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Integrated environmental assessment of future energy scenarios based on economic equilibrium models

E. Igos[1], B. Rugani[1], S. Rege[1], E. Benetto[1], L. Drouet[1], D. Zachary[1] and T. Haas[2]

[1] *Public Research Centre Henri Tudor, Resource Centre for Environmental Technologies (CRTE), 6A, avenue des Hauts-Fourneaux, 4362 Esch-sur-Alzette, Luxembourg*
[2] *Institut national de la statistique et des études économiques du Grand-Duché du Luxembourg (STATEC), 13 rue Erasme, 1468 Luxembourg*

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Abstract – The future evolution of energy supply technologies strongly depends on (and affects) the economic and environmental systems, due to the high dependency of this sector on the availability and cost of fossil fuels, especially on the small regional scale. This paper aims at presenting the modeling system and preliminary results of a research project conducted on the scale of Luxembourg to assess the environmental impact of future energy scenarios for the country, integrating outputs from partial and computable general equilibrium models within hybrid Life Cycle Assessment (LCA) frameworks. The general equilibrium model for Luxembourg, LUXGEM, is used to evaluate the economic impacts of policy decisions and other economic shocks over the time horizon 2006–2030. A techno-economic (partial equilibrium) model for Luxembourg, ETEM, is used instead to compute operation levels of various technologies to meet the demand for energy services at the least cost along the same timeline. The future energy demand and supply are made consistent by coupling ETEM with LUXGEM so as to have the same macro-economic variables and energy shares driving both models. The coupling results are then implemented within a set of Environmentally-Extended Input-Output (EE-IO) models in historical time series to test the feasibility of the integrated framework and then to assess the environmental impacts of the country. Accordingly, a disaggregated energy sector was built with the different ETEM technologies in the EE-IO to allow hybridization with Life Cycle Inventory (LCI) and enrich the process detail. The results show that the environmental impact slightly decreased overall from 2006 to 2009. Most of the impacts come from some imported commodities (natural gas, used to produce electricity, and metalliferous ores and metal scrap). The main energy production technology is the combined-cycle gas turbine plant "Twinerg", representing almost 80% of the domestic electricity production in Luxembourg. In the hybrid EE-IO model, this technology contributes to around 7% of the total impact of the country's net consumption. The causes of divergence between ETEM and LUXGEM are also thoroughly investigated to outline possible strategies of modeling improvements for future assessment of environmental impacts using EE-IO. Further analyses focus first on the completion of the models' coupling and its application to the defined scenarios. Once the coupling is consistently accomplished, LUXGEM can compute the IO flows from 2010 to 2030, while the LCI processes in the hybrid system are harmonized with ETEM to represent the future domestic and imported energy technologies.

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Energy supply and use represent critical issues for at least three spheres of interest, which are interlinked [1–3]: (1) economic, due to the extensive and binding demand of all types of sectors and industries, (2) political, due to the high dependency on fossil fuels, which are produced by a restricted number of countries, and (3) environmental, because of the resource scarcity (depletion) and the impacts associated with extraction refining and combustion processes of large amounts of non-renewable resources. Energy policies and strategies therefore need to be carefully defined while comprehensively accounting for socio-economic and environmental constraints.

Multi-sector computable general equilibrium (CGE) economic models, based on social accounting matrices, are used to evaluate the economy-wide ramifications of policy decisions or price shocks, in contrast to partial equilibrium models that focus explicitly on the interaction of supply-demand curves for a particular sector and its implications for price and quantity supplied [4–7]. With regard to environmental assessment techniques, Life Cycle Assessment (LCA) is the most recognized methodology worldwide [8, 9] and evaluates the potential impacts of a product or a process during its overall life cycle.

One observes a rising interest globally, specifically with regard to new technologies in the energy sector, which mandates the development of methodologies that straddle different approaches with the purpose of bolstering the decision-making and support systems for the energy sector [10–12]. For example, in the FP6 NEEDS project (2004−2009), a partial European equilibrium model [13], calibrated on one existing general equilibrium model for Europe (GEM-E3), has defined the energy scenarios in a time horizon until 2050. The NEEDS model also includes the environmental impact profile of several emerging and new future technologies through the use of LCA and external cost valuation (monetarized environmental impacts).

