Land use change and electricity models in a multi-regional hybrid inpunt output framework

S. Merciai and J. Schmidt (2.-0 LCA consultants)

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Abstract

The purpose of this paper is to present an extended version of the hybrid version of the multiregional Input-Output table (MR-HIOT) EXIOBASE v.3. The extensions include cause-effect based modelling of indirect land use changes (iLUC) and electricity markets. The paper examines the effect on selected product groups from the inclusion of iLUC and the electricity model.

In the multi-regional hybrid supply-use tables (MR-HSUTs), which are used to derive the input-output tables, tangible goods are accounted in metric tons, energy flows in TJ, and services in euros. The HSUTs respect mass, energy and monetary balances. The extensions include emissions, stock addition, stock reduction/depletion, supply and use of waste, supply and use of packaging, extraction of resources, use and withdrawal of water and land use. The MR-HIOT presented here adopts a generalized version of the by-product technology model (Stone's method).

The generalized by-product technology model extends the Stone's method to a multi-regional framework and focuses on the respect of mass balance, whenever by-products substitute products with different properties produced elsewhere as principal productions.

The electricity model introduces the concept of national electricity grid where only non-constrained and competitive producers react to changes in demand. The electricity model was introduced by Schmidt et al. (2011).

The iLUC model considers the substitution effects of the land use. The model was introduced by Schmidt et al. (2015). It simulates the effect of the substitution of land anytime a new production comes into place in any region of the world. Depending on the peculiarities of a country, the new demand of land may be obtained either by intensification the crops or occupying new land, i.e. forest or grassland. The emissions due to intensification and land use changes are taken into account.

The transaction matrix presented in this paper has a format 8213x8213; 164 products for 48 countries/world regions, 48 national electricity markets, six types of national land use markets for each of the 48 regions, and 5 world land use markets.

Introduction

Input-output tables (IOTs) are an excellent tool for modelling the structure of economies. IOTs have been used for several types of analyses, from economic to environmental sphere[1]. They are built using observed data, usually the time period is one year. Therefore, the structure of the economies is built considering what has been observed in that period.

During one year, new activities open, while some others already existing may close. Models based on IOTs are so constructed on average productive recopies that take into account all the activities in that period. In this context, average behaviours describe economies but may have some limitations when a change of the production capacity is at stake. If the aim of the analysis is to simulate the expansion, or a reduction, of an economy, average productive functions may fail the target. In other words, when it is required to know what technology will be used to produce an additional product, the average technology may result to be an incorrect answer. We define the technology used for the production of an additional or a change in demand as *marginal.*

In the economic literature, this issue is known since long and has been treated with dynamic input-output models, general economic models, etc. Within the industrial ecology community, the introduction of marginal producers is a core issue of the *consequential life-cycle analysis (CLCA)*[2], which opposes to the *attributional LCA* that makes use of average recopies [3] [4].

In this paper, we focus on the *marginal production of electricity* and on the *marginal* effects induced by a change in demand for land. The objective is to internalize these two models in the multi-regional hybrid supply-use tables (MR-HSUTs) of EXIOBASE v3[5,6]. For this aim, we define a rule for the choice of the marginal producers of electricity and for the marginal use of land, which will be activated when an addition product is requested. The internalization of marginal producers will occur adding new activities that we define as *markets.* Therefore the MR-SUTs will move from a 9660x7872 to a 9941x8231 product by activity framework. This is the first time that the concept of marginal producers/use of land are applied to such detailed multi-regional framework accounted in mixed units.

In the paper, the rule for choosing marginal producers will be explained in the Methodology section. Once internalized the marginal producers, it will be shown in the Results section how these two models affect the product footprints.

Methodology

The starting point of the procedure is the time series 2000-2011 of EXIOBASE v3 MR-HSUTs. These tables are constructed in mixed unit, i.e. tonnes for accounting tangible goods, TJ for intangible energy flows (e.g. electricity) and euros for services. MR-HSUTs are built respecting mass and electricity balances.

The MR-HSUTs have been further extended by internalization of the electricity model [7] and the iLUC model[8]. The electricity model tries to define what will be the marginal mix for any of the 48 regions included in EXIOBASE if an additional unit of electricity is requested. The iLUC models aims to define what will be the effects when in one region additional land is requested. Of course, the ultimate goal is that of calculating the impact due to marginal changes of the modern economies.

Figure 1 shows how it is the original MR-HSUTs and how have been extended. For convention, we use positive values to indicate outputs and negatives for inputs. On the left side there is the EXIOBASE MR-HSUTs with some selection of extensions that would be modified by the current procedure. On the right it can be seen the extended version obtained internalizing the electricity and the iLUC model. New activities and flows are inserted. Going from left to right, the first new activities are the *markets of electricity*, one for each country. The market of electricity has as production function the mix of marginal electricity producers. The sum of each market of electricity function is 1. Marginal producers for a country may be national producers, but also another national market. The latter refers to the case of imported electricity. Market of electricity are accounted in TJ. The rows of market of electricity indicate the input of electricity to productive activities. Markets of electricity do not extract resources neither produce emissions.

The next new activities are the *land use change activities* (LUC_As) and are accounted in ha weighted with potential productivity factors (based on potential net primary production). For each country there are six transformating activities relating to production of land (or land equivalents, i.e.

intensification can release new productive land just as transformation of land not in use to productive purposes):

- Transformation from secondary forest to cropland;
- Intensification of arable land;
- Transformation from primary forest to managed forest;
- Transformation from secondary forest to managed forest;
- Transformation from grassland to pasture;
- Intensification of pasture.

The LUC_As indicate the process of changing the use of the land from an original state to another. These activities are transformation activities, therefore they have input and outputs. The output of the LUC_As is the amount of land that undergoes that transformation. Further, they produce emissions. Moving to the input side, LUC_As naturally ask for land, but may require also fertilizers and other products. For simplicity, we have considered just fertilizers.

