Background:

The BeWhere model was developed initially at IIASA[1] and has been already extensively adapted multiple ways to study problems related to, for example, finding optimal locations for bioenergy production technologies, decreasing energy costs or examining feasibility of new technologies on national as well as continental levels. The modification of BeWhere in the present paper used the previously developed BeWhere Europe and extended its use for iron and steel industry by restructuring the model in such a way that all industries following uniform structure: Raw materials -> Upgrading technology -> Bio-product -> Demand, as shown in the Figure below. For the demand that uses raw material (such as sawmills), artificial technology and artificial by-products with conversion efficiency equal to 1 were introduced, so that the model structure is preserved, whilst enabling the process steps currently or potentially used for biomass to be included.

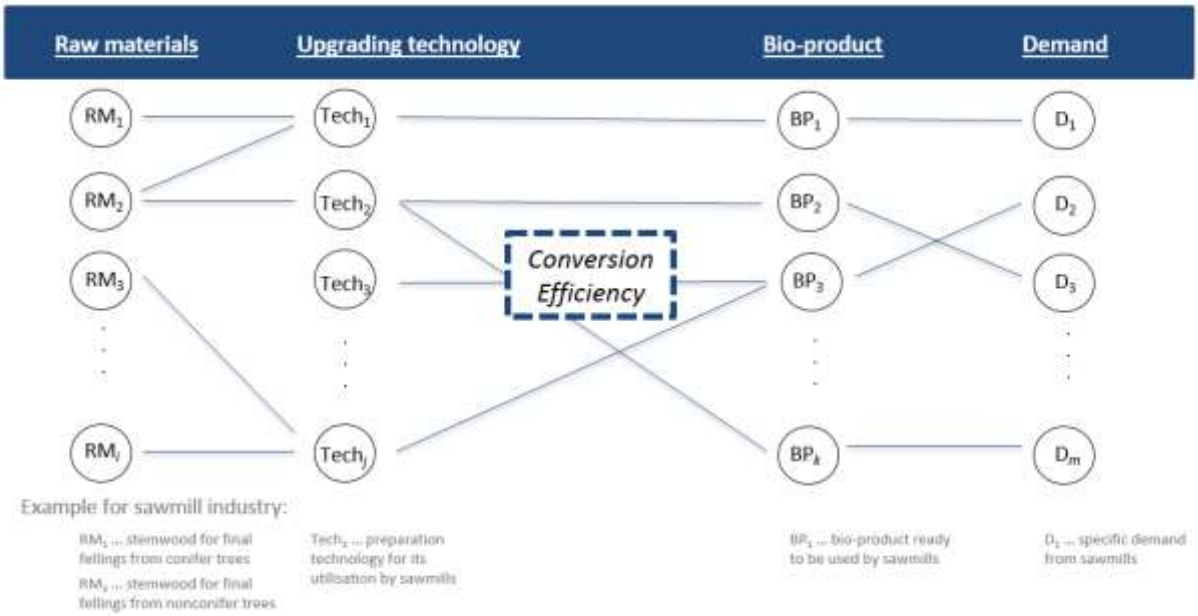

Figure 1 BeWhere structure used for the current work.

Below is description of the modified BeWhere model, focusing specifically on the model development in the present paper for the iron and steel application.

Nomenclature:

Indices:

C	Set of all 28 countries within the European Union
P	Set of all plants for which biomass demand is considered
Tech	Set of all upgrading technologies that will be able to produce the bio-product suitable for the specific demand
RM	Set of all raw materials considered within this study

[1] IIASA. (2015). BeWhere. Retrieved October 16, 2017, from http://www.iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/BEWHERE/BEWHERE.en.html

Hd	Import point for biomass from different country
S	Supply location of biomass feedstock

<u>Positive variables</u>:

* Indicates further details can be found in previous literature on the BeWhere model

$\mathrm{TOTCOST}_C$	Total cost of the studied system (M€)
$\mathrm{TOTEMISSIONS}_C$	Total CO_2 emissions occurred within the studied system (Mt)
$CostBM_{C,P,Tech,RM}$	*Cost of biomass that has been domestically supplied (M€)
$CostBiomassTrade_C$	*Cost of biomass imported from other EU country (M€)
$CostBMTransport_{C,P,Tech,RM}$	*Cost of biomass transport (M€)
$CostProduction_{C,P,Tech}$	*Cost of biomass upgrading using a specific technology (M€)
$CostFossilFuelSteel_C$	Cost of coals used within iron and steel industry (M€)
$EmissionSteel_C$	Emissions resulting from coal use within iron and steel industry (Mtonne CO_2)
$XFossilCokingCoal_P$	Amount of coking coal used which is fossil based (PJ)
$XBioCokingCoal_{P,Tech,BP}$	Amount of coking coal used which comes from biomass (PJ)
$XFossilCoke_P$	Amount of Coke that is fossil based (PJ)
$XBioCoke_{P,Tech,BP}$	Amount of coke used which comes from biomass (PJ)
$XFossilPCI_P$	Amount of PCI that is fossil based (PJ)
$XBioPCI_{P,Tech,BP}$	Amount of PCI used which comes from biomass (PJ)
$SteelEmissionsCokingCoal_C$	Emission intensity of coking coal (Mt PJ^{-1})
$SteelEmissionsCoke_C$	CO_2 emission intensity of coke (Mt PJ^{-1})
$SteelEmissionsPCI_C$	CO_2 emission intensity of PCI (Mt PJ^{-1})
$BSP_{S,RM,P,Tech}$	*Raw material RM delivered from supply region S to plant P, which should be upgraded by technology Tech
$BIMP_{Hd,RM,P,Tech}$	*Raw material RM which is imported from import-point Hd

