled in a dynamic and iterative process. The results show that regional price disruptions caused by the ISI's new biomass use affect geographical preferences for bio-production plants. Forest industries with competing demand for the same biomass assortments are accordingly affected negatively regarding both feedstock allocation and biomass supply costs. If the ISI substitutes fossil fuels and reductants with biomass-based alternatives, forest sector industries and the district heating sector could thus be at an economic disadvantage.

Keywords: iron and steel, soft-linking, partial equilibrium modelling, biomass supply modelling, resource competition, forest sector

Abbreviations:

BAU	Business as Usual
BF	Blast Furnace
CAPEX	Capital Expenditure
CECPI	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
GDP	Gross Domestic Product
HFO	Heavy Fuel Oil
ISI	Iron and Steel Industry
LFO	Light Fuel Oil
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
OPEX	Operating Expenditure
PC(I)	Pulverised Coal (Injection)
PoP	Pulp and Paper industry
SM	Sawmill industry
SCFSM	Swedish County Forest Sector Model

1 Introduction

The Swedish iron and steel sector accounts for less than 0.3% of global steel production [1]. Specialising in niche products with an export value of over 53 M€ [2], fossil energy use in the iron and steel industry (ISI) accounts for 51% of the total industrial fossil energy use in Sweden [3], thus becoming the largest industry emitter of CO_2 in Sweden [4]. The ISI in Sweden thus faces similar challenges as with the global iron and steel industry, namely, reduction of its fossil CO_2 emissions resulting from the energy- and reductant intensity. National climate targets set by the Swedish government to achieve net-zero CO_2 emissions by 2045 [5] require quicker actions on the part of the ISI to curtail its fossil CO_2 emissions in the short to medium term. Efforts to reduce fossil CO_2 emissions in the ISI have been targeted at coal and coke use in blast furnaces as this represents over two-thirds of iron and steel produced globally [6]. For other process routes accounting for the remaining steel production, e.g., electric arc furnaces (EAF), direct reduction, secondary processing, etc., replacing fossil gas fuels is equally on the agenda for CO_2 mitigation within the industry. Of all the options available to mitigate the ISI's fossil CO_2 emissions, the substitution of fossil energy and reductants with renewable biomass products stands out as one of the few short to medium term strategies that can be implemented with relative technical ease, i.e. requiring little or no modification to existing processes [7,8].

Refined forest biomass in the form of charcoal, product gas, and synthetic natural gas (SNG) have been found to be suitable replacements (to varying extents) in studies and review literature that have considered their technical feasibility, see for examples [8–16]. Potential CO_2 reductions have also been estimated in some studies, see [17,18]. Although it is not technically possible to replace all the fossil energy with biomass, a major concern from utilising biomass in the ISI is the large biomass quantities required. Another concern is the increased competition for limited and varied biomass resources that are also used by other industries as a primary raw material or as a means of achieving their CO_2 mitigation targets. A large demand for biomass-derived fuels implies that the ISI will become a major actor within the regional biomass markets [19]. Increased competition for biomass will have an impact on biomass markets, creating a ripple effect on the biomass supply costs for existing biomass users and on the economic feasibility of the ISI to use biomass. Techno-economic impacts from allocating and supplying large quantities of forest biomass for the purpose of iron and steelmaking has been left unexplored. Most studies [20–22] that have analysed the feasibility of using biomass in iron and steel making from an economic perspective have omitted the impacts of the increased competition for forest biomass on the practicability of the ISI using the feedstock itself. This paper aims to address this research gap and explore the relationship between the biomass markets and the options to use biomass in the ISI.

Techno-economic assessments of using forest biomass in steel production identify the costs for biomass feedstock and plant capital as the major contributors to the overall production cost (see [17,23,24]). Sensitivity analysis is the general method of addressing uncertainty in techno-economic parameters such as biomass prices. However, this method ignores the market dynamics resulting from competing uses of biomass. Since the markets for biomass are regional [25], market effects leading to feedstock prices changes will be on the local level as well [19]. Capturing the interactions between biofuel production and the forest sector have been studied using partial equilibrium (PE) models. One conclusion from a study by [26] is that biomass feedstock prices increase at different levels of large-scale biofuel deployment, and industries affected by the resulting feedstock re-allocation will lose market. Using similar methods, Mustapha et al. [27] use a forest sector model to investigate the dependencies between feedstock cost and biomass conversion pathways. Their results indicate that feedstock costs can increase from 12%-35% depending on the conversion pathway chosen, although technological learning can lead to a reduction of these costs [27]. However, these studies have not explicitly included the ISI as a new biomass user. Olofsson [19] analysed the effects from an increased competition for forest biomass assortments on regional biomass markets in three regions in northern Finland and Sweden using PE modelling. Observations from the study indicated that the ISI partial transition to charcoal will lead to price increases for the secondary biomass assortments [19].

Even as PE-modelling studies can provide evidence for the need to account for the effects of forest-based biomass fuels on other industries and users of biomass, such micro- economic modelling does not cover the technological details as would be found when optimising the biomass supply costs for bio-production. For instance, technologies for upgrading raw biomass into relevant bio-products has been missing in these PE studies. In addition, the spatial component, a crucial aspect for biomass supply is lacking in the analysis. Since forest biomass assortments vary regionally, biomass supply costs make a significant contribution to the fuel production costs and, in many cases, these costs must be optimised for plants that are located far from the biomass source. The application of geographically-explicit optimisation for biomass supply chains for bio-fuel production has the benefit of identifying the least costs of using bio-fuels within a studied system (e.g. see [28–30]). Additionally, the logistics surrounding the supply of biomass quantities from one point to another can be captured adequately for each technology pathway that is considered, including the diversity of the biomass feedstock used. A few studies have paid close attention to biomass availability and logistics regarding bio-products for the ISI e.g. [22,31]. Strategic use of biomass resources as alternatives in blast furnaces across Europe was studied and identified using the geographically-explicit BeWhere model in [21,31]. However, the biomass prices used in the study were exogenous and remained static. 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 making techno-economic and investment calculations for the ISI obsolete.

Overcoming the limitations of either modelling approach requires combining the strengths of a PE model and a techno-economic (bio-)energy supply chain model. Model linking approaches – soft and hard linking – are discussed in [32] where the authors study the interactions between the energy sector and the rest of the economy via a soft linking approach. Mustapha et al. [33] hard-linked a forest sector model with an energy system model to study the effects of large-scale implementation of forest-based biofuel production on the heat and power sector. Using an iterative process characteristic of soft-linking, Zetterholm et al. [34] combine value chain cost optimization and a market model to identify the level of policy support needed to facilitate sawmill-integrated production of liquefied bio-methane on a large scale.

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 research gap by combining the economic impacts of biomass competition (price effects), supply costs of forest biomass, and technologies for biomass conversion. This will be 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 and forestry sectors, and a 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-production plants?
3. How are supply costs and feedstock allocation for the competing industries within the forest and energy sectors influenced 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?

The opportunities for biomass utilisation are included for the entire steel production chain, starting with production of iron ore pellets and across 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 will impact feedstock prices. That is, how the explicit localisation of the ISI and its demand for bio-products is expected to influence the supply costs and allocation of biomass resources across existing forest industries. Likewise, forest industries demand for biomass assortments will impact the availability of feedstock that can be allocated to the ISI sector's bio-product needs, and thus, the physical location of 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 was 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 spatially explicit supply chain model. Section 2.1 describes models used and the soft-linking process. Section 2.2 provides descriptions of the systems studied including the conversion technology pathways. Input data and general assumptions are documented in section 2.3, while scenarios evaluated are described in section 2.4.

2.1 Modelling framework

2.1.1 Techno-economic supply chain model

The techno-economic supply chain model, BeWhere Sweden, is a geographically explicit optimisation model that has been developed for extensive system analysis of bioenergy systems, with a particular focus on forest biomass [28,35]. BeWhere Sweden is a mixed-integer linear programming problem, written in the commercial software General Algebraic Model System (GAMS) and using CPLEX as solver. The model is solved for a time period 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.

BeWhere Sweden was originally developed to analyse the production and use of advanced biofuels for transportation [28,35,36], but has recently been extended with a module that allows for analysis of biomass use in the ISI [22,37]. 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.

BeWhere Sweden operates with static prices for biomass, which means that the biomass prices and production quantities in other industries are not affected by the adaptation of a specific new demand of bio-products from the ISI. However, the biomass prices have spatial differences depending on geographical variations and distances, see [28,38].

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 [39] 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 [40,41]. The model is implemented in GAMS software and solved using the CONOPT solver.

The modelling structure used by the SCFSM was first developed by Kallio et al. [42] and later refined by the likes of e.g. Bolkesjø [43]. The model utilises a system of fixed input-output production functions, which entails that 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 can be solved for one period (i.e., a static model), or for continuous linked periods (recursive dynamic). The latter is used in this work, see Figure 1.

When solving the objective function of the SCFSM, the model tries to satisfy a regional exogenous demand (i.e., production targets), which is based on current 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 the data estimate for biomass availability as in the BeWhere Sweden model (based on [44], see [28,38] 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 sawmill sector and is based on observed regional production levels.

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).

2.1.3 Soft-linking procedure

The soft-linking procedure starts with BeWhere Sweden first run without any new bio-production in the system. This establishes the *Reference* scenario, i.e., the business-as-usual (BAU) case where the ISI does not use biomass in any of its processes. Next, the BeWhere Sweden model is run with biomass to the ISI included, from which optimal bio-production quantities and plant locations (for each bio-product) are obtained (depending on the substitution assumptions) based on the initial static exogenous biomass prices. This is the initial exogenous run in BeWhere Sweden (Iteration_0), and the output, i.e., biomass quantities used for bio-production and optimal plant localisations, is used as input to SCFSM. SCFSM runs a market analysis based on the equilibrium results from BeWhere Sweden to obtain the resulting endogenous feedstock price implication. The new price estimates from SCFSM along with forest industry production volumes are then used as input in BeWhere Sweden in its supply chain analysis for bio-production. Observed import quantities from the SCFSM are used as upper import limits in BeWhere Sweden.

