Bioenergy with or without carbon dioxide removal: influence of functional unit choice and parameter variability

Supplementary material

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Choice of functional unit

When performing a comparative LCA with substitution as allocation method, systems, functions, reference activities and functional units are defined. As an example, a system, S, is defined, with three functions and three corresponding reference activities. S produces the amounts a_1, a_2, and a_3 of Function 1, Function 2 and Function 3, respectively, and the reference activities, b_1, b_2, b_3, produce one unit of their corresponding function (Fig. S1). The functional unit can then be represented by an array, F, with the entries y_1, y_2 and y_3, which are the amounts of Function 1, Function 2 and Function 3 that are defined for F, respectively. The entire system S can be represented in a technosphere matrix A (Table S1) with the corresponding array F, and the emission factors, $EF_j, j = S, 1, 2, 3$, for each activity. Furthermore, I is defined as the impact of the entire system studied when fulfilling F (including both S and reference activities).

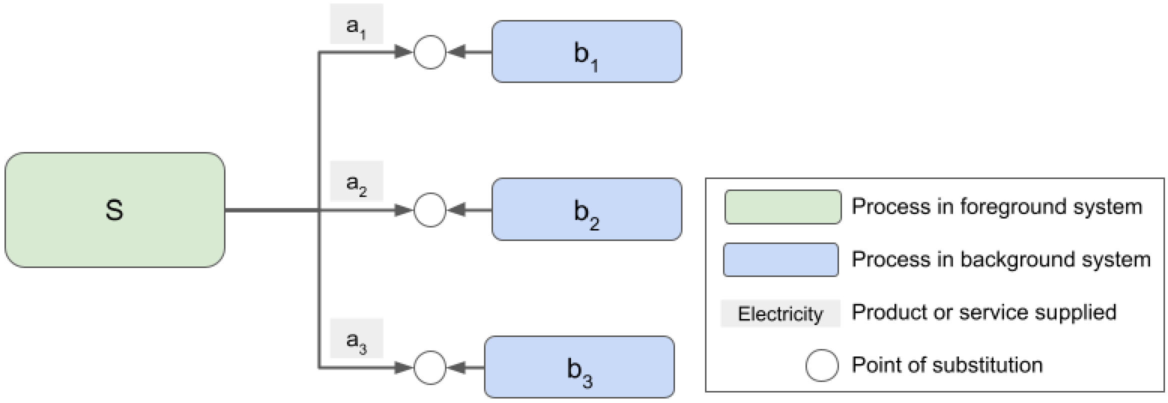

Figure S1. Conceptual flowchart of a system, S, which produces the amounts a_1, a_2 and a_3 of the defined functions, Function 1, Function 2 and Function 3. The reference activities, b_1, b_2, b_3, fulfil the same function as the functions from S, respectively.

Table S1. The corresponding technosphere matrix, A, for system S, with the respective emission factors and the functional unit, which is represented as the array F.

A	**S**	**b_1**	**b_2**	**b_3**
Function 1	a_1	1	0	0
Function 2	a_2	0	1	0
Function 3	a_3	0	0	1

F
y_1
y_2
y_3

Emission factors	EF_S	EF_1	EF_2	EF_3

Calculating impacts for a given system and functional unit

Case 1: Single function functional unit

The functional unit is defined as function i in quantity y_i and no other functions. The function is to be delivered from S only, therefore the reference activity producing the function i is not part of the impact. The other functions from S must be accounted for by system expansion. The impact of the system is:

$$I = \frac{y_i}{a_i} EF_S - \frac{y_i}{a_i} \sum_{j \neq i} a_j \, EF_j \qquad \text{Equation S1.}$$

In this expression, the first term corresponds to emissions from the studied activities, and the second part corresponds to substitutions of the co-functions, avoiding generation of the same functions from reference activities.