The project LUXEN[1] (Integrated assessment of future energy scenarios for Luxembourg) aims at evaluating prospective energy scenarios for Luxembourg using economic partial and general equilibrium models, including the associated environmental impacts through LCA. Compared with NEEDS, this project is oriented to obtain the environmental impacts of the total net consumption of the investigated region of Luxembourg and not only of the energy technologies.

Indeed, the framework of analysis in LUXEN encompasses the coupling of partial and general equilibrium models for Luxembourg and the use of Environmental Extended Input-Output (EE-IO) tables, while integrating process inventory data for the energy sector, in order to take into account both monetary and physical results from the economic coupling. The present paper introduces and discusses the main features and challenges underlying the methodology for integrating models in LUXEN.

The rest of the paper is organized as follows: in the materials and methods section, the requirements and assumptions for the use of different models, techniques and datasets in LUXEN are presented. The following section analyzes and discusses the results with regard to the historical timeframe (2006−2009). Moreover, preliminary results on the future time horizon and a comprehensive investigation of the advantages and limitations behind the integrated modeling system are outlined. Conclusions and the outlook are drawn on the basis of the current state-of-the-art for LUXEN and its future applicability.

1 Materials and methods

1.1 Coupling of equilibrium models

The first step of the LUXEN methodology is represented by the assessment of the energy supply and demand, as well as their economic consequences on the Luxembourg scale in the time horizon 2006−2030. The Energy Technology Environment Model (ETEM) is a partial equilibrium model computing the future energy consumptions in Luxembourg [14]. The model, which includes a catalog of 676 technologies, determines the lowest cost for energy supply structures satisfying the future demand for energy services. For each technology, the energy-related emissions of carbon dioxide, methane, nitrous oxide, nitric oxide, nitrogen dioxide and non-methane volatile organic compounds are also calculated.

The Luxembourg General Equilibrium (LUXGEM, developed by Ecomod, financed

[1] Project initiated by the Public Research Centre Henri Tudor, the Luxembourg statistics institute STATEC and the Luxembourg Ministry of Sustainable Development and Infrastructures, and co-funded by the European Regional Development Funds (ERDF; http://ec.europa.eu/regional_policy/thefunds/regional/index_en.cfm).

and maintained by STATEC) Model [15] is a sequentially dynamic model of the economy of Luxembourg with 16 sectors producing 20 commodities with one representative household. The production process is represented by a constant-returns-to-scale (CRS) nested Constant Elasticity of Substitution (CES) function, while the demand system for the household follows a Linear Expenditure System (LES). The LUXGEM model has 6 energy commodities whose consumption is influenced by an exogenously specified energy intensity parameter for each sector and energy commodity over time. The model operates in pure monetary terms, while energy demand in physical units (Tera-Joules TJ) is obtained via a price of energy in Euro/TJ using the base year monetary flows and energy consumption in TJ.

Coupling standalone CGE models with standalone partial equilibrium (energy) models such as ETEM has always been challenging due to the independent nature of these models. One cannot achieve a complete harmonization in terms of prices and consumption between both models. The approach generally pursued is as follows: ETEM computes the activity levels of various processes to meet a particular evolution of demand for energy services over time. The demand for energy services is dependent on the demand drivers, which are macro-economic variables and are consistently provided by an economy-wide CGE model such as LUXGEM. The latter, therefore, computes the energy shares from a nested production function that responds to price elasticity, while being unable to incorporate structural changes such as large swings in energy shares or energy intensities of energy commodities. In order to couple ETEM with LUXGEM, three approaches have been planned: changes in energy intensity parameters, changes in demand system parameters and changes in the share parameters in the production function, the latter being still under development. In this paper, the drivers from LUXGEM were used to run ETEM and the energy shares from ETEM were used to modify the energy intensity parameters in LUXGEM for the production process, and the demand system parameters for final consumption. Iterations were run until no changes in the parameters and the drivers were observed.