Figure 1 presents the schematic for the soft-linking framework. The procedure is carried out in an iterative manner, with output from each model serving as connection points between the two models. A total of five iterations were done between the two models (Iteration_1 to Iteration_5). Results from each iteration are evaluated for several substitution scenarios at the ISI and the endogenous price estimates are used to determine the economic performance of bio-production in BeWhere Sweden. As discussed in [32], while it may be arbitrary to conduct a certain number of iterations, the step-wise analysis allows for insights into interactions between the industry sectors.

A dynamic element is introduced by recursively solving each scenario over five linked periods, where each scenario iteration is evaluated separately to assess whether the spatial locations of bio-production industries is altered, and how the established forest industry is affected. The results produced are stable for the specific scenario assumptions and underpins the explorative approach of this study. Observation from each iteration shows the price stability, or lack of, for biomass assortments and regional biomass markets. The value of the iterative procedure is that it enables an understanding of how the impacts from the ISI's inclusion in the biomass market may vary over time.

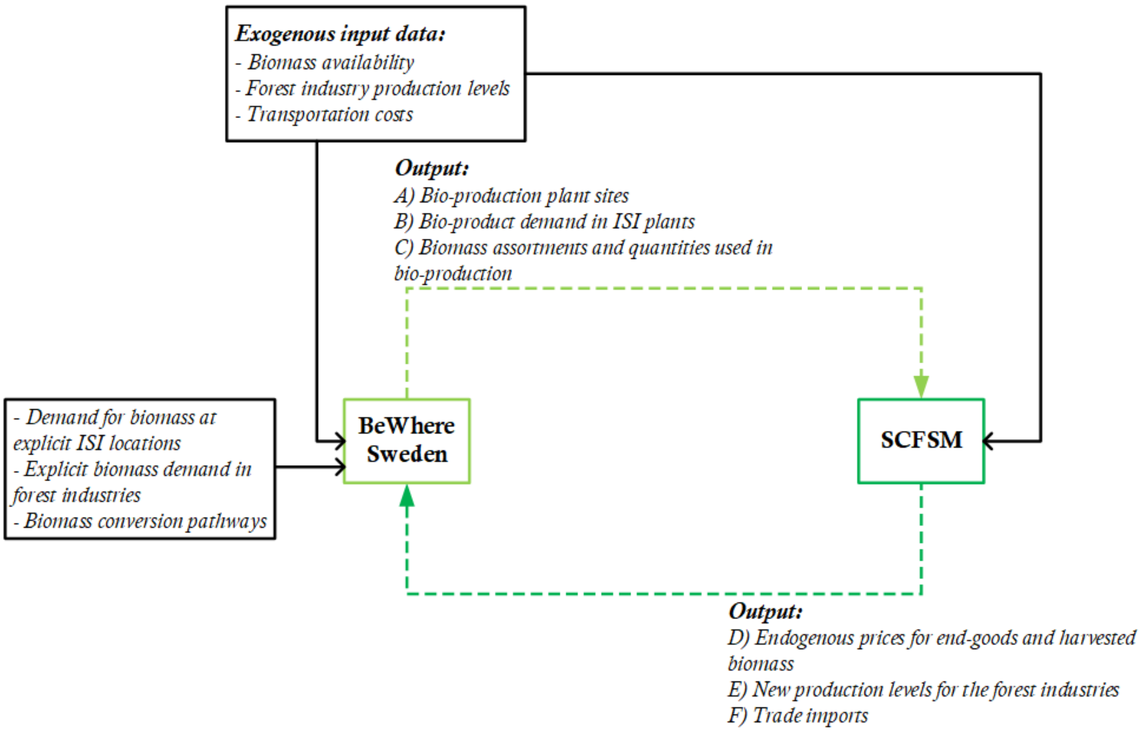

Figure 1: Schema showing the soft-linking process between the two models. Coloured dashed lines represent the iterative procedure where output from one model serves as input in the other. Exogenous input to models is represented with the black boxes and lines.

2.1.4 Difference in data between the models

Where possible, numerical estimates were collected from BeWhere Sweden, 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 BeWhere Sweden. 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 [39].

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.

2.2 Description of systems studied

2.2.1 Iron and steel industry

We cover the entire iron and steel production in Sweden, which includes three iron ore production plants, two integrated steel plants, one direct reduction (DR) plant, 13 electric arc furnaces (EAF) and secondary processing plants. Figure 2 shows the geographical distribution of the included ISI 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 is carried out in the northernmost parts of Sweden and require coal, coke, and fuel oils to pelletise iron ore that is mined from the region. Iron production via reduction of iron ore pellets in a blast furnace is conducted at two integrated steel mills located in both the south and north of the country, whereas sponge iron produced via a direct reduction process is carried out in one plant located in the south-west. Secondary steel production (EAF) and other steel processing plants are coupled and mainly concentrated in the mid- and southern parts of the country. The total modelled fossil demand amounts to 20.6 TWh, which comprises fuels used for energy purposes and/or material use, i.e., slag-formers, heating fuels, and reducing agents, as summarised in Table 1.

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).

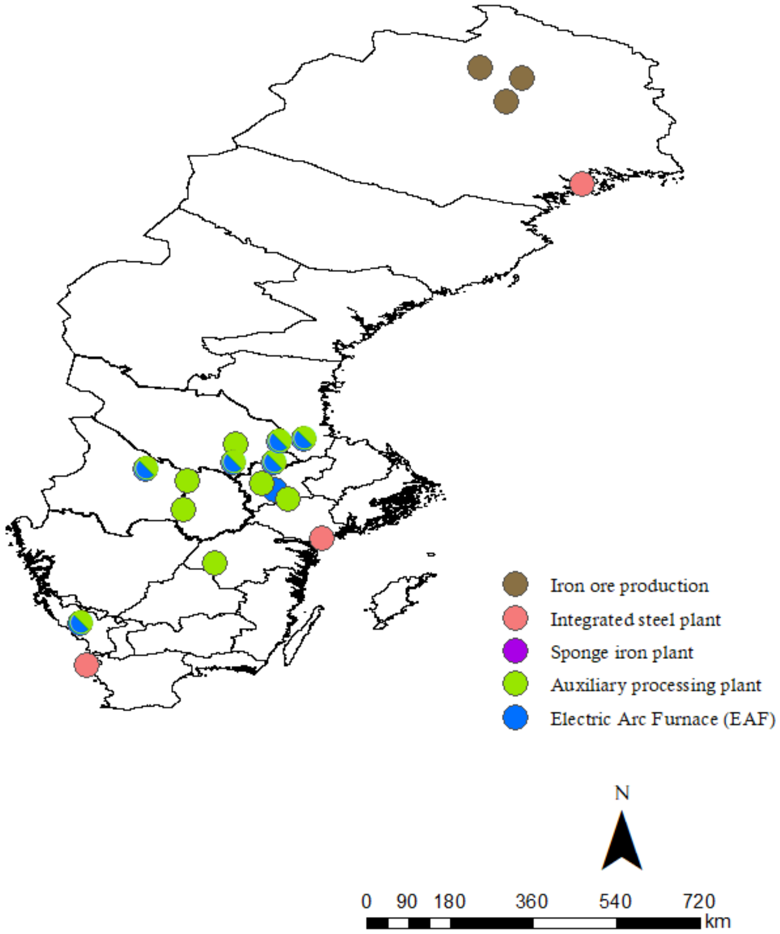

Figure 2: Location of ISI plants included in this study. Several auxiliary processing and secondary steelworks are co-located with the integrated steel plants and sponge iron plant.

Table 1: Selected fossil energy substitution in the different process units across the entire iron and steel production chain.

Process unit	Fossil fuel used	Application	Bio-product as substitute	Maximum Substitution potential	Ref.
Pelletising kilns	Coal Light and Heavy fuel oils	Heating fuel	Charcoal L-SNG or product gas	100% 100%	[13,45]
Coke ovens	Coking coal	Raw material for coke making	Charcoal	5%	[8,9]
Blast furnace	Pulverised coal	Fuel and reductant	Charcoal	100%	[18]
EAF	Coal Pet-coke	Slag former Fuel	Charcoal Charcoal	100% 100%	[10]
DRI	Coal Coke	Heating fuel and reducing agent	Charcoal Charcoal	100% 100%	[13]
Furnaces and secondary processing	LNG, LPG, NG, LFO	Heating fuel	L-SNG or product gas	100%	[15,24]

2.2.2 Competing industries

The Swedish forest industry sector is highly diversified and is 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. The two largest forest industries are pulp and paper (PoP) and sawmill (SM) sectors, which in 2016 together exported 103.3 billion SEK worth of goods [46]. The aggregated forest industry sector constitute between 2.2 to 3.3% of Sweden's GDP [47]. As such, the 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 source of heat in Sweden, satisfying approximately a third of all heating needs in the residential and services sector. Biomass (e.g., wood chips, waste wood, harvesting residues, etc.) and household waste constitute the main fuels for DH production in Sweden. 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.

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

	Production	Ref.
Sawmills (SM)	17.2 million m^3	[48,49]
Pulp mills (PoP)	11.6 million tonnes	[49]
Pellets production (PI)	1.80 million tonnes	[50]
District heating (DH)	47.2 TWh	[51]

2.2.3 Bio-production pathways

Production of charcoal, product gas and liquefied synthetic natural gas (L-SNG) was 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. A total number of 111 potential host sites in the form of sawmills and ISI plants were considered. Process modelling, via mass and energy balance, was carried out for each production or technology configuration (see Table 8).