<u>Binary variables</u>:

$BFBinary_P$	Binary variable selecting either coking coal substitution or coke substitution, to consider material flow within the plant and prevent double counting

Parameters:

$CarbonPrice_C$	CO_2 price set for each country (in this evaluation same carbon price was set for all countries) (€ t^{-1})
$priceFossilCokingCoal_C$	Market price of coking coal – due to limited data availability, same price is considered for all countries (M€ PJ^{-1}}
$priceFossilCoke_C$	Market price of coke – due to limited data availability, same price is considered for all countries (M€ PJ^{-1}}
$priceFossilPCI_C$	Market price of PCI – due to limited data availability, same price is considered for all countries (M€ PJ^{-1}}
$SteelCokeDemand_P$	Total demand for coke by each plant (PJ)
$SteelPCIDemand_P$	Total demand for PCI by each plant (PJ)
$CostByProducts$	Scaling parameter introduced in the present work to balance the model, as the monetary value of the produced by-products produced during coking was not consider here
$EnergyByProducts$	Scaling parameter introduced in the present work to balance the model from the energy perspective, as utilisation of the by-products is not considered
$EmissionByProducts$	Scaling parameter introduced in the present work to balance the model from the emission perspective, as the offset emissions from by-products utilisation is not considered
$plantEfficiency_{P,Tech,BP}$	Amount of energy preserved during conversion of raw biomass into a specific bio-product, using a specific technology
$Calibration_{Tech}$	Balancing parameter to define 1.1 unit of bio-based energy input for every unit of fossil energy input for low grade bio-based products such as wood pellets, hydrochar and torrefied fuel.

Model description:

The idea of BeWhere model is to find optimum use of biomass in Europe, evaluated based on cost. Emissions are integrated into the model by multiplying them by a monetary value, considered here as the carbon price. The objective function is therefore defined as:

Objective function:

$$\min \sum_{C} (\mathrm{TOTCOST}_C + \mathrm{TOTEMISSIONS}_C \times \mathrm{CarbonPrice}_C)$$

Where

$$\text{TOTCOST}_C = \sum_{P,Tech,RM} CostBM_{C,P,Tech,RM} + \sum_{P,Tech,RM} CostBMTransport_{C,P,Tech,RM} + CostBiomassTrade_C + \sum_{P,Tech} CostProduction_{C,P,Tech} + CostFossilFuelSteel_C$$

and

$$\text{TOTEMISSIONS}_C = EmissionSteel_C,$$

which is a modification of previous studies where TOTEMISSIONS_C considered also emissions resulting from biomass supply chain.

Details on $CostBM_{C,P,Tech,RM}$, $CostBMTransport_{C,P,Tech,RM}$, $CostBiomassTrade_C$, $CostProduction_{C,P,Tech}$ as well as constraints related to:

- Biomass supply
- Biomass trade
- Capacity of each pre-processing and upgrading plants

can be found in previous literature, for example by Leduc et. al (2009)[2], Leduc (2009)[3], Leduc et. al (2010)[4], Wetterlund (2010)[5] and Wetterlund et. al (2012)[6].

The following model description is related specifically to BeWhere for iron and steel industry. Total costs which results from using fossil fuels is summed within variable $CostFossilFuelSteel_C$. It contains costs related to coking coal or coke use as well as PCI. Coking coal price is scaled down using parameter $CostByProducts$ to take into consideration that some of the input energy will end up within the by-products, which are then used as fuel somewhere else. The used value for $CostByProducts$ is 0.975, which is the ratio of total cost of coke against total cost of coking coal. See Fossil_Steel tab in the supplementary material for further details.

$$CostFossilFuelSteel_C = \sum_P priceFossilCokingCoal_C \times XFossilCokingCoal_P \times CostByProducts + \sum_P priceFossilFossilCoke_C \times XFossilCoke_P + \sum_P priceFossilPCI_C \times XFossilPCI_P$$

Amount of coking coal, coke and PCI used within the model is represented by $XFossilCokingCoal_P$, $XFossilCoke_P$ and $XFossilPCI_P$, respectively. To prevent possibilities where biomass is substituting coking coal as well as coke, which can cause double counting, binary variable $BFBinary_P$ was