Case 2: Multifunction functional unit

The functional unit is defined for two functions: function i_1 in quantity $y_{i_1}$and function i_2 in quantity y_{i_2}. There are now two options to solve the system: either the studied activity S delivers fully function i_1 (and thus the reference activity for i_1 is not needed) or vice versa with function i_2. In the first case, where i_1 is fully delivered by the studied activity S, the impact is:

$$I = \frac{y_{i_1}}{a_{i_1}} EF_S + \left(y_{i_2} - \frac{y_{i_1}}{a_{i_1}} a_{i_2}\right) EF_{i_2} - \frac{y_{i_1}}{a_{i_1}} \sum_{j \notin \{i_1, i_2\}} a_j \, EF_j \qquad \text{Equation S2}$$

General expression

The calculated impact for a system and a functional unit can therefore be expressed as the following, where Function 1 is fully delivered from the system and y_j is equal to 0 if Function j is not defined in the functional unit:

$$I = \frac{y_{i_1}}{a_{i_1}} EF_S + \sum_{j \neq i_1} \left(y_j - \frac{y_{i_1}}{a_{i_1}} a_j\right) EF_j \qquad \text{Equation S3}$$

Ranking and equivalent functional units

When comparing several systems, as has been done in this study, it is interesting to analyse the impacts in relation to each other; in particular, the differences between the impacts of two systems. These differences in impacts between pairs of systems yield a ranking, i.e. a list of the systems in the order of the lowest to highest impacts. Assuming that the impact will be calculated by several different functional units, it is possible that some of the functional units will yield the same ranking between systems, irrespective of data from the life cycle inventory. These groups of functional units are hereafter referenced to as equivalent functional units.

Definition: Equivalent functional units

When comparing n systems, $S_1, S_2, \ldots, S_n$, the ranking will be determined by the difference in impact between the systems, which is defined as the following:

$$R_{i,j} = I_i - I_j \, , i \neq j \qquad \text{Equation S4}$$

where I_i is the impact for system i and I_j is the impact for system j.

Two functional units, a and b, are said to be equivalent when comparing systems $S_1, S_2, \ldots, S_n$ if the following two equations have the same solutions for all pairs of systems i and j:

$$R_{i,j_a} > 0, R_{i,j_b} > 0, i \neq j \qquad \text{Equation S5}$$

where R_{i,j_a} is the difference in impacts calculated for functional unit a and vice versa for functional unit b.

Difference in impacts

Two systems, S_1 and S_2 deliver n different functions: $f_1, f_2, \dots, f_n$. For every amount a_{i1} of function f_1 delivered from system S_i, the system also delivers a_{ij} of function f_j, $i = 1, 2$, $j = 1,2, \dots n$. All functions have reference activities defined, where b_1 is the reference activity to f_1, etc. The functional unit is defined for function p_i in quantity y_i, $i = 1, 2, \dots, n$.

The difference in impacts between S_1 and S_2 is

$$R_{1,2} = \frac{y_i}{a_{1i}} EF_{S_1} - \frac{y_i}{a_{2i}} EF_{S_2} + \sum_{j \neq i} \left(\frac{y_i}{a_{1i}} a_{1j} - \frac{y_i}{a_{2i}} a_{2j} \right) EF_j \qquad \text{Equation S6}$$

where function i is the function that is fully delivered from the systems.

It is now clear that the amount of the functions in the functional unit, other than function i, will not affect the expression R, since they are not present in the expression. This means that all functional units which have the same function fully delivered from the system will have the same ranking, assuming that $y_i > 0$. However, there is no information regarding how the differences relate to each other when the same functions are not fully delivered from the system.

LCI Data

Table S2. Ecoinvent activities used in the LCI model.