Production of product gas from forest biomass was assumed to be carried out via a multi-stage gasification process. Data for mass and energy balance used in this technology configuration were obtained from previous studies [23,52]. 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 an indirect dual fluidised bed gasification and hosted at a sawmill, based on the technology configuration studies carried out by Ahlström et al. [53]. As our previous investigation [23] showed that higher costs would be incurred if the production is carried out at the ISI, this technology configuration was here restricted to sawmills. The sawmills were 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. Production of charcoal for metallurgical purposes is required to have at least 80% fixed carbon content [54]. Mass and energy balances were calculated using studies from literature on standalone production systems e.g. [55,56]. 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 was allowed for this technology.

2.3 Input data

Data input is calibrated using 2018 as the reference year, and all costs are given in Euro (€) using the average 2018 rate of 1.18 $/€ [57]. 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

As described in section 2.1.1, biomass supply is in BeWhere Sweden modelled using a half-degree spatial resolution (Figure 3), whereas in SCFSM it is modelled on a county basis (NUTS 3 [58]). Biomass assortments considered are limited to forests (sawlogs, pulpwood, harvesting residues) and industries (sawmill by-products, wood pellets, and waste wood). Supply elasticity estimates used in the SCFSM are presented in Table 4. Data estimates in [28,59] were used to obtain supply potential for forest assortments based on data from the Swedish Forest Agency's "Today's forestry scenario" [44], while biomass quantities from industry operations were obtained based on data from [49–51,60]. The available biomass quantities are modelled as static from the modelling perspective in both BeWhere Sweden and SCFSM models.

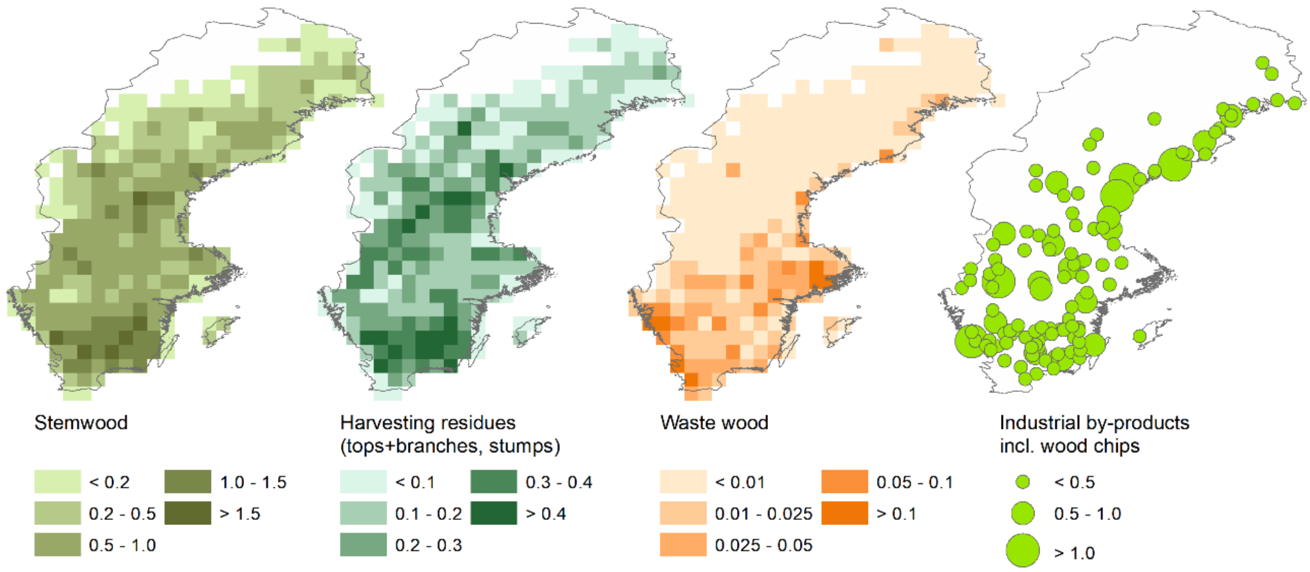

Figure 3: Spatial distribution of biomass supply, as modelled in BeWhere Sweden. All values are in TWh/y. Stemwood includes both sawlogs and pulp wood

Table 3: Available quantities for biomass assortments in BeWhere Sweden.

Assortment	TWh/year
Sawlogs	89.3
Pulpwood	66.3
Waste wood	5.1
Wood pellets	8.1
Industry by-products	2.1
Harvesting residues and stumps	52.6

Table 4: Supply elasticities for biomass assortments used in SCFSM

Sawlogs [61]	0.47
Pulpwood [61]	0.28
Harvesting residues and stumps [40]	1.26

2.3.2 Biomass demand

Table 5 shows the biomass demand as modelled in BeWhere Sweden, including which assortments that can be used to fulfil each demand, and Figure 4 shows the spatial distribution of the competing demand. Demand for biomass from forest industry and district heating was considered explicitly based on a bottom-up estimation described in [28], while demand for biomass to substitute fossil fuels in the ISI was represented explicitly using a bottom-up estimation of the energy requirement at each ISI plant.

Table 5: Demand for biomass assortments as modelled in BeWhere Sweden [22].

Demand	Aggregated demand (TWh/y)	Biomass assortments: Sawlogs	Pulpwood	Harvesting residues and stumps	Wood pellets	Industry by-products	Waste wood
Sawmills	74.6	▪					
Pulp and paper mills	96.1	▪	▪			▪	
Heat demand at sawmills	0.2					▪	
Heat demand at pulp and paper mills	24		▪	▪		▪	▪
DH (unrefined wood)	24.4		▪	▪	▪		▪
DH (refined wood)	3.1		▪	▪	▪	▪	▪
Pellets production	8.1					▪	
Charcoal production	Varying		▪		▪	▪ [a]	
Product gas production	Varying		▪	▪		▪	
L-SNG production	Varying		▪	▪		▪	

[a] Excluding lower grade by-products e.g. bark.

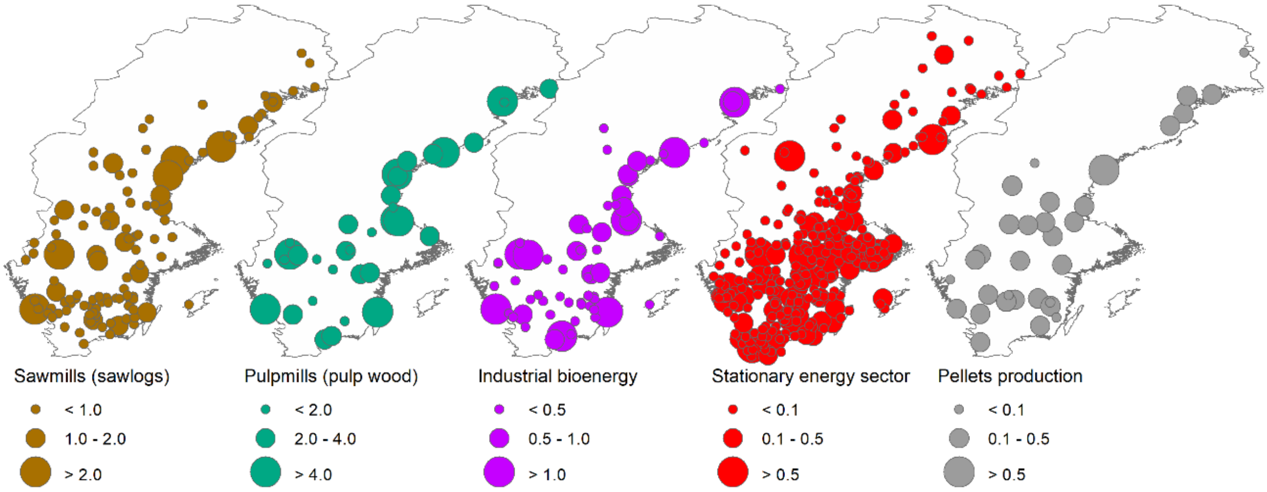

Figure 4: Biomass demand as modelled in BeWhere Sweden.

2.3.3 Biomass transportation and supply of bio-products

Transportation of biomass assortments and bio-products was assumed to be carried out via road, rail, and waterway. Transportation costs were obtained as functions of the distance between explicit geographic points according to the cost values from [59], which are reported in Table 6.

Table 6: 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 [59,62] *and CO_2 emissions are adapted from* [63,64].

	Transport cost (€/MWh)			CO_2 emissions (tCO_2/TWh, km)	
	Truck	Train	Boat	Truck	Train
Sawlogs and 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
Industry by-products, pellets, and 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

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 7. Assuming an economic lifetime of the equipment using an annuity factor of 0.1, the investments were discounted at an 8% rate and an economic lifetime of 20 years. Operation and maintenance costs (O&M) were calculated as a percentage of the investment costs depending on the bio-production technology.

All investment costs related to the plant and equipment were adjusted to the year 2018 currency value using the Chemical Engineering Plant Cost Index (CEPCI).

Table 8 presents the energy output for each biomass conversion technology.

Table 7: Investment cost function for main equipment relevant to the bio-production and electricity co-generation. The investment cost is calculated as $A*S^n$ ($M€_{2018}$).

	A	S (MW)	n	O&M (%)	Reference
Charcoal	1.97	biomass input	0.72	8.0	[65]
Product gas	3.54	biomass input	0.67	6.3	[23]
L-SNG	0.02	Sawmill prod. capacity (m^3fub)	0.73	4.0	[53]
Steam cycle	1.82	Electricity produced	0.67	4.0	[66]

Table 8. 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 [23,52]
[b] Calculated based on [55,56]
[c] Based on data from [53]. The electricity requirement for liquefaction is 0.104 per unit of biomass input.

2.3.5 Energy prices and policy instruments

All biomass flows, including the bio-products and other energy carriers, are presented in energy units based on their lower heating value. Table 9 presents average energy prices and CO_2 emission factors of the fossil fuels used in ISI and those of raw biomass assortments. The biomass prices represent the initial exogenous prices for BeWhere Sweden, as described in section 2.1.3. The EU-ETS CO_2 price was set to 25 €/ton CO_2 [67]. Additional support instruments in the form of green certificates from the Swedish electricity certificate system is included for co-generated electricity during bio-production.