Finally on the right sides, there are the *markets for land*. These markets are global, which means that they are valid indifferently for all the countries and are accounted in ha. The market for lands are:

- Market for arable land;
- Market for forest land;
- Market for grassland.

The market for land are inputs for activities that require land. Therefore the original input of land included in EXIOBASE are converted in demand for markets for land.

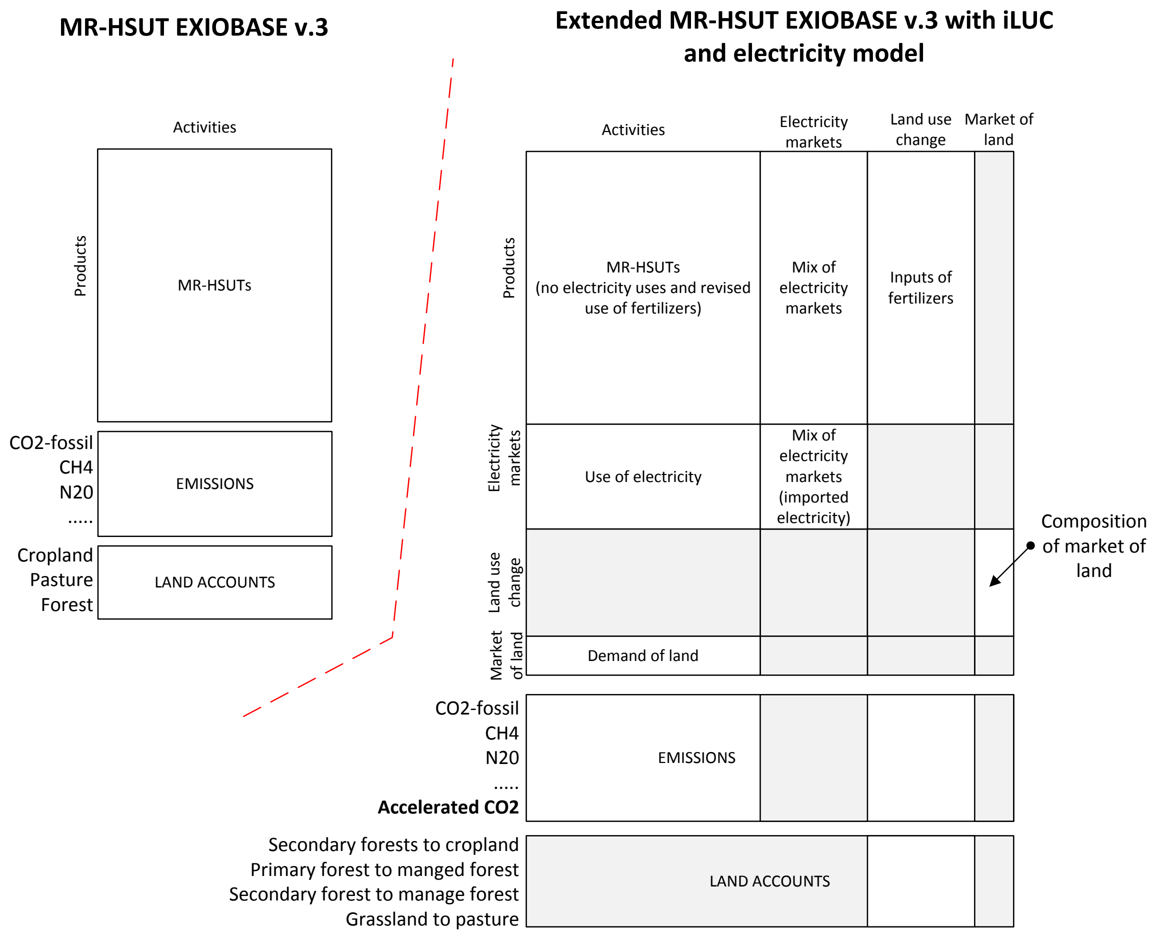

Figure 0 – Extended version of EXIOBASE v.3 with iLUC and electricity models. On the left side it is shown the structure of original MR-HSUTs EXIOBASE v.3 while on right the changed occurred when applied the electricity and iLUC models. The grey area indicates that no data are there included in.

In the next sessions we will try to define better the two models internalized in the MR-HSUTs.

Electricity model

The aim of the electricity model is that of defining the mix of electricity that will be produced anytime there is an additional demand of electricity.

An important concept of the electricity model is that in each country all the actors use the same mix of electricity, which is provided by the market. In practice, the market may be thought as a nation grid.

A marginal producer of electricity is the activity than in the last five years has increased its productive trend. Therefore, all the expanding electricity producers are considered as marginal producers. The fraction of each producer to the total market supply is proportional to its contribution to the total electricity increase of supply.

Equation 1 shows how is selected a marginal producer. Y_x^t indicates the production of electricity by activity *x* at time *t*.

Equation 1
$$\begin{cases} if\ \Delta x = Y_x^{2011} - Y_x^{2006} > 0 \quad x\ is\ a\ marginal\ produces \\ if\ \Delta x = Y_x^{2011} - Y_x^{2006} \leq 0 \quad x\ is\ not\ a\ marginal\ producer \end{cases}$$

The composition of the market is determined as follows:

Equation 2 $$f_x = \Delta_x / \sum_{y \in E} \Delta_y$$

Where the set *E* indicates all the producers of electricity. Equation 2 is applied to any country. It is assumed that a country that produces domestically more than 75% of its total use of electricity, it will have only domestic activities as marginal producers. When the percentage drops below 75%, it is assumed an import of electricity from other national markets.