Ecoinvent activity	Description	System (CHP, BECCS, BC)
Ash treatment		
Forwarding, forwarder, RER	Spreading of ashes	All
Biomass extraction		
Forwarding, forwarder, RER	Transport of biomass from forest to roadside	All
Wood chipping, mobile chipper, at forest road, RER	Chipping of wood	All
Reference activities		
Electricity production, hard coal, DE	Substitution for electricity generation	All
Electricity production, natural gas, 10MW, DE	Substitution for electricity generation	All
Electricity production, wind, 1-3MW turbine, onshore, SE	Substitution for electricity generation	All
Heat production, heavy fuel oil, at industrial furnace 1MW, Europe without Switzerland	Substitution for heat production	All
Heat production, natural gas, at industrial furnace >100kW, Europe without Switzerland	Substitution for heat production	All
Heat production, wood chips from industry, at furnace 5000kW, state-of-the-art 2014. CH	Substitution for heat production	All
Sand, gravel and sand quarry operation, CH	Substitution for landscaping soil	BC
Peat moss, peat moss production, horticultural use, CA-QC	Substitution for landscaping soil	BC
Transportation		
Transport, freight, lorry 16-32 metric ton, EURO5, RER	Transportation of biomass, biochar, ashes and landscaping soil.	All
Transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas, GLO	Transportation of CO_2.	BECCS.

System description
All systems are assumed to emit 0.011 g of methane and 0.006 of nitrous oxide per MJ of biomass during combustion and pyrolysis, assuming that all plants are equipped with advanced flue gas cleaning technologies (Azzi et al, 2019). For CHP and BECCS systems, it is assumed that 2.5% of the biomass is left as ashes after combustion. For the Biochar system, 0.5% of the biomass is assumed to be left as ashes after pyrolysis. After production, the biochar from the Biochar system is mixed with peat and sand and the mix is used as landscaping soil.

Transports
All transports are assumed to be by lorry, except for transport of CO_2. These transports are transport of biomass from location of biomass harvesting to power plant, of ashes from power plant to landfill, transport of biochar from power plant to location of application, as well as transport of reference landscaping soil. The CO_2 captured from the BECCS system is liquefied, stored in an intermediary storage, transported away by ship and stored in a second intermediary storage before it is transported by pipeline and injected into the final storage (Erlandsson and Tannoury, 2020).

Reference activities
Extracting one tonne of biomass reduces the forest stock of carbon by 89.1 kg CO_2-eq (Hammar et al, 2019); therefore, using one tonne of biomass is set equivalent to emitting the same amount of greenhouse gases.

The biochar from the pyrolysis plant is assumed to be used as landscaping soil; therefore, the corresponding reference activity is the same amount of conventional landscaping soil, measured in cubic meters. One cubic meter of conventional landscaping soil is assumed to be made by 0.5 cubic meters of peat and 950 kg of sand (Azzi, 2022), and the transport distance from production to site of use is assumed to be about 100 km.

Parameters
For parameters with a normal uncertainty distribution, the maximum and minimum values were defined by setting the possible interval as three standard deviations added and subtracted to the median values, respectively. For each functional unit, the impact of a system is computed as an algebraic expression, containing all foreground parameters and possible reference activities as variables, and all background inputs (from the database) as numerical values. Algebraic expressions allow for fast computations of statistical distributions (Jolivet, 2020).

Results

Table S3: Biomass use [tonnes] for each other functional unit and system.

Functional unit	System	Mean value	Median value	Standard deviation
1 GJ heat produced	CHP	0.080	0.079	0.0086
	BC	0.14	0.14	0.022
	BECCS	0.065	0.064	0.0070
1 MWh electricity produced	CHP	0.61	0.61	0.065
	BC	1.23	1.19	0.30
	BECCS	1.58	1.56	0.23
1 kg CO_2 sequestered	BC	0.0018	0.0017	0.00042
	BECCS	0.00067	0.00067	0.000049

Decision trees
In each decision node, the following is showed: the decision criteria, the number of scenarios considered, for how many of these scenarios each system has the lowest climate impact and is therefore preferable, and the system which is preferable for the majority of cases. The color indicates which system wins, and the stronger the color, the higher the share for the majority. The data is then further divided, where a left arrow indicates that the decision criteria is true, and a right arrow indicates that it is false. For the discrete parameters, the decision criteria are given as e.g. “elecWindpower <= 0.5”. The right arrow here indicates that the reference electricity is wind power, and the left indicates that the reference electricity is something else, i.e. either natural gas or coal. For these trees, the maximum depth is three, i.e. the trees only generate three levels of decision nodes, in order not to make them enormous.