Table 9: 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)	Reference
HFO	71.0	270	[3,68]
LNG	42.0	198	[68,69]
LPG	42.0	234	[68,69]
NG	42.5	202	[3,68]
Coal	9.6	344	[68,70]
LFO	85.0	267	[3,68]
Coke & pet-coke	19.4	400	[68]
Coking coal	14.3	335	[68]
Electricity	46.0	47[a]	[71,72]
Sawlogs [c]	25.0	1.5[b]	[73,74]
Pulpwood [c]	15.0	1.5[b]	[73,74]
Harvesting residues and stumps [c]	15.0	1.5[b]	[73,75]
Waste wood	4.2		[75]
Wood pellets	24.0		[75]
Industry by-products	24.0		[75]

[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 [38]

2.4 Substitution scenarios

To study the competition effects from biomass utilisation in the ISI, three substitution scenarios are constructed to reflect full or partial substitution of fossil energy and reductants with biomass.

i. The first substitution scenario, the *All_bio-products* scenario, assumes full substitution of all fossil fuels and reductants with charcoal, product gas and L-SNG in all ISI processes (see Table 1) as a short to medium term strategy to decarbonising emissions from the ISI.
ii. The *Charcoal* 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. In the *Gas-fuels* scenario, replacing fossil gas-fuels with alternatives derived from biomass is assumed to be a low hanging fruit for the ISI since bio-based gas fuels can be used as full replacements [23].

The constructed scenarios consider maximum (100%) substitution with the bio-products according to technical limits and replacement ratios in section 2.2.1. In addition to the substitution scenarios, the *Reference* scenario (i.e., BAU scenario) is considered, where biomass is not yet introduced in the ISI. Since this scenario corresponds to no new bio-production, it will be 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. The initial input biomass prices in the reference and substitution scenarios are based on the exogenous prices for the reference year 2018.

2.4.1 Evaluation of scenarios

Results obtained from the soft-linking process are iteratively compared to the previous iteration (i.e., results for Iteration_1 are compared to results from Iteration_0), thus presenting a dynamic approach. The results in Iteration_0 are compared to the *Reference* scenario for the competing industries.

The substitution scenarios are evaluated in each iteration for:

i. *Price changes in biomass assortments*: Resulting biomass price development solved on a county (regional) basis in SCFSM is used as an endogenous input to BeWhere Sweden, in an iterative manner. SCFSM solves the new equilibrium prices as a percentage increase or decrease from the subsequent iteration. In BeWhere, the percentage changes from SCFSM are multiplied by the price factors in each county to obtain an average price per assortment on a national level.
ii. *Plant localisations for bio-production*: Initial plant localisations resulting from the initial exogenous run (i.e., Iteration_0) in BeWhere Sweden 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 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 BeWhere Sweden and include the costs for supplying and transporting biomass feedstock, bio-production plant costs, electricity costs, and transport costs for distributing bio-products (see [22]). Supply costs for competing industries are also computed in BeWhere Sweden 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 were used throughout the model-linking. Nonetheless, the evaluated parameters can provide guidance when highlighting optimal bio-production sites for investors and policy-makers.

3 Results

3.1 Biomass prices

Figure 5 shows the output average prices in BeWhere Sweden for six biomass assortments in the three fossil substitution scenarios per iteration.

Initial exogenous prices, i.e., Iteration_0 (see Table 9), for the various biomass assortments are the same in the three substitution scenarios. However, with the first model calibration (Iteration_1), price increases are observed for the biomass assortments although the extent of significance differs according to the bio-product scenario. Subsequent iterations show stable price developments for some assortments, whereas for other assortments volatile prices are observed. Again, the price changes occur on a regional basis (county-wise). The effects from the new price developments are further discussed in section 3.4 in terms of their impact on resulting supply costs for the ISI and the competing industries.

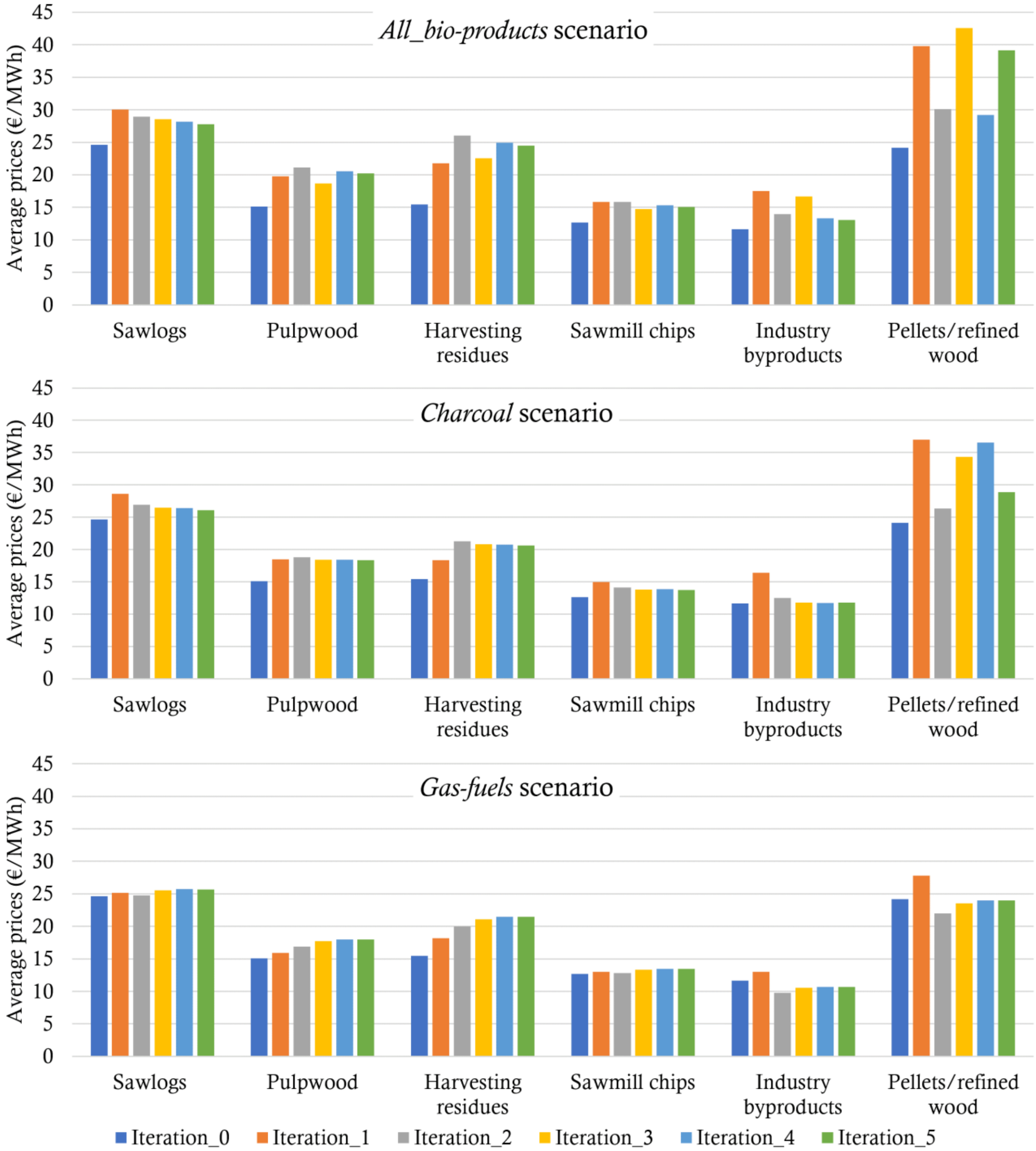

Figure 5: National average prices for different biomass assortments in the three fossil substitution scenarios, over all iterations. Waste wood is excluded since no price changes are observed as the assortment is not used for any bio-production.

In the *All_bio-products* scenario, where the running assumption is that the ISI replaces all fossil fuel and reductant use with bio-products within technical limits, significant price changes occur for all assortments in Iteration_1. These occurrences are linked to the high use of some feedstock assortments for bio-production of charcoal and gas-fuels and the corresponding impact on feedstock use in the competing industries. For example, volatile price movements for pellets indicate the instances when pellets are used as feedstock for charcoal production (high price spikes) compared to when they are not used (price dips).

In the *Gas-fuels* scenario, pulpwood and harvesting residues have the only significant price impact compared to the other assortments. Pellets, harvesting residues, pulpwood, and sawlogs see significant price spikes amongst other assortments in the *Charcoal* scenario. Sawlogs are not used for bio-production. However, the price increase suggests that sawlogs are increasingly used in another industry as a consequence of introducing bio-production for the ISI in the system. Sawlog prices see increment with each iteration, pointing to its re-allocation as feedstock in the pulp industry due to competition of assortments used for bio-production, especially sawmill chips for charcoal production. For instance, sawmills in the reference case have significant demand for sawlogs. However, when bio-production is implemented, the demand for sawlogs increases since the pulp mills start using some sawlogs to compensate loss of their primary assortments. The price increase for wood pellets, observed in Figure 5 is primarily caused by increased demand for sawmill by-products, the input feedstock for the pellets production, while simultaneously increasing the use of the wood pellets as an end-good.

In the *All_bio-products* scenarios, higher price spikes occur compared to the other two scenarios. This is obviously a result of the high biomass use for ISI purposes. This observation suggests that implementing fossil substitution with all three bio-products will impact the biomass markets significantly. Price developments observed for each feedstock assortment may imply that some forest industries will have to either adjust their business models or lower their own production, which confirms previous results from Olofsson [19] for a more limited geographical scope.

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 Figure 6 as possible locations for bio-production for the ISI. Details of all selected locations are given in Appendix A.