Data for the construction of the markets are taken from the EXIOBASE, which in turns uses data from IEA [9].

Indirect land use change model (iLUC)

The iLUC model consists of three steps. The source of data on agriculture production and land use for this procedure id FAOSTAT[10]. Data on fertilizers are from IFA[11].

Initially, it is derived for each EXIOBASE agricultural activity if there has been an increase, or a reduction, of production (i.e. Δ_Y with Y=crop, grass/ensilage, live animals). This is done as in Equation 1. Likewise, it is determined if there has been an increase of the land use (i.e. Δ_{Land} with Land=arable or forest). Then it is determined if there has been an increase of the yield during the years (i.e. Δ_{yield}). An increase of yield is seen as an *intensification of the land already in use.*

Next step is to calculate what has contributed to increase the production during the considered period. $\mathrm{f}_{\mathrm{intens}}$ indicates the contribution of intensification and $\mathrm{f}_{\mathrm{Land}}$ of increasing land use. The following formula is applied:

Equation 3 $$\begin{cases} f_{intens} = min[\Delta_{yield} \cdot \left[\frac{Land_{2011}+Land_{2001}}{2}\right] / \Delta_Y, 1] \\ f_{land} = 1 - f_{intens} \end{cases}$$

Where $Land_{2011}$ indicates the use of land in 2011. In a similar way it is calculated if the contribution to the production of grass/ensilage of intensification (g_{intens}) and new land (g_{iland}).

The land used in each country is homogenised by transformation factors that take into account the carbon stocked into land. The carbon stock factors are shown in the following figure.

Carbon stock: country specific		**t C/ha**
Land in use		
Cropland	C_{crop}	27.023
Managed forest (country-specific)	C_{man_forest}	(De Rosa et al., 2017)
Grassland	$C_{pasture}$	15.89
Land not in use		
Primary forest (country-specific)	$C_{prim\text{-}forest}$	(De Rosa et al., 2017)
Secondary forest (country-specific)	C_{sec_forest}	(De Rosa et al., 2017)
Grassland / scrubland	C_{grass_scrub}	37

Figure 1 – Carbon stock factor, used to homogenize the demand of land[12].

It now time to analyse what action have been undertaken in each country in order to get new land. Figure 2 shows the source of data for this task, while Figure 3 how the land use mixes are built. These calculation will be used to determine the extension *land use accounts* (see Figure 0). Notice that intensification has no input of land.

Data for and use change mix - ha	
loss of primary forest (LPF)	(FAO Statistic division, 2016)
loss of secondry forest (LSF)	(FAO Statistic division, 2016)
loss of forest (LF)	loss of primary forest + loss of secondry forest
transformation arable land (Δarable)	(FAO Statistic division, 2016)
transformation forest land (Δforest)	(FAO Statistic division, 2016)

Figure 2 – source of data for the calculation of land use change mix

Land use change mix	Conversion to cropland	Conversion to managed forest	Conversion to grassland
Secondary forest => cropland	1		
Primary forest => managed forest (%PF)		min[LPF / Δforest,1]	
Secondary forest => managed forest (%SF)		1 - min[LPF / Δforest,1]	
Grassland => pasture			1

Figure 3 – Calculation of land use change mix of the land use transformation activities. (see Figure 2 for the name of the variables)

We can now move to calculate the output, the inputs of fertilizers and the emissions of the country-specific land transformation activities. The output of transformation activities is expressed in ha weighted with carbon of net primary productivity (NPP_0).

Activities	Transformation from secondary forest To cropland	Intensification of arable land	Transformation from primary forest to managed forest	Transformation from secondary forest to managed forest	Transformation from grassland to pasture	Intensification of pasture
Output:	Δarable*Pw	IF (Δarable >0) THEN ((f_intensiv x Δarable) / f_land) x PW ELSE IF Δcrop > 0 THEN Δcrop /yield x PW_arable ELSE 0	Δforest x PW x %PF	Δforest x PW x %SF	Δgrass x PW	((g_intens x Δgrass) / (1-g_intens)) x PW
Product inputs						
N-fertiliser		ΔN-fertilizers(+)				
P- and other fertiliser		ΔP-fertilizers(+)				
Emissions						
Accelerated CO2	IF (Δarable >0) THEN 44/12 x Δarable x (C_{sec_forest} - C_{crop}) ELSE 0		44/12 x Δforest(+) x (C_{prim_forest} - C_{man_forest}) x share_prim	44/12 x Δforest(+) x (C_{sec_forest} - C_{man_forest}) x share_sec	44/12 x Δgrass(+) x ($C_{grass/schrub}$ - $C_{pasture}$)	
N2O		IF Δcrop > 0 THEN (Dalagard and Schmidt, 2012) ELSE 0				
NH3		IF Δcrop > 0 THEN (Dalagard and Schmidt,				
NOx		IF Δcrop > 0 THEN (Dalagard and Schmidt, 2012) ELSE 0				
NO3		IF Δcrop > 0 THEN (Dalagard and Schmidt, 2012) ELSE 0				

Figure 4 – Calculation of outputs, inputs of products and emissions of the land transformation activities.

Finally, the global markets for land can be constructed. These will be the sum of all the national markets. Shows how the national transformation of land activities are allocated to markets.

Activities	**Market for arable land**	**Market for forest land**	**Market for grassland**	**Market for land in barren regions**
Transformation from secondary forest To cropland	x			
Intensification of arable land	x			
Transformation from primary forest to managed forest		x		
Transformation from secondary forest to managed forest		x		
Transformation from grassland to pasture			x	
Intensification of pasture			x	

Figure 5 – Allocation of transformation of land activities to the global markets of land

Therefore, the output of the market for arable land will be the sum of all the country-specific *transformation from secondary forest to cropland* plus all the *intensifications of land*.