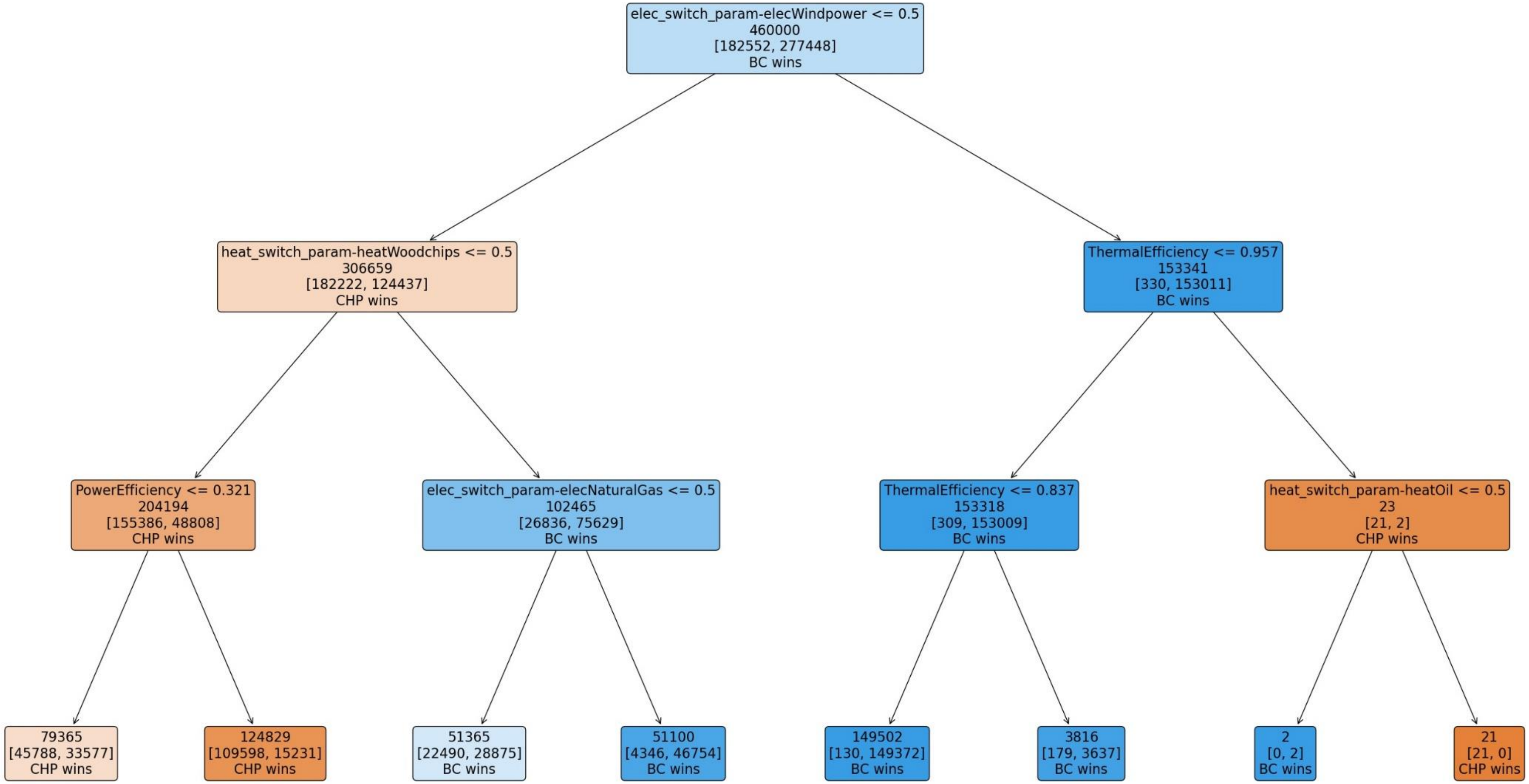

Figure S2. Decision tree for Biochar and CHP system with biomass usage as FU. Biochar is shown as blue, CHP is shown as red.