From Figure 6, it is observed that there are more plant localisations in several regions for production of gas-fuels from biomass, unlike for charcoal production which has only nine appearing plant localisations. 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 high compared to the charcoal demand in other regions where it is only used in the EAFs. 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 Iterations 1 & 5 in two different regions, suggesting that localisation is affected by the regional price difference (in the assortments).

For the *Gas-fuels* scenario, plant localisations are mostly at the ISI industry due to the lower investment costs of producing product gas compared to L-SNG. Almost all plant localisations are found to be at auxiliary processing plants, where large volumes of fossil gases such as NG, LNG, LPG for heating purposes are required. Other ISI plants using fuel oils, and NG used in iron ore production and sponge iron production, appear as production sites for gas-fuels. The occurrence of one sawmill-integrated L-SNG production in subsequent iterations is driven by the lower prices for sawmill by-products (sawdust and bark) used as feedstock. Regional price increases for harvesting residues (branches and tops) in Iteration_1 results in the introduction of L-SNG production at a sawmill plant using available feedstock assortments.

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. 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.

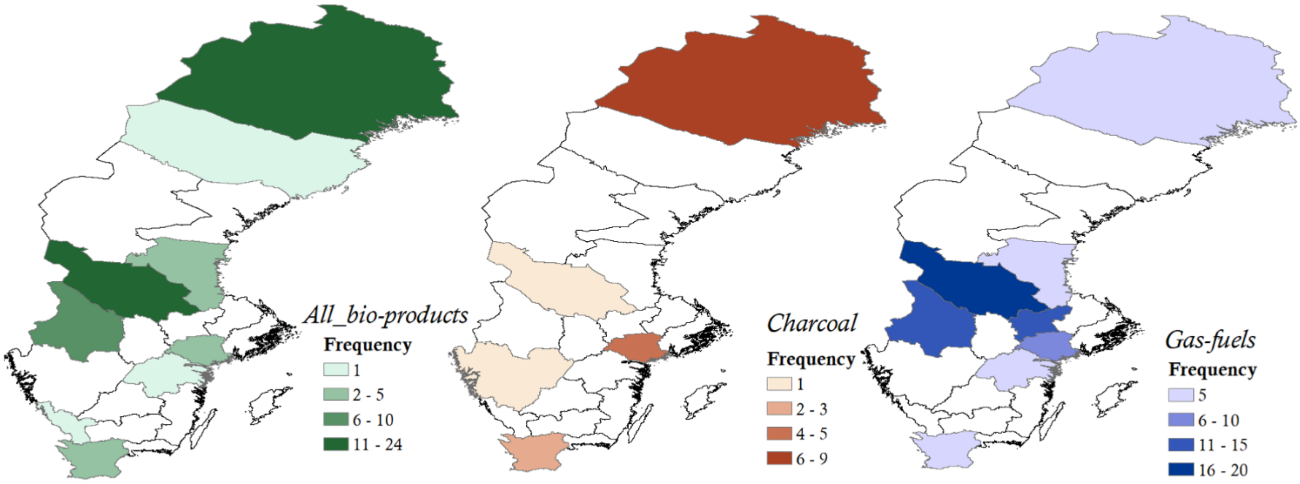

Figure 6: Plant localisations on a regional level for All_bio-products *scenario,* Charcoal *scenario, and* Gas-fuels *scenario, respectively. Legend refers to frequency of plants occurring within each region throughout the iterative process (Iterations_0 to 5).*

3.3 Feedstock use

Biomass demand for the competing forest industries is static when executing BeWhere Sweden in the *Reference* scenario (as given in Table 5). Exogenous biomass prices are used in the *Reference* scenario, as well as in Iteration_0 when bio-production for the ISI is introduced in the system. Feedstock allocation for competing industries in the *Reference* scenario is shown in Figure 7. Availability of biomass assortments in this scenario is based on domestic supply and imports. During the iterative process, forest production levels and import quantities obtained from SCFSM because of the regional biomass price development, serves as input to BeWhere Sweden as described in section 2.1.3. Thus, with each iteration, the biomass availability varies according to the new equilibrium solved in SCFSM.

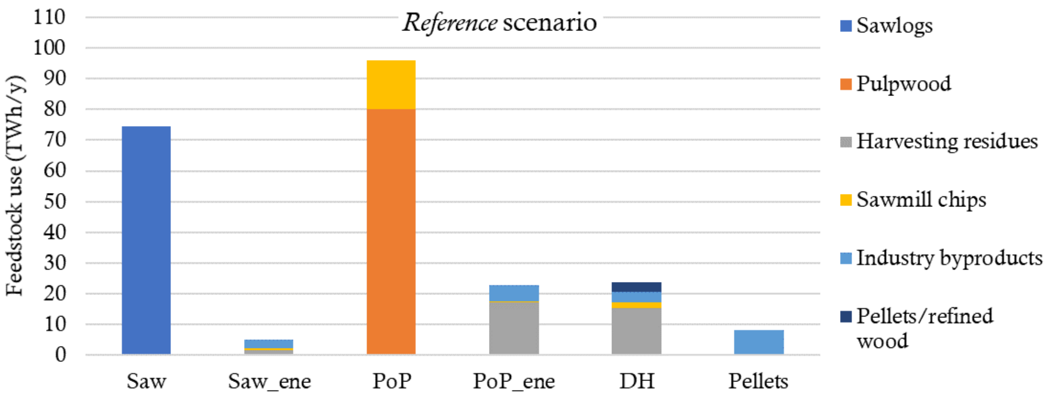

Figure 7: Feedstock use by competing industries in the Reference *scenario (BAU). Saw = sawlog demand, Saw_ene = sawmill energy demand, PoP = pulp mill fibre demand, PoP_ene = pulp and paper mill external energy demand, DH = unrefined plus refined biomass demand for district heating, pellets = pellets industry demand.*

The resulting feedstock re-allocation and use from the soft-linking procedure is presented in Figure 8. From the results, competition for some assortments 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 as a result of competition with bio-production for sawmill chips and pulpwood assortments. While this initial observation occurs in the three substitution scenarios, the extent of competition is contingent on the bio-product 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), the pulp industry increases its use of sawlogs and sawmill chips to satisfy its fibre demand. This applies to all three substitution scenarios. In pulp industries, use of sawmill chips is connected to the regional price impacts seen in Figure 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. Pellets are also increasingly allocated to the DH sector that typically uses more of harvesting residues than refined wood, i.e., pellets. 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 in Figure 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 above 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.

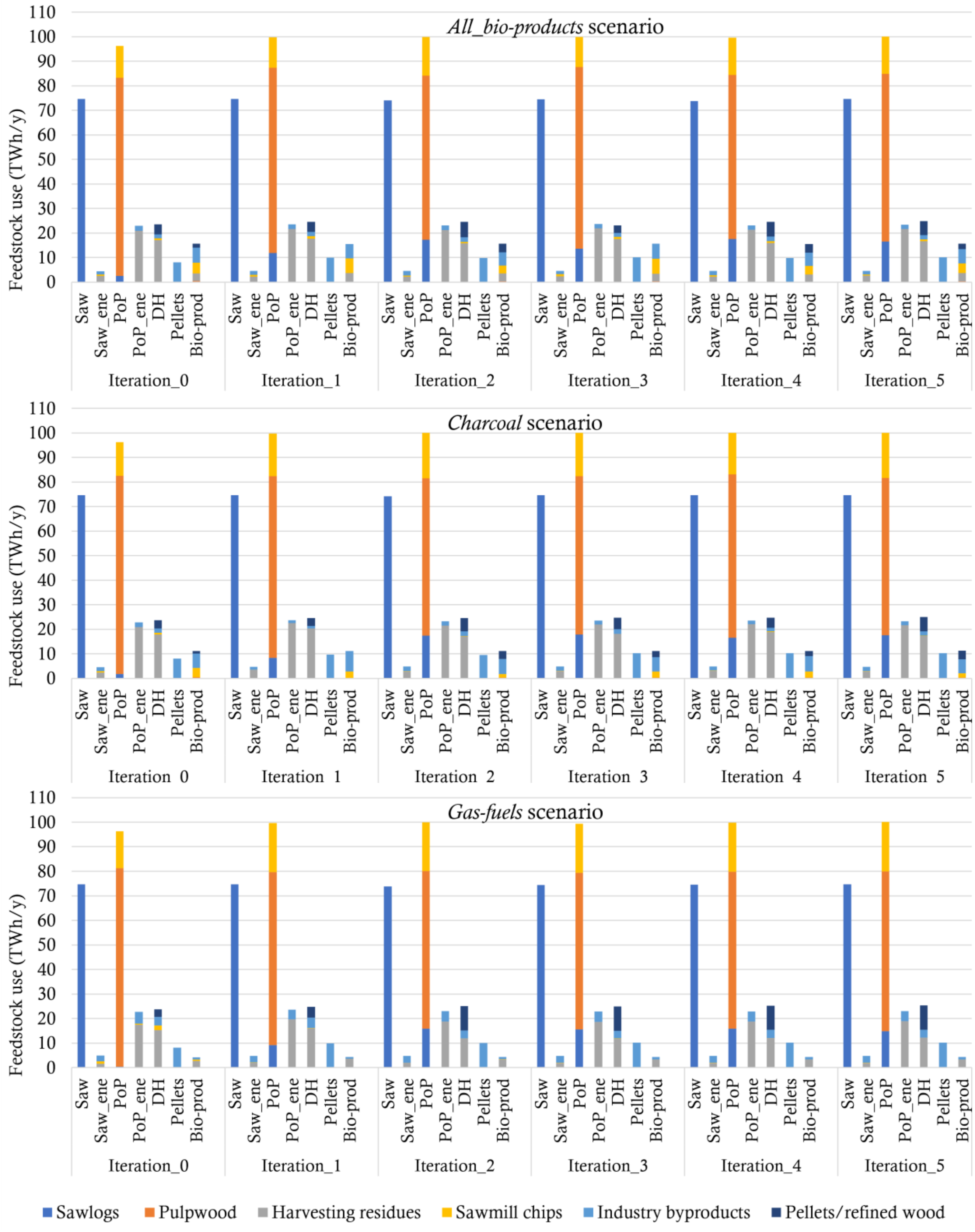

Figure 8: Feedstock use in competing industries and for bio-production in the three substitution scenarios. Saw = sawlog demand, Saw_ene = sawmill energy demand, PoP = pulp mill fibre demand, PoP_ene = pulp and paper mill external energy demand, DH = unrefined plus refined biomass demand for district heating, pellets = pellets industry demand, Bio-prod = feedstock demand for bio-production.