At this point, the MR-HSUTs have been extended with the electricity and iLUC model. The last step is to determine the input-output table to calculate the product carbon footprint.

Input-output table: generalized by-product technology assumption

The methodology used to determine the squared input out tables is the by-product technology assumption, known as the Stone's method[13,14]. Yet, the Stone's method has some limitation when applied to multi-regional framework. Indeed, there could be countries that recycle materials but do not produce virgin productions. Therefore, when the recycled material is inserted as negative input, it will substitute products that are not produced.

The generalized approach that we introduce implies that, considering a generic country, a by-product will substitute products following the composition mix that provide products to the users. In other words, if for example a country imports virgin materials and do not produce them, the by-product of recycling activities will substitute the imported products. In this way, an increase of recycling materials will imply that less virgin materials are imported.

Input-output tables are made square aggregating the rows.

Results

In this section we show how the implementation of electricity and iLUC models change the carbon footprint of products of the MR-HSUTs of EXIOBASE v.3.

Figure 6 shows how the marginal energy mix changes, i.e. the electricity markets, compared to the average energy in three biggest economies of the world, i.e. China, United States and Germany. These countries have done investments towards a cleaner electricity production and indeed the GHGs emissions of the electricity markets are lower respect to average productions. The bold percentage value indicates the variation when moving from average values to marginal producers. Germany is the country that has mostly reduced the carbon footprint, with a 68% of reduction of GHGs emissions. This is due to investments in renewable energy source and to new gas fueled plant that have a lower impact respect to coal fueled ones. US have invested a lot in gas power plant and wind, this has reduced of 53% the carbon footprint of electricity. China, although still strongly relying on coal, has increased the contribution of gas and renewable sources, reducing its GHGs emissions of 4%.

Figure 7 shows how the countries that have registered the highest and the lowest change in terms of GHGs emissions. Norway has increased its emissions of 876%. The reason for that lies in the fact that Norway has an high production of electricity from hydroelectric power plant. However, the hydroelectric sector is almost saturated, therefore new investments are mainly towards gas fueled plants. This explains why there is such an high increase of GHGs emissions. However, in absolute terms, the marginal electricity mix has still a low footprint compared to other world regions.

Rest of Europe has also increased considerably its carbon footprint. This is due to new investments in coal power plants that have an higher carbon footprint. Denmark, on the contrary, has considerably reduced its carbon footprint due to high investments in wind energy and, in minor scale, of biomass plants.

A complete picture of the EXIOBASE countries/regions variation of GHGs emissions due to adoption of marginal electricity producers may be seem in Figure 8. It can be seen which are the countries that have done investments towards cleaner technologies and which instead toward more carbon emitting sources, mainly coal.