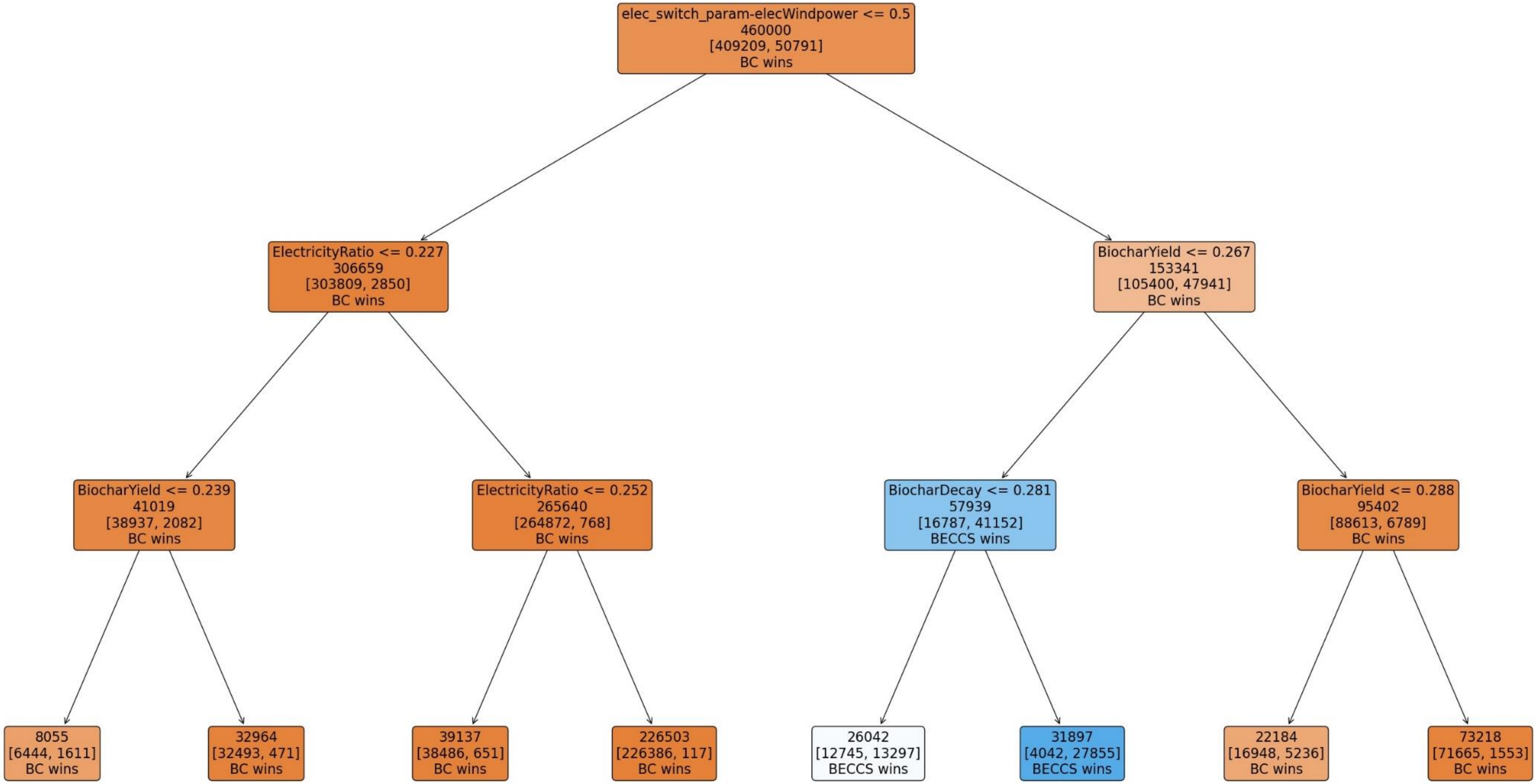

Figure S3. Decision tree for BECCS and Biochar with heat as FU. BECCS is shown as blue, Biochar is shown as red.