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 BeWhere Sweden 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. This has already been highlighted 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 Figure 9, supply costs in the *Gas-fuel* 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 Figure 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-fuel* scenario compared to the *All_bio-products* scenario. Higher supply costs correspond to lower quantities of L-SNG produced in the *Gas-fuel* scenario, while relatively lower supply costs in the *All_bio-products* scenario tally with more significant L-SNG production.

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 BeWhere Sweden, 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 Figure 9, it can be said that charcoal at supply costs in the range of 45-55 €/MWh is economically appealing as a bio-product for the ISI. Supply costs for L-SNG and product gas fall in the ranges of 66-102 €/MWh and 49-59 €/MWh, respectively.

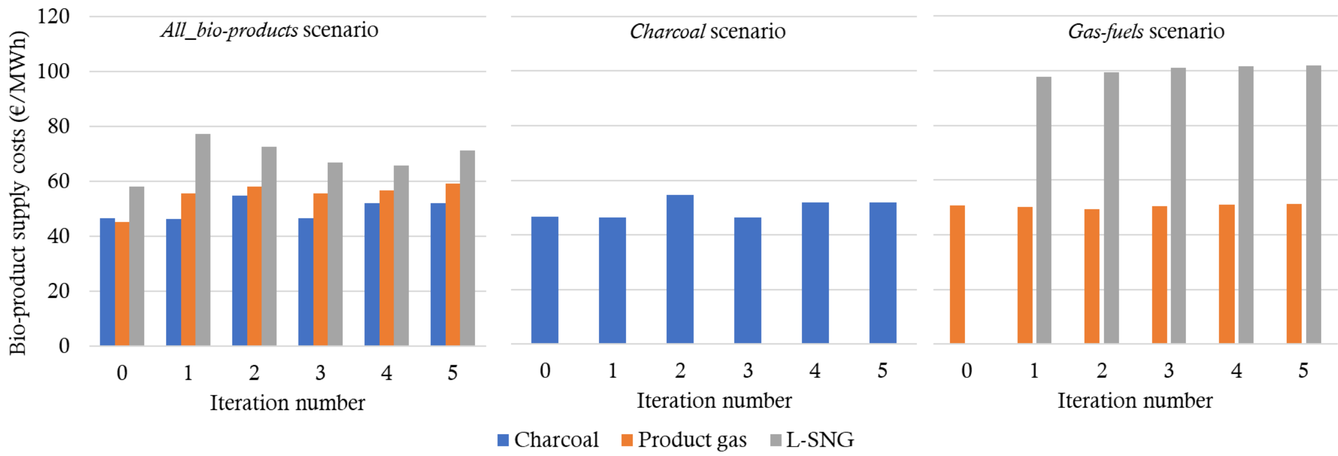

Figure 9: Supply costs for bio-products to the ISI produced in the three substitution scenarios.

3.4.2 Supply costs for competing industries

Based on exogenous biomass prices used in the *Reference* scenario (BAU) and in Iteration_0, supply costs for the competing industries are calculated for both the BAU case and when bio-production for the ISI is implemented in the system. After Iteration_0, endogenous biomass prices are applied to obtain supply costs for the competing industries in the subsequent iterations. Figure 10 shows the resulting supply costs for each substitution scenario.

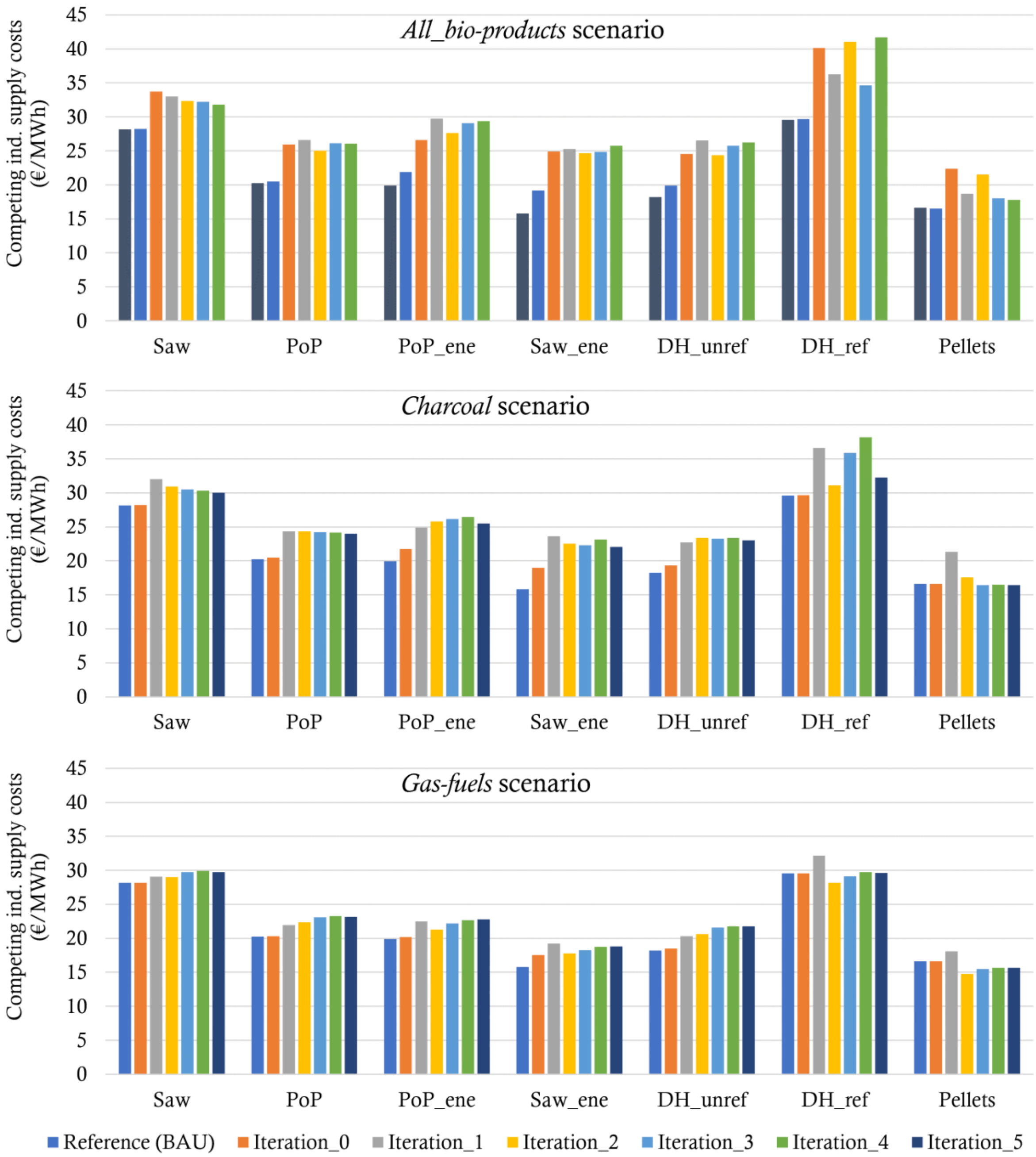

Figure 10: Supply costs for competing industries

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. 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 Figure 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 Iterations 1-5 follow a similar pattern as the endogenous price development for biomass assortments (in Figure

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 and 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 Iterations 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 Discussion

In the *Gas-fuels* scenario, replacement of total fossil fuel demand of 3.3 TWh is fully satisfied with the bio-based gas fuels, mostly product gas, in all the iterations. In Iteration_0, using exogenous biomass prices in BeWhere Sweden results in product gas as the only bio-based gas-fuel produced in the system. However, a general increase in the price of the major feedstock used for gas-fuels (i.e., harvesting residues) results in the production of small quantities of L-SNG to boost replacement of fossil fuels in more ISI plants (than 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. Biomass supply costs for competing industries is less pronounced in the *Gas-fuels* scenario, even though supply costs for product gas are on average 4 €/MWh more than for charcoal.

The results of the model linking procedure 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 of the study indicate specific counties well-situated for bio-production plants. Plant localisation for charcoal production is shown to be more sensitive to changing feedstock prices compared to that of gas-fuels. However, two sites are constantly selected across all iterations as well-suited for large-scale charcoal production. The localisation of gas-fuels is shown to be relatively constant and unaffected by changing feedstock prices or to changes in the type of feedstock assortment used. 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. Plant localisations found to occur in the three scenarios constitute bio-production plants that could attract potential investment regardless of the substitution strategy. As can be seen, L-SNG production does not show stable plant localisation. This observation could discourage any investment into this technology pathway.

As indicated in Figure 5, the increased utilisation of bio-products in the ISI sector will have a significant price impact on feedstock prices. However, depending on the extent of the bio-products used and the feedstock assortment used in the bio-production, the price impact will vary in magnitude. The largest price impacts are experienced in the *All-bio-products* scenario, which is also associated with the greatest increase in additional biomass demand for the ISI (15.7 TWh), with smaller price impacts for the *Charcoal* scenario (11.2 TWh) and *Gas* scenario (4.3 TWh).