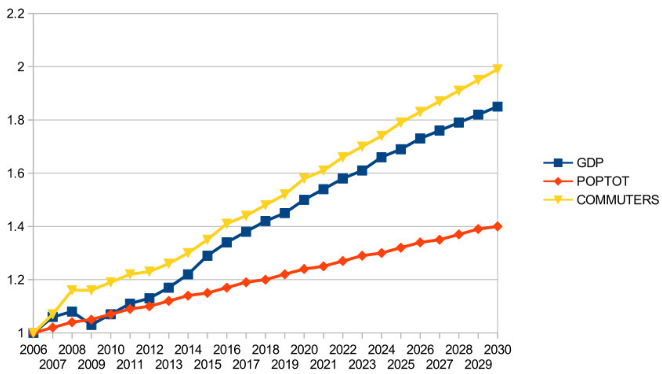

Fig. 1. Drivers adopted to set up the baseline scenario used by LUXGEM and ETEM (Population-POPTOT, Commuters, GDP growth index evolution (2006 = 1; reference year for elasticity factors).

The assessment of the environmental and economic consequences of the energy policies in Luxembourg implied the construction of a baseline scenario along with a set of alternative scenarios (e.g. high oil price, late Kyoto target, Europe's effort sharing decision, etc., which are still under simulation and thus are not presented in this paper). The baseline scenario was defined with exogenous assumptions on the drivers, on the energy prices (i.e. importation energy price evolution; [16]) and policies, following a business-as-usual trend. These assumptions had to be representative of the commonly accepted trends and hypotheses used in similar exercises (e.g. energy policy assessments). The main drivers were issued from MODUX, the econometric model of STATEC [17]. As shown in Figure 1, these drivers are (i) population growth, (ii) evolution of the number of commuters, and (iii) Gross Domestic Product (GDP) growth.

1.2 Environmentally-extended input-output modeling

Input-output (IO) models are monetary tables built to describe the economic relationships and exchanges of commodities across the different economic sectors of a region. The use of IO analysis is increasing more and more in environmental accounting, thanks to numerous developments achieved during recent years, including IO-based techniques

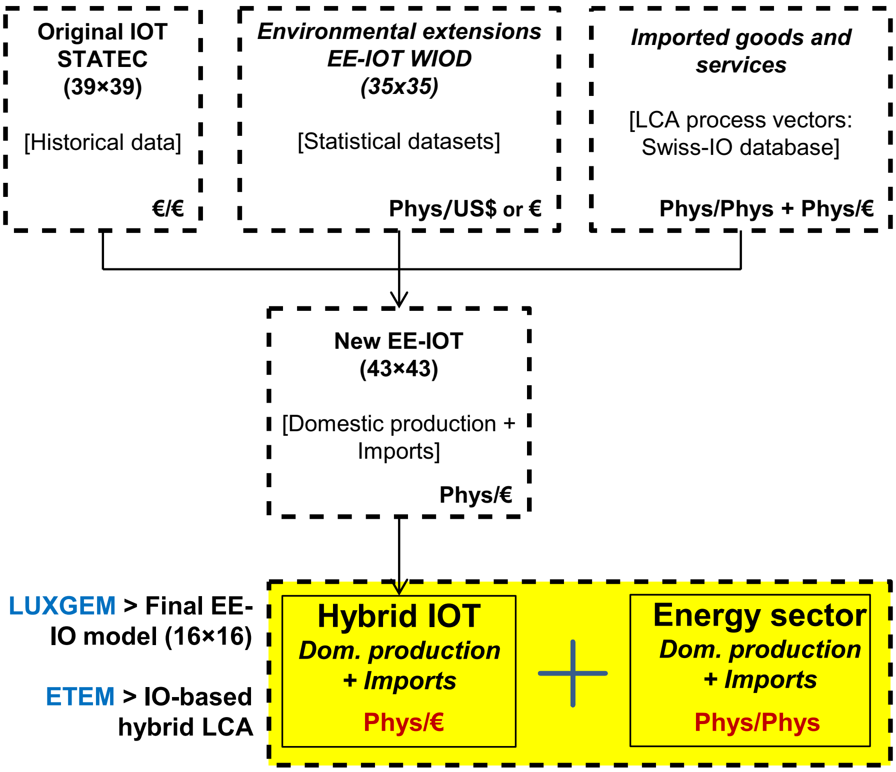

Fig. 2. Schematic representation of the hybrid LCA framework.