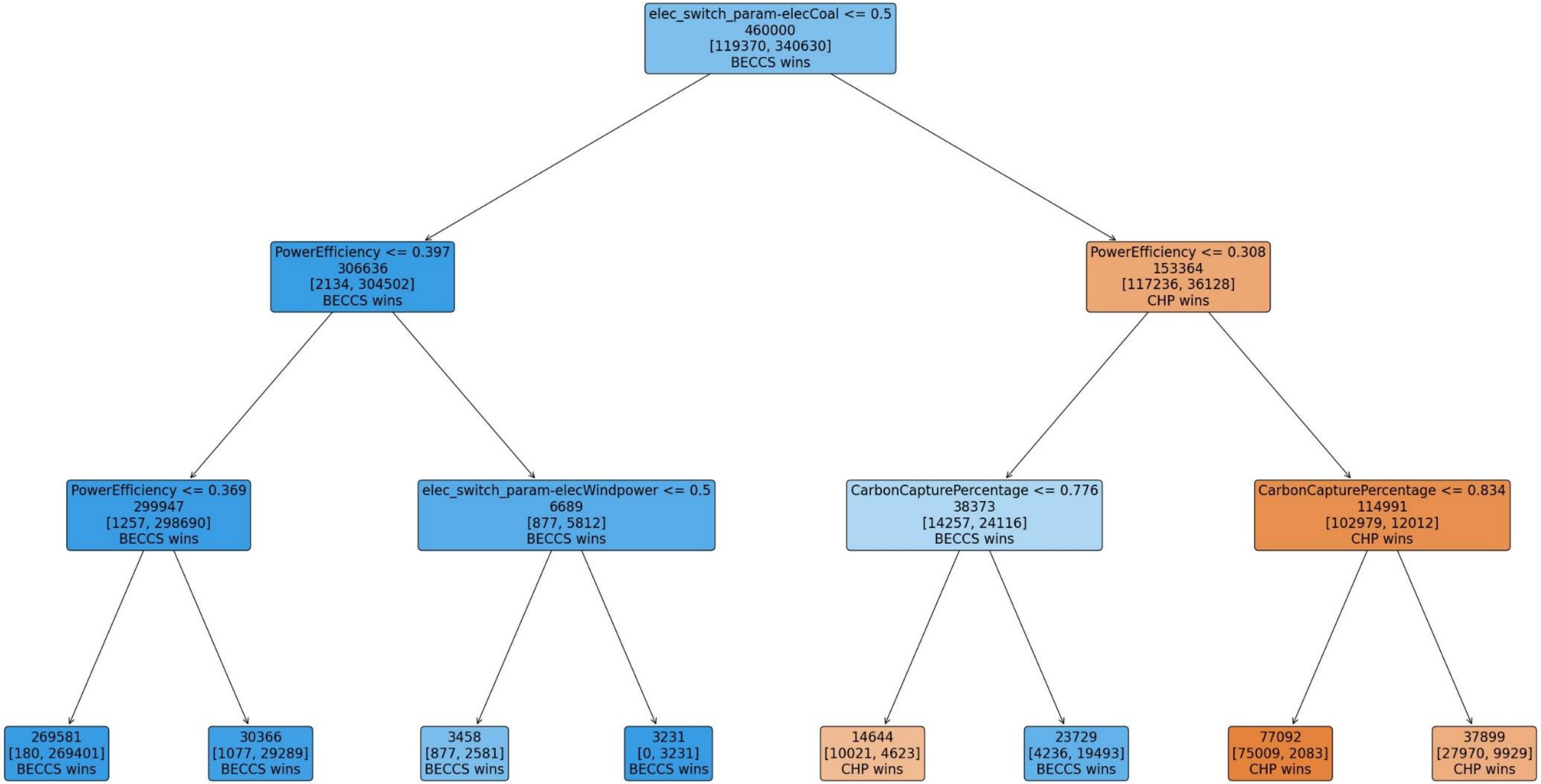

Figure S4. Decision tree for BECCS and CHP with heat as FU. BECCS is shown as blue, CHP is shown as red.