[2] Leduc, S., Schmid, E., Obersteiner, M., & Riahi, K. (2009). Methanol production by gasification using a geographically explicit model. Biomass and Bioenergy, 33(5), 745–751.
[3] Leduc, S. (2009). Development of an optimization model for the location of biofuel production plants, PhD Thesis. Thesis. Luleå University of Technology.
[4] Leduc, S., Lundgren, J., Franklin, O., & Dotzauer, E. (2010). Location of a biomass based methanol production plant: A dynamic problem in northern Sweden. Applied Energy, 87(1), 68–75.
[5] Wetterlund, E. (2010). Interim report: Optimal localization of biofuel production on a European scale. IIASA publications.
[6] Wetterlund, E., Leduc, S., Dotzauer, E., & Kindermann, G. (2012). Optimal localisation of biofuel production on a European scale. Energy, 41(1), 462–472.

introduced to give each plant a selection of where bioenergy will be utilised. As more energy is required initially, before coke over rather than after coke over, the demand for coking coal is scaled by parameter $EnergyByProducts$ to preserve energy balance within the model. The value for $EnergyByProducts$ is 1.38, which is the ratio of coking coal demand and coke demand energy input per tonne of crude steel.

Same as for the fossil fuel case, the amount of biomass used to substitute coking coal, coke and PCI is represented by $XBioCokingCoal_{P,Tech,BP}$, $XBioCoke_{P,Tech,BP}$ and $XBioPCI_{P,Tech,BP}$, respectively. As wood pellets, hydrochar and torrefied fuel are lower grade fuels, the model assumes 1 unit of fossil-based material will require substitution of 1.1 unit of bio-based material. This is done using $Calibration_{Tech}$ parameter, which contains value 1.1 for wood pellets, hydrochar and torrefied fuel. Charcoal is considered in this analysis as high-grade fuel, therefore substitution 1 to 1 is assumed. (For this reason, $Calibration_{Tech}$ is not used within the $XBioCokingCoal_{P,Tech,BP}$ and $XBioCoke_{P,Tech,BP}$ equations and contains value 1 when dividing $XBioPCI_{P,Tech,BP}$.)

$$XFossilCokingCoal_P + \sum_{Tech,BP} XBioCokingCoal_{P,Tech,BP} = BFBinary_P \times SteelCokeDemand_P \times EnergyByProducts$$

$$XFossilCoke_P + \sum_{Tech,BP} XBioCoke_{P,Tech,BP} = (1 - BFBinary_P) \times SteelCokeDemand_P$$

$$XFossilPCI_P + \sum_{Tech,BP} \frac{XBioPCI_{P,Tech,BP}}{Calibration_{Tech}} = SteelPCIDemand_P$$

Amount of biomass required to supply a production of the specific bio-product that would replace the corresponding coal type is described in the equations below. Amount of produced bio-product from nationally sourced as well as imported biomass is calculated based on energy retention efficiency, described as $plantEfficiency_{P,Tech,BP}$ in the following equations.

$$XBioCokingCoal_{P,Tech,BP} = plantEfficiency_{P,Tech,BP} \times \left(\sum_{S,RM} BSP_{S,RM,P,Tech} + \sum_{Hd,RM} BIMP_{Hd,RM,P,Tech} \right)$$

$$XBioCoke_{P,Tech,BP} = plantEfficiency_{P,Tech,BP} \times \left(\sum_{S,RM} BSP_{S,RM,P,Tech} + \sum_{Hd,RM} BIMP_{Hd,RM,P,Tech} \right)$$

$$XBioPCI_{P,Tech,BP} = plantEfficiency_{P,Tech,BP} \times \left(\sum_{S,RM} BSP_{S,RM,P,Tech} + \sum_{Hd,RM} BIMP_{Hd,RM,P,Tech} \right)$$

Calculation of the costs, transport and emissions which correspond to using specific $BSP_{S,RM,P,Tech}$ and $BIMP_{Hd,RM,P,Tech}$ then follow previous BeWhere structure, and can be found in the previously mentioned literature on BeWhere.

Total emissions from steel plants are sum of all coking coal, coke and PCI used, multiplied by their corresponding emission factors ($SteelEmissionsCokingCoal_C$, $SteelEmissionsCoke_C$, $SteelEmissionsPCI_C$), which calculation is provided in the supplementary material. As the values for the each specific plant from $SteelEmissionsCokingCoal_C \times XFossilCokingCoal_P$ and would not give the same emission intensity, due to $SteelEmissionsCoke_C$ not taking into account the emission intensity of coke production, a scaling factor has been applied. $EmissionByProducts$ contains value 1.15, which is the ratio of coking coal emission intensity and coke emission intensity per tonne of crude steel.

$$EmissionSteel_C = \sum_P SteelEmissionsCokingCoal_C \times XFossilCokingCoal_P + \sum_P SteelEmissionsCoke_C \times XFossilCoke_P \times EmissionByProducts + \sum_P SteelEmissionsPCI_C \times XFossilPCI_P$$