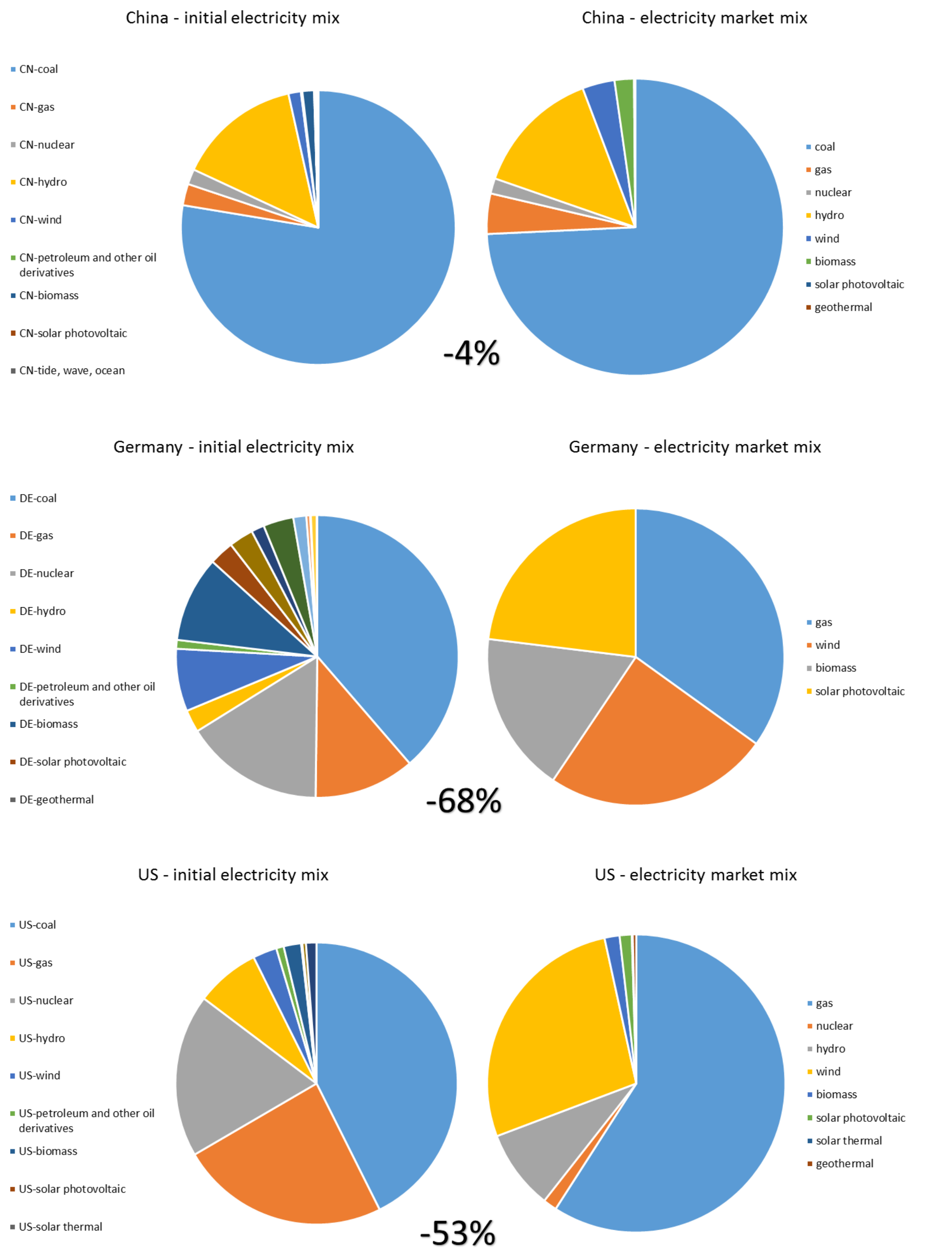

Figure 6 – Comparison of electricity mixes in the standard EXIOBASE v.3.3.11 (left pie) and the extended version (right pie) for three main economies in 2011. The percentages between the two national chart shows the variation of GHGs emissions when implementing the electricity model.

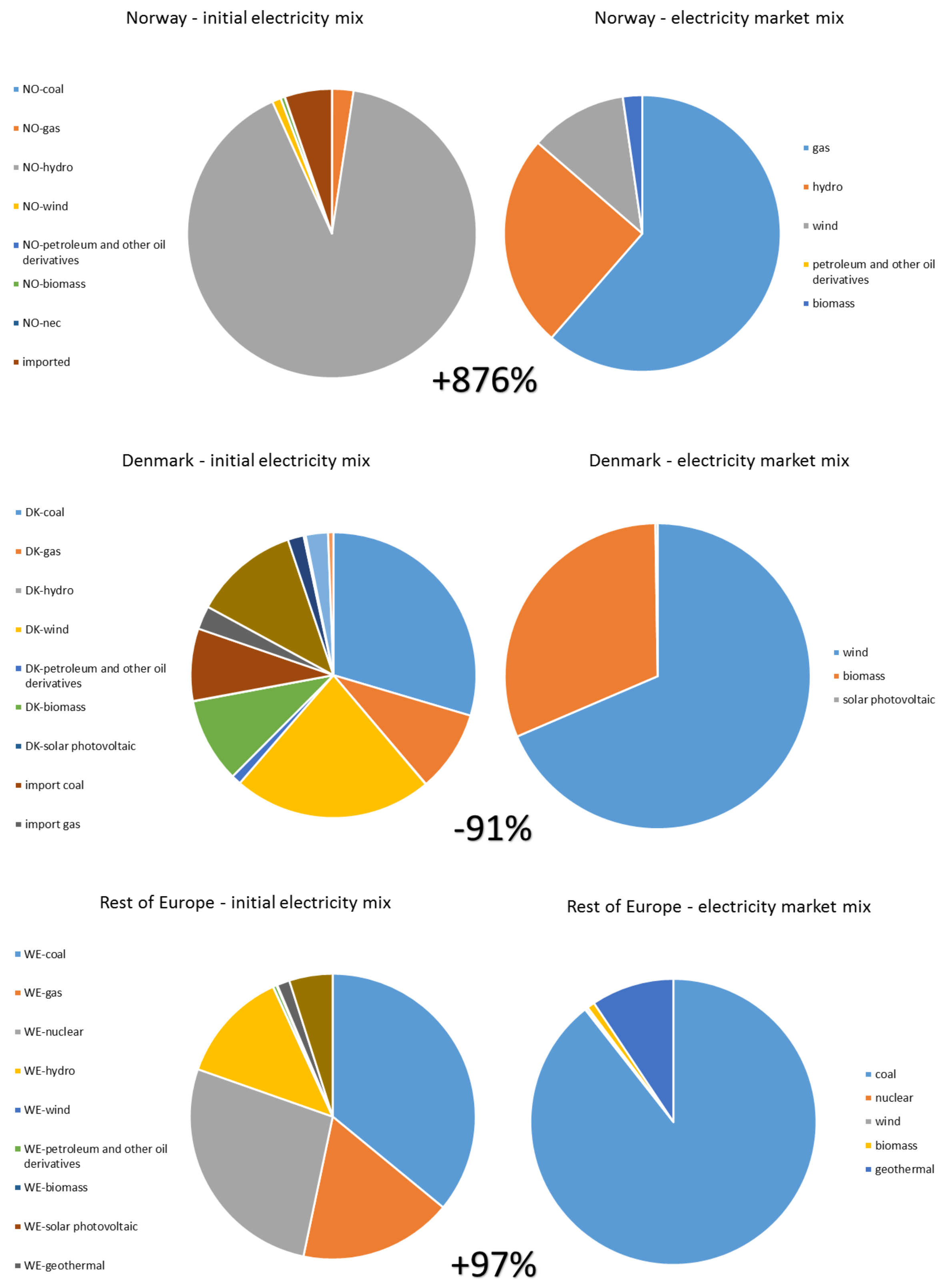

Figure 7 -Comparison of electricity mixes in the standard EXIOBASE v.3.3.11 (left pie) and the extended version (right pie) for three areas with the highest variation of GHSs emissions in 2011. The percentage between the two charts indicates the variation dur to introduction of electricity markets.