For roundwood (sawlogs and pulpwood), the market impact in the *All-bio-products* and *Charcoal* scenarios equates to an initial average price increase of approximately 5 €/MWh (i.e., difference between Iteration_1 and Iteration_0), while in the *Gas-fuels* scenario the price effect is smaller (0.65 €/MWh). This price development is driven by an increased feedstock competition, where the pulp mill industry increases its utilisation of sawlogs as a way of securing biomass feedstock under the new market composition. As shown in Figure 7, the pulp industry does not initially consume any sawlogs rather only pulpwood and sawmill chips. As demand for these inputs increase due to the introduction of the ISI sector having an increased demand for bio-products, the pulp mill will shift some of its feedstock demand to sawlogs, as shown in Figure 8. The sawmill industry cannot substitute its feedstock demand to another assortment but rather continues to demand 74.6 TWh of sawlogs across all iterations. However, such a market development is likely to damage the profitability and long-term existence of the sawmill industry sector rather than the pulp mill sector since costs for forest biomass constitutes a larger share of the total average cost for sawmills than what it does for pulp mills (e.g., [76]). Furthermore, a reduction of the production capacity of the sawmill industry sector will result in additional negative market implications since this sector produces secondary woody materials (sawmill chips and industrial by-products) that are extensively used by the other industries.

The pulp industry is affected by the decreased imports of pulpwood after Iteration_0 (in Figure 8), leading to an increased reliance on domestically supplied biomass assortments, e.g., increased use of sawlogs. Although increased domestic demand for biomass assortments are likely to be partially met by imports, the results observed in Figure 8 are driven by the import levels observed from the results of SCFSM. As such, the total amount of biomass assortments available in BeWhere Sweden 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.

Model solutions in BeWhere Sweden show high sensitivity to minor changes, i.e., for instance, small changes in forest production levels can result in significant changes in bio-production, plant localisations, etc. However, this feature can be seen as an advantage in the sense that absolute (optimal) values are found.

5 Conclusions

This study explored the implications of introducing the ISI as a user of bio-products from forest biomass by evaluating how this development will influence biomass prices, localisation of bio-product plants, feedstock allocation, and supply costs. Soft-linking between a geographically explicit techno-economic energy system model (BeWhere Sweden) and a partial equilibrium forest model (Swedish County Forest Sector Model (SCFSM)) show the benefit of accounting for biomass competition and market effects on other existing users of forest biomass such as forest industries and district heating plants.

Our results show 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 results in an economic impact on prices for various forest biomass assortments. Substituting fossil gas fuels results in limited impact on biomass price developments and supply costs for the different competing industries. Substitution options involving charcoal result in increased price impacts for refined wood, harvesting residues, pulpwood, and sawlogs, incurring changes in feedstock composition and supply costs for district heating plants, pulp mills and sawmills. These regional price developments influence localisation of plants for charcoal production, which replaces the dominant coal used in the ISI.

Lower investment costs for bio-production pathways are necessary to counteract the potential biomass price increase for assortments relevant to the ISI. The modelling approach applied in this study identifies bio-production technology pathways that result in low supply costs for the ISI. Iterations based on evolving production levels of forest industries ensures that industries affected by the increased regional biomass competition are identified and acknowledged in decisions and policies that aim to facilitate fuel substitution options for the ISI. We conclude that recognizing deficits and surpluses in trade imports (regional or global) allows for optimal resource allocation within the system, while highlighting geographic areas that will benefit from improved economic policies on forest biomass supply.

Acknowledgements

This work was carried out within a project financed by the Swedish Energy Agency (project no. 42194-1). Bio4Energy, a strategic research environment appointed by the Swedish government, is also gratefully acknowledged for the support.

CRediT authorship contribution statement

Chinedu M. Nwachukwu: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original draft, Writing – review & editing, Visualisation, Project administration. **Elias Olofsson**: Methodology, Software, Validation, Formal analysis, Investigation, Writing – review & editing, Visualisation, Project administration. **Robert Lundmark**: Supervision, Writing – review & editing, Funding acquisition. **Elisabeth Wetterlund**: Methodology, Software, Writing – review & editing, Supervision, Visualisation, Funding acquisition.

Appendix A

Table A1: Resulting plant locations in the All_bio-products *scenario.*

Plant location	Plant ID	Iteration_0	Iteration_1	Iteration_2	Iteration_3	Iteration_4	Iteration_5
Charcoal production							
Norrbotten	102	X					
Norrbotten	173			X	X		X
Norrbotten	261	X	X	X	X	X	X
Norrbotten	779			X	X	X	X
Östergötland	905	X					
Södermanland	31	X	X	X	X	X	X
Västerbotten	801					X	
Halland	903	X	X				
Product gas production							
Plant location	Plant ID	Iteration_0	Iteration_1	Iteration_2	Iteration_3	Iteration_4	Iteration_5
Dalarna	34	X	X	X	X	X	X
Dalarna	95	X	X	X	X	X	X
Dalarna	215	X		X		X	X
Dalarna	273	X	X	X	X	X	X
Gävleborg	39	X	X	X	X	X	X
Norrbotten	198	X	X	X	X	X	X
Östergötland	136				X		
Skåne	141	X	X	X	X	X	X
Värmland	590	X	X	X	X	X	X
Värmland	689	X	X	X	X	X	X
L-SNG production							
Plant location	Plant ID	Iteration_0	Iteration_1	Iteration_2	Iteration_3	Iteration_4	Iteration_5
Dalarna	783	X		X	X	X	X
Norrbotten	779		X				

In the *All_bio-products* scenario (Table A1), 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 A2: Resulting plant locations in the Charcoal *scenario*

		Charcoal production					
Plant location	Plant ID	Iteration_0	Iteration_1	Iteration_2	Iteration_3	Iteration_4	Iteration_5
Södermanland	31	X	X	X	X	X	X
Norrbotten	102	X					
Skåne	141			X	X	X	
Norrbotten	173			X	X	X	X
Norrbotten	261	X	X	X	X	X	X
Dalarna	783	X					X
Halland	903	X	X				

The *Charcoal* scenario (Table A2) 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 A3: Resulting plant locations in the Gas-fuels *scenario.*

		Product gas production					
Plant location	Plant ID	Iteration_0	Iteration_1	Iteration_2	Iteration_3	Iteration_4	Iteration_5
Dalarna	34	X	X	X	X	X	X
Dalarna	95	X	X	X	X	X	X
Dalarna	215	X	X	X	X	X	X
Dalarna	273	X	X	X	X	X	X
Gävleborg	39	X	X	X	X	X	X
Halland	269	X					
Norrbotten	198	X	X	X	X	X	X
Norrbotten	261	X					
Östergötland	136	X	X	X	X	X	X
Skåne	141	X	X	X	X	X	X
Södermanland	31	X	X	X	X	X	X
Södermanland	263	X	X	X	X	X	X
Värmland	73	X	X	X	X	X	X
Värmland	590	X	X	X	X	X	X
Värmland	689	X	X	X	X	X	X
Västmanland	53	X	X	X	X	X	X
Västmanland	681	X					
		L-SNG production					
Plant location	Plant ID	Iteration_0	Iteration_1	Iteration_2	Iteration_3	Iteration_4	Iteration_5
Västmanland	876		X	X	X	X	X

While the results for the Gas-fuels scenario (Table A3) 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.

References

[1] Worldsteel Association. Statiscal Yearbook 2018. 2018.

[2] Statistics Sweden. Sweden's exports n.d. https://www.scb.se/hitta-statistik/sverige-i-siffror/samhallets-ekonomi/sveriges-export/ (accessed May 9, 2020).

[3] Swedish Energy Agency. Energy in Sweden - Facts and Figures 2018. 2019.

[4] Swedish Environmental Protection Agency. Emissions of greenhouse gases from industry n.d. http://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-utslapp-fran-industrin/ (accessed April 21, 2020).

[5] Ministry of the Environment and Energy. The Swedish climate policy framework. 2017.

[6] WorldSteel Association. The three Rs of sustainable steel. Worldsteel Association 2010.

[7] Babich A, Senk D. Biomass use in the steel industry: back to the future? Stahl Und Eisen 2013;133:57–67.

[8] Mousa E, Wang C, Riesbeck J, Larsson M. Biomass applications in iron and steel industry: An overview of challenges and opportunities. Renewable and Sustainable Energy Reviews 2016;65:1247–66.

[9] Suopajärvi H, Umeki K, Mousa E, Hedayati A, Romar H, et al. Use of biomass in integrated steelmaking – Status quo, future needs and comparison to other low-CO_2steel production technologies. Applied Energy 2018;213:384–407.

[10] Bianco L, Baracchini G, Cirilli F. Sustainable Electric Arc Furnace Steel Production: GREENEAF. BHM Berg-Und Hüttenmännische Monatshefte 2013;158:17–23.

[11] Fick G, Mirgaux O, Neau P, Patisson F. Using biomass for pig iron production: A technical, environmental and economical assessment. Waste and Biomass Valorization 2014;5:43–55.

[12] Norgate T, Haque N, Somerville M, Jahanshahi S. Biomass as a source of renewable carbon for iron and steelmaking. ISIJ International 2012;52:1472–81.

[13] Suopajärvi H, Kemppainen A, Haapakangas J, Fabritius T. Extensive review of the opportunities to use biomass-based fuels in iron and steelmaking processes. Journal of Cleaner Production 2017;148:709–34.

[14] Buergler T, Donato A Di. Biomass gasification for DRI production. Revue de Métallurgie 2009:1–2.

[15] Johansson MT. Bio-synthetic natural gas as fuel in steel industry reheating furnaces - A case study of economic performance and effects on global CO_2 emissions. Energy 2013;57:699–708.

[16] Mathieson, J.; Rogers, H.; Somerville, M.; Ridgeway, P.; Jahanshahi S. Use of biomass in the iron and steel industry - An Australian perspective. InSteelCon 2011:1–10.

[17] Suopajärvi H, Pongrácz E, Fabritius T. Bioreducer use in Finnish blast furnace ironmaking - Analysis of CO_2 emission reduction potential and mitigation cost. Applied Energy 2014;124:82–93.

[18] Wang C, Mellin P, Lövgren J, Nilsson L, Yang W, et al. Biomass as blast furnace injectant - Considering availability, pretreatment and deployment in the Swedish steel industry. Energy Conversion and Management 2015;102:217–26.