and databases for consumption footprint assessment on the macro-scale of a country (e.g. [18–22]) and hybrid analysis with LCA on the meso- to micro-scale of process (e.g. [23–25]). A common end-point of these attempts is the implementation of so-called Environmentally-Extended IO (EE-IO) models, where environmental inventory and impact methods (usually elaborated within the LCA framework) are thoroughly combined with classical IO systems.

The environmental impacts of the energy scenarios were assessed in LUXEN starting from the outputs of the equilibrium models' coupling. Because this latter provided results expressed in monetary (from LUXGEM) and physical (from ETEM) units, a hybrid LCA framework was built to integrate the two output metrics and to provide a comprehensive evaluation dataset representing the entire (present and future) system boundaries of the country. Accordingly, EE-IO tables were designed with high specificity of country-related data. First, IO tables were retrieved from STATEC, whereby the sectorial structure was aggregated (from the original 39×39 matrix) to match the 16-sector classification used in LUXGEM. Environmental extensions were added afterward to link the production and import layers to satellite accounts inclusive of resource extractions and emission data by sector[2].

To represent the current and future Luxembourg economy and energy scenarios, the time-explicit EE-IO model was essentially composed of two parts: the years from 2006 to 2009 were modeled starting from the original STATEC-IOTs, while future estimations of the IOTs have to be performed using LUXGEM to model the years from 2010 to 2030. Since the coupling between LUXGEM and ETEM is still under development, for the purposes of this paper only the historical results (the years from 2006-2009) are shown with regard to the EE-IO model development.

The framework is represented in Figure 2.

[2] Main source of environmental data: World Input-Output Database-WIOD, available at: http://www.wiod.org/database/ea.htm

1.3 Integrated modeling framework and environmental assessment

The above-mentioned EE-IO model and the energy use and production results from the coupling were used to build an IO-based LCA framework. In the newly created EE-IO tables, the energy sector was disaggregated and no longer expressed in monetary terms but by physical flows (MJ). The LCA methodology enabled us here to recall datasets of Life Cycle Inventory (LCI) to describe the life cycle of the current and future energy technologies defined by ETEM.

Accordingly, several unit processes were retrieved from the ecoinvent database [26] (see Tab. 1) and modified according to the assumptions used in ETEM (efficiency ratios and emissions of combustion used to modify the quantity of certain raw material inputs and emitted substances). Since IO coefficients were distinguished between domestically produced and imported commodities in the EE-IO framework, the same was applied to model the LCI systems to avoid double counting.

This unit process re-organization in the hybrid system enabled both spatial regionalization of the inventory and impact assessment and full representativeness of the entire supply-chain of the technologies. However, original monetary flows in the IOT representing those energy technologies had to be excluded from the model.

In this connection, specific criteria of cut-off were applied upstream of the integration, according to the techniques described in [27], to avoid any possible double counting with other sectorial data already modeled with the IO. Indeed, a typical energy production process from ecoinvent contains inputs and outputs directly linked to the environmental sphere (e.g. energy from wind or emissions of carbon dioxide into air) and others linked to the technosphere (e.g. consumption of refined materials or waste in a treatment plant). The flows from LCI process data, which should have been included in the EE-IO, reflect the environmental impacts of the energy sector only, i.e. excluding the exchanges with the other sectors. In this perspective, the direct emissions (mainly linked to fuel combustion) were integrated, as well as the land use of the production plant (gate-to-gate perspective). Furthermore, the fuel input was accounted as import data, which was linked to a cradle-to-gate unit process associated with its upstream life cycle. All the other process flows were excluded since they were already taken into account in the EE-IO framework through the monetary exchanges.