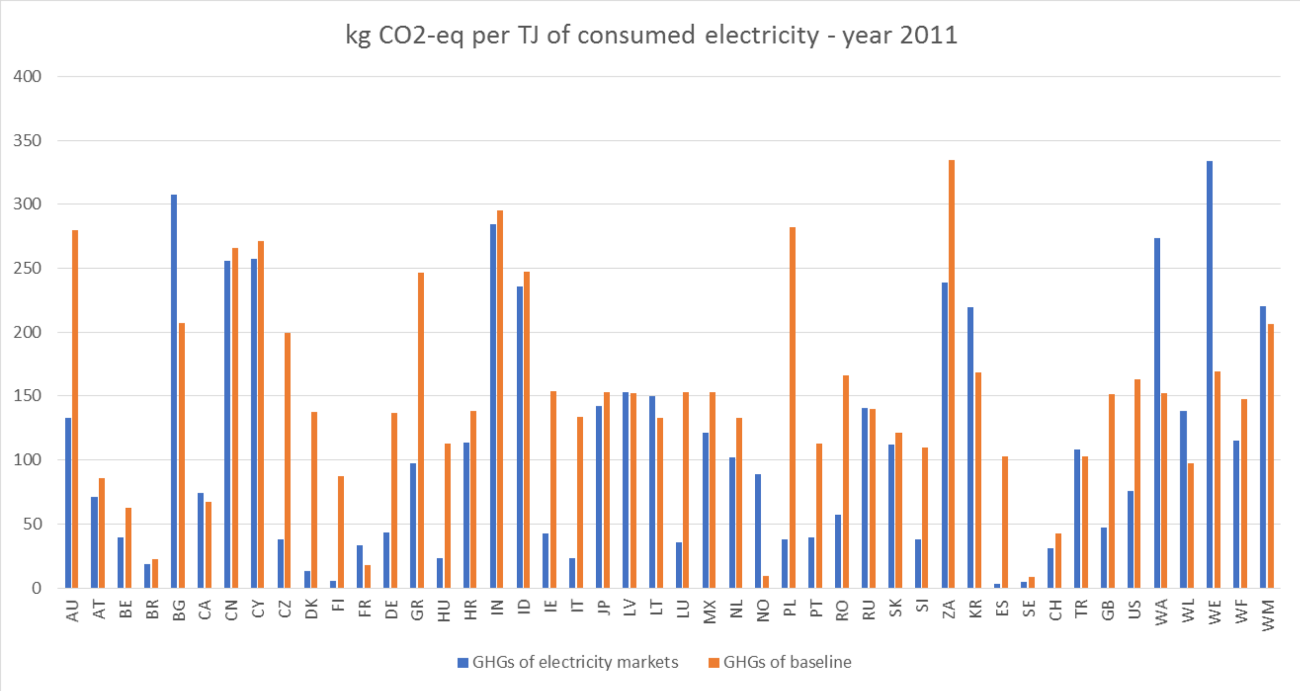

Figure 8 – Comparison of reenhouses gas emission per unit of consumed electricity in the EXIOBASE regions when applying the electricity model. Left bar shows the impact of the electricity markets, the right bar the impact in the baseline.

We can now to see the total effect on the carbon footprint for some selected products due to introduction of the electricity models. The analysis is implemented for all the countries/regions of EXIOBASE. Figure 9 shows the effect on some agricultural products, i.e. wheat, vegetables and live cattle. For these products, which obviously require land, it can be seen that there is an increase of the carbon footprints. The effect of the electricity model is negligible. Difference by countries are due essentially to the different yields and to the different potential production of the soils. Countries that have higher yields and more fertile land are expected to ask less land and therefore their footprint increases less. At the same time, it must be also considered that countries with a higher footprint due to high carbon demanding inputs, may have a relative smaller variation.

It can be seen that, for the same countries, the variation is higher for some products and less for other. This is clear indicator of the differences in yields that may be driven by differences in climate areas. With regard to cattle, the use of pasture land and the higher or smaller dependence on imported products, may affect the footprint.

Figure 10 shows the variation in food products. It can be seen that for pig meat the impact of electricity model in not anymore negligible. This because the processing of meat pig requires, directly and indirectly, more electricity per unit of output than other food products.