[19] Olofsson E. Regional effects of a green steel industry – Fuel substitution and feedstock

competition. Scandinavian Journal of Forest Research 2019;34:39–52.

[20] Feliciano-Bruzual C. Charcoal injection in blast furnaces (Bio-PCI): CO2 reduction potential and economic prospects. Journal of Materials Research and Technology 2014;3:233–43.

[21] Mandova H, Patrizio P, Leduc S, Kjärstad J, Wang C, et al. Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. Journal of Cleaner Production 2019;218:118–29.

[22] Nwachukwu CM, Wang C, Wetterlund E. Exploring the role of forest biomass in abating fossil CO2 emissions in the iron and steel industry – The case of Sweden. Applied Energy 2021.

[23] Nwachukwu C. M, Toffolo A, Wetterlund E. Biomass-based gas use in Swedish iron and steel industry – Supply chain and process integration considerations. Renewable Energy 2020;146:2797–811.

[24] Johansson MT, Söderström M. Bio-syngas as fuel in the steel industry's heating furnaces : a case study on feasibility and CO2 mitigation effects. ECOS 2011 24th Int. Conf. Effic. Cost, Optim. Simul. Environ. Impact Energy Syst. July 4 - 7, 2011; Novi Sad, Serbia, 2011, p. 3842–53.

[25] Olofsson E, Lundmark R. Competition in the forest sector: an extensive review. 2018.

[26] Jåstad EO, Bolkesjø TF, Trømborg E, Rørstad PK. Large-scale forest-based biofuel production in the Nordic forest sector: Effects on the economics of forestry and forest industries. Energy Conversion and Management 2019;184:374–88.

[27] Mustapha WF, Bolkesjø TF, Martinsen T, Trømborg E. Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning. Energy Conversion and Management 2017.

[28] Pettersson K, Wetterlund E, Athanassiadis D, Lundmark R, Ehn C, et al. Integration of next-generation biofuel production in the Swedish forest industry – A geographically explicit approach. Applied Energy 2015;154:317–32.

[29] Kim J, Realff MJ, Lee JH, Whittaker C, Furtner L. Design of biomass processing network for biofuel production using an MILP model. Biomass and Bioenergy 2011;35:853–71.

[30] Leduc S, Natarajan K, Dotzauer E, McCallum I, Obersteiner M. Optimizing biodiesel production in India. Applied Energy 2009;86:S125–31.

[31] Mandova H, LEDUC S, Wang C, Wetterlund E, Patrizio P, et al. Possibilities for CO2 emission reduction using biomass in European integrated steel plants. Biomass and Bioenergy 2018;115:231–43.

[32] Krook-Riekkola A, Berg C, Ahlgren EO, Söderholm P. Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model. Energy 2017;141:803–17.

[33] Mustapha WF, Kirkerud JG, Bolkesjø TF, Trømborg E. Large-scale forest-based biofuels production: Impacts on the Nordic energy sector. Energy Conversion and Management 2019;187:93–102.

[34] Zetterholm J, Ahlström JM, Bryngemark E. Large-scale introduction of forest-based biorefineries: actor perspectives and the impacts of a dynamic biomass market. Biomass and Bioenergy 2020;142.

[35] Wetterlund E, Pettersson K, Mossberg J, Toren J, Hoffstedt C, et al. Optimal Localisation

of Next Generation Biofuel Production in Sweden – Part I. 2013.

[36] Zetterholm J, Pettersson K, Leduc S, Mesfun S, Lundgren J, Wetterlund E. Resource efficiency or economy of scale: Biorefinery supply chain configurations for co-gasification of black liquor and pyrolysis liquids. Applied Energy 2018;230:912–24.

[37] Ahlström JM, Zetterholm J, Pettersson K, Harvey S, Wetterlund E. Economic potential for substitution of fossil fuels with liquefied biomethane in Swedish iron and steel industry – Synergy and competition with other sectors. Energy Conversion and Management 2020;209:112641.

[38] Lundmark R, Athanassiadis D, Wetterlund E. Supply assessment of forest biomass - A bottom-up approach for Sweden. Biomass and Bioenergy 2015;75:213–26.

[39] Olofsson E. An introduction to the Norrbotten County Forest Sector Model - Technical report for a regional partial equilibrium model. 2018.

[40] Samuelson P. Spatial price equilibrium and linear programming. America Economic Review 1952;42:283–303.

[41] Takayama T, Judge G. Spatial Equilibrium and Quadratic Programming. Journal of Farm Economics 1964;46:67–93.

[42] Kallio AM, Dykstra DP, Binkley CS. The Global Forest Sector: An Analytical Perspective. 1987.

[43] Bolkesjø TF. Modeling supply, demand, and trade in the Norwegian forest secto. Agricultural University of Norway, Ås, 2004.

[44] Claesson S, Duvemo K, Lundström A, Wikberg P-E. Skogliga konsekvensanalyser 2015 – SKA15. Skogsstyrelsen rapport nr. 10 (In English: Forest impact assessments 2015. Swedish Forest Agency report no. 10). Jönköping: 2015.

[45] Bäckström D, Johansson R, Andersson K, Wiinikka H, Fredriksson C. On the use of alternative fuels in rotary kiln burners - An experimental and modelling study of the effect on the radiative heat transfer conditions. Fuel Processing Technology 2015;138:210–20.

[46] Swedish Forest Industry Federation (SFIF). Statistics 2016. https://www.forestindustries.se/forest-industry/statistics/ (accessed October 23, 2020).

[47] Swedish Forest Agency. Swedish Statistical Yearbook of Forestry. 2014.

[48] SDC. Skogsindustrins virkesförbrukning samt produktion av skogsprodukter 2011- 2016. (In English: The forest industry's timber consumption and production of forest products 2011-2016). 2017.

[49] Swedish Forest Industry Federation (SFIF). Database of member companies. 2015.

[50] Bioenergitidningen and Svebio. Pellets i Sverige 2017 (Pellets in Sweden 2017). 2017.

[51] Swedish District Heating Association. Statistics over fuels and deliveries in Swedish district heating systems 2009 - 2018. n.d.

[52] Gunarathne DS, Mellin P, Yang W, Pettersson M, Ljunggren R. Performance of an effectively integrated biomass multi-stage gasification system and a steel industry heat treatment furnace. Applied Energy 2016;170:353–61.

[53] Ahlström JM, Pettersson K, Wetterlund E, Harvey S. Value chains for integrated production of liquefied bio-SNG at sawmill sites – Techno-economic and carbon footprint evaluation. Applied Energy 2017;206:1590–608.

[54] Antal Jr MJ, Grönli M. The art, science, and technology of charcoal production. Industrial and Engineering Chemistry Research 2003;42:1619–40.

[55] Leme MMV, Venturini OJ, Lora EES, Rocha MH, Luz FC, et al. Electricity generation from pyrolysis gas produced in charcoal manufacture: Technical and economic analysis. Journal of Cleaner Production 2018;194:219–42.

[56] Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J. Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. Environmental Science and Technology 2010;44:827–33.

[57] European Central Bank. ECB euro reference exchange rate 2018. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html (accessed October 12, 2018).

[58] SCB. Karta över NUTS-indelningen i Sverige (t.o.m. 2007-12-31) n.d. https://www.scb.se/contentassets/4e32573a1c8f46d1a5ca29e381fb462f/nutskarta-2_3_tom2007.pdf (accessed March 17, 2021).

[59] de Jong S, Hoefnagels R, Wetterlund E, Pettersson K, Faaij A, Junginger M. Cost optimization of biofuel production – The impact of scale, integration, transport and supply chain configurations. Applied Energy 2017;195:1055–70.

[60] Danielsson B. Uppskattning av sågverkens produktion av trädbränslen inom mål 1-området i Dalarna-Gävleborg. Bioenergi i WX Mål. (In English: Estimation of the sawmills' production of wood fuels within the Objective 1-area in Dalarna-Gävleborg. Bioenergy in WX Goals). 2003.

[61] Geijer E, Bostedt G, Brännlund R. Damned if you do, damned if you do not-Reduced Climate Impact vs. Sustainable Forests in Sweden. Resource and Energy Economics 2011;33:94–106.

[62] Börjesson P, Lantz M, Andersson J, Björnsson L, Fredriksson Möller B, et al. Methane as vehicle fuel - A well-to-wheel analysis (METDRIV). 2016.

[63] European Commission JRC. Elcd data sets - Version 3 2016.

[64] Network for Transport Measures. NTMcalc basic 4.0 environmental performance calculator 2017.

[65] Wiklund C-M, Helle M, Kohl T, Järvinen M, Saxén H. Feasibility study of woody-biomass use in a steel plant through process integration. Journal of Cleaner Production 2017;142:4127–41.

[66] Holmgren KM. Investment cost estimates for biomass Investment cost estimates for gasification- based biofuel production systems. 2015.

[67] Sandbag. Carbon Price Viewer n.d. https://sandbag.org.uk/carbon-price-viewer/ (accessed September 20, 2019).

[68] IEAGHG. Iron and Steel CCS Study (Techno-economics Integrated Steel Mill). 2013.

[69] European Commission. Quarterly Report on European Gas Markets. 2018.

[70] Swedish Energy Agency. Energy in Sweden 2017. 2018.

[71] SCB. Energy prices on natural gas and electricity 2018.

[72] Swedish Energy Agency. Växthusgasberäkning (in Swedish) n.d.

[73] Anheden M, Ehn C, Lundberg V, Pettersson K, Fugelsang M, Hjerpe C. Value chains for

production of renewable transportation fuels using intermediates. 2016.

[74] Swedish Forest Agency. Prices on roundwood 2018.

[75] Swedish Energy Agency. Wood fuel- and peat prices 2018.

[76] Murray BC, Prestemon JP. Structure And Efficiency Of Timber Markets. Forest in a Market Economy 2003;72:153–76.