This approach was validated by computing midpoint impacts of the energy technologies with the ReCiPe (H,A) method [28]. This screening revealed that the combustion emissions were mainly responsible for climate change impact, while infrastructure land use flows usually had a large contribution in the urban land occupation impact category. Accordingly, only these inputs were considered relevant to be integrated as environmental extensions for the energy sector (i.e. unit processes of technologies) into the EE-IO tables.

Once the EE-IO model (adapted to the 16-sector classification of LUXGEM) was completely integrated with the ETEM-based modified ecoinvent processes in the energy sector, the ReCiPe method (Recipe Endpoint (H) V1.07 / Europe ReCiPe H/A; [28]) was further applied to assess the potential environmental impacts generated by the energy supply and demand scenarios in Luxembourg described in Section 1.

2 Results and discussion

2.1 Results using historical data

The environmental impact assessment was firstly generated for the historical profile of the Luxembourg net consumptions from 2006 to 2009. For the sake of clarity, the net consumption of a country is commonly calculated as the total country's uses (i.e. total output = domestic production + imports) minus the exports vector, and is useful to outline the actual impacts of Luxembourg with a consumer-based perspective [29].

As shown in Figure 3, the environmental impact slightly decreased overall from 2006 to 2009. However, for some impact categories we observe a variable trend. For example, while the fossil resource depletion category is typically dominant (annual contributions always greater than 40%) but decreasing over time, with the lowest impact

Table 1. Characteristics and typology of the life cycle process flows linked to the ecoinvent unit processes (i.e. modified according to the assumptions underlying ETEM and then integrated within the IO-based hybrid system to model the energy supply and demand in Luxembourg). See Suh (2004) for further details on the procedure of hybridization.

	Energy type	**Ecoinvent module of reference**	**Features**
Commodities modeled as inputs to the various IO sectors (including the energy sector)	Air heat potential	–	Domestic input (natural resource)
	Hydraulic energy	Energy, potential (in hydropower reservoir), converted [in water]	
	Municipal solid waste	–	
	Solar energy	Energy, solar, converted [in air]	
	Wind energy	Energy, kinetic (in wind), converted [in air]	
	Biodiesel	Rape methyl ester, at regional storage [CH]	Imported input (cradle-to-gate unit process from ecoinvent)
	Biogas	Biogas, mix, at agricultural co-fermentation, covered [CH]	
	Coal	Hard coal, at regional storage [LU]	
	Diesel oil	Light fuel oil, at regional storage [RER]	
	Natural gas	Natural gas, high pressure, at consumer [RER]	
	Gasoline	Petrol, low-sulfur, at regional storage [RER]	
	Imported electricity (mix BE, DE, FR)	Electricity, prod. mix [BE]; Electricity, prod. mix [DE]; Electricity, prod. mix [FR]	
	Kerosene	Kerosene, at regional storage [RER]	
	Liquefied petroleum gas	Liquefied petroleum gas, at service station [CH]	
	Refined fuel oil	Light fuel oil, at regional storage [RER]	
	Wood and wood waste	Wood chips, mixed, u = 120%, at forest [RER]	
Technologies of electricity and heat production replacing the original energy sector of the IO	Electricity, from nat. gas (10 diff. technol.)	Electricity, natural gas, at power plant [LU]	Included: - Direct resource extraction and emissions as domestic - Fuel input as import Excluded: other inputs or outputs from the technosphere to avoid double counting with the IO dataset Allocation rules based on energy
	Electricity, from hydropower	Electricity, hydropower, at power plant [LU]	
	Electricity, from photovoltaic	Electricity, production mix photovoltaic, at plant [LU]	
	Electricity from municipal solid waste	Electricity from waste, at municipal waste incineration plant [CH]	
	Electricity, from biogas	Electricity, at cogen with biogas engine, agricultural covered, alloc. exergy [CH]	
	Electricity, from wind (3 diff. technol.)	Electricity, at wind power plant 600kW [CH]	
	Heat, from natural gas (7 diff. technol.)	Electricity, natural gas, at power plant [LU]	
	Heat, from biogas	Heat, at cogen with biogas engine, agricultural covered, alloc. exergy [CH]	
	Heat from wood	Heat, mixed chips from forest, at furnace 1000 kW [CH]	