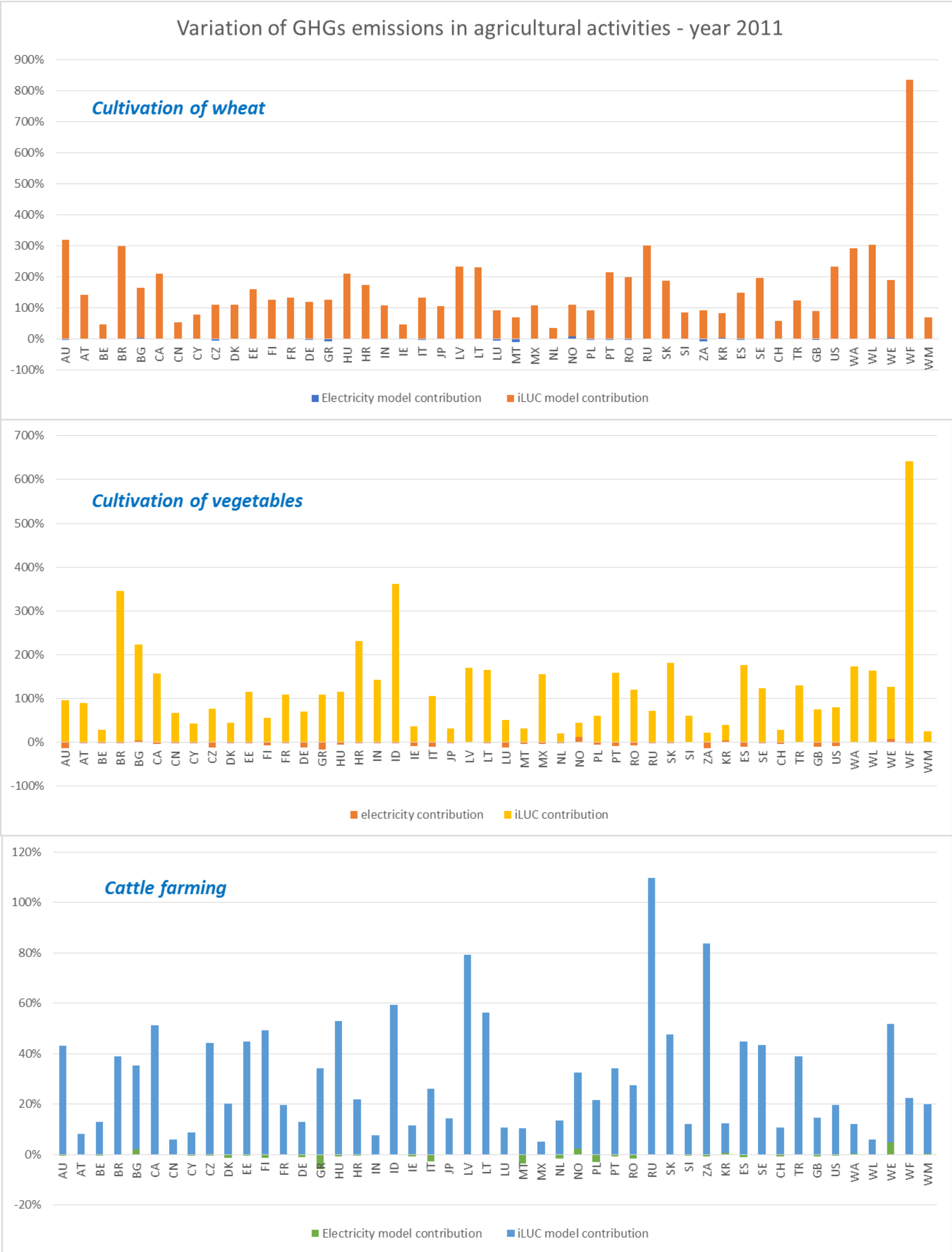

Figure 9 – Effect on GHGs emissions in three agricultural activities when applying the electricity and iLUC models to EXIOBASE v.3.3.11. The charts show the variation in percentage per dry-matter unit.

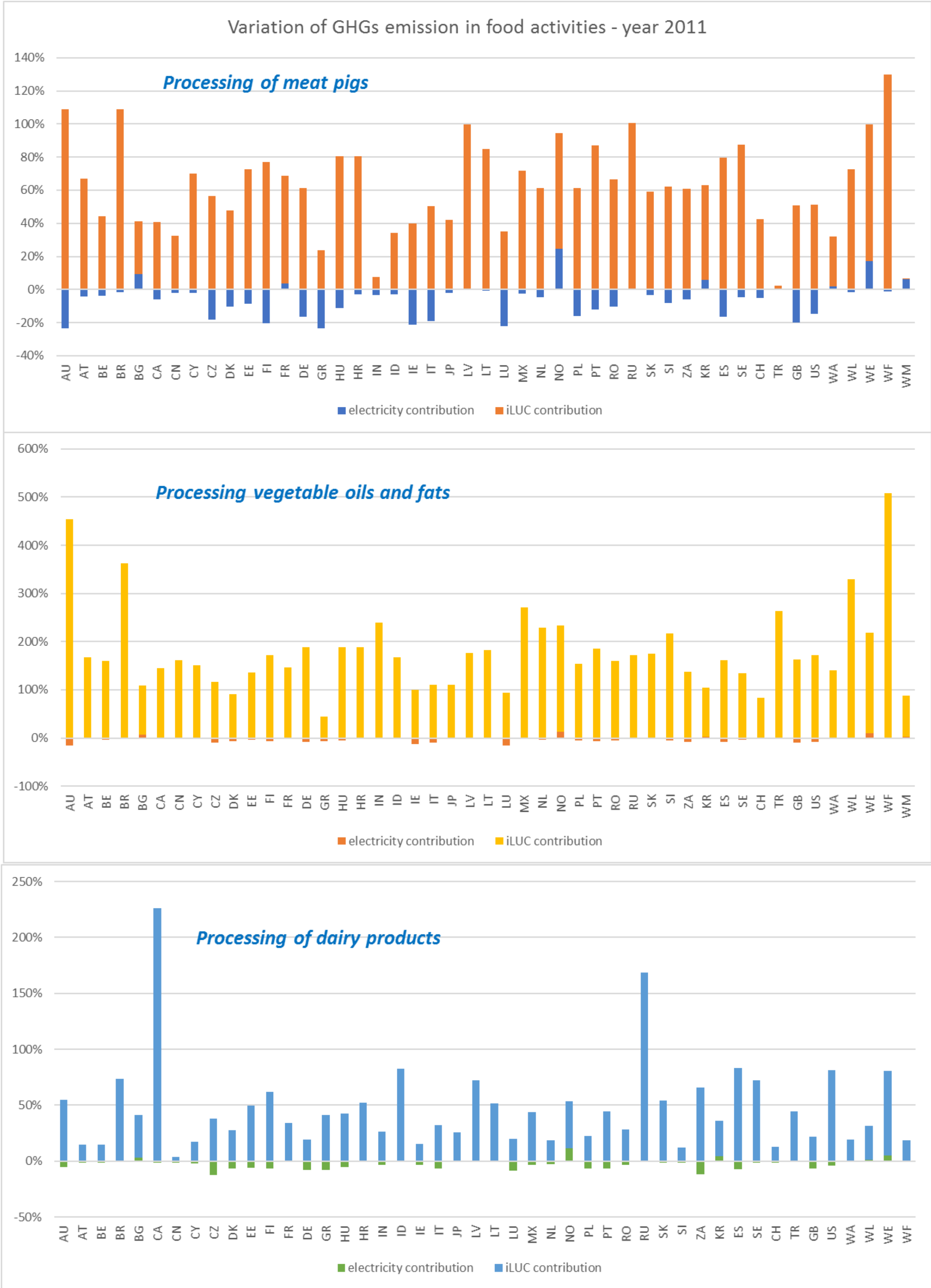

Figure 10 - Effect on GHGs emissions in three food activities when applying the electricity and iLUC models to EXIOBASE v.3.3.11. The charts show the variation in percentage per dry-matter unit.

Figure 11 shows the effects on three manufactured products, wood, plastic and aluminium products. The chart confirms what could have been predicted. With regard to wood product, the contribution of iLUC model is still very high and has the major contribution over the change of the carbon footprint. In the other two products, the electricity models become to have a strong influences. It can be seen that the marginal electricity producers influence positively or negatively the footprints. As said above, the sign is due to different investment made within the countries. Leaner technology contribute negatively, dirtier technologies positively. This is very clear for aluminium products, because aluminium requires a lot electricity to be produced.

It is interesting to notice the case of Brazil. This country has an high impact of iLUC model for the production of manufactured products. The main reason for that can be found in the fact that biomass has an important role between marginal producers. The biomass requires land, therefore an increase of demand of electricity requires indirectly new land.

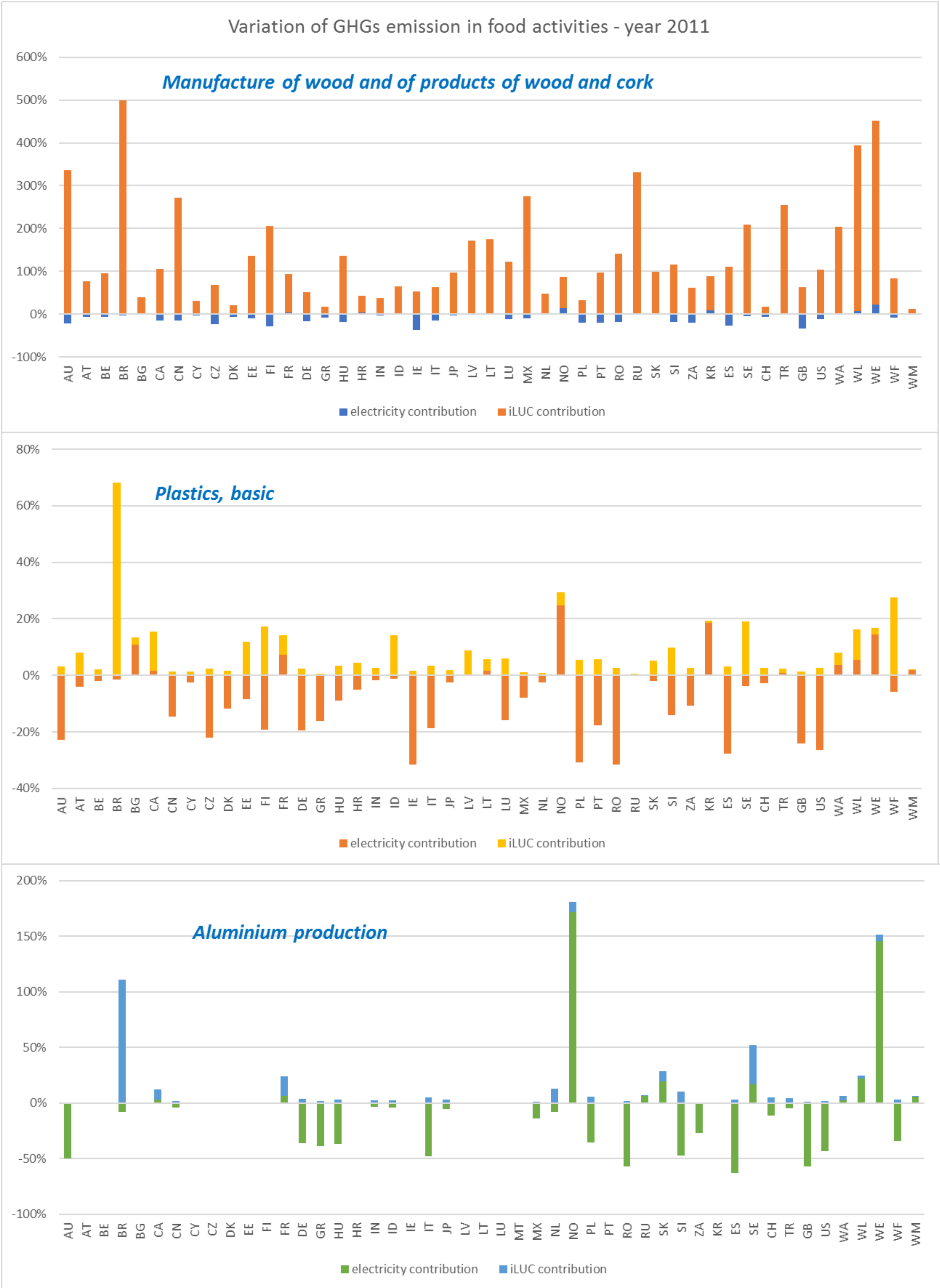

Figure 11 - Effect on GHGs emissions in three manufactural activities when applying the electricity and iLUC models to EXIOBASE v.3.3.11. The charts show the variation in percentage per dry-matter unit.

Conclusions

We have shown an extended version of EXIOBASE-HSUTs, where we have included the concept of marginal producers developed within the consequential LCA community. In particular we have applied consequential models for electricity and the iLUC.

The internalization of the two models is surely facilitated by the hybrid framework adopted in EXIOBASE. It is the first time that these models are implemented in a multi-regional framework. At the same time, the large amount of information included in the MR-HSUTs may help in the future to further develop the iLUC and electricity models and, at the same time, may open more possibilities to introduce marginal producers in other sectors.

The extended MR-HSUTs assures a better description of the effects from a change in demand than traditional yearly average IO-models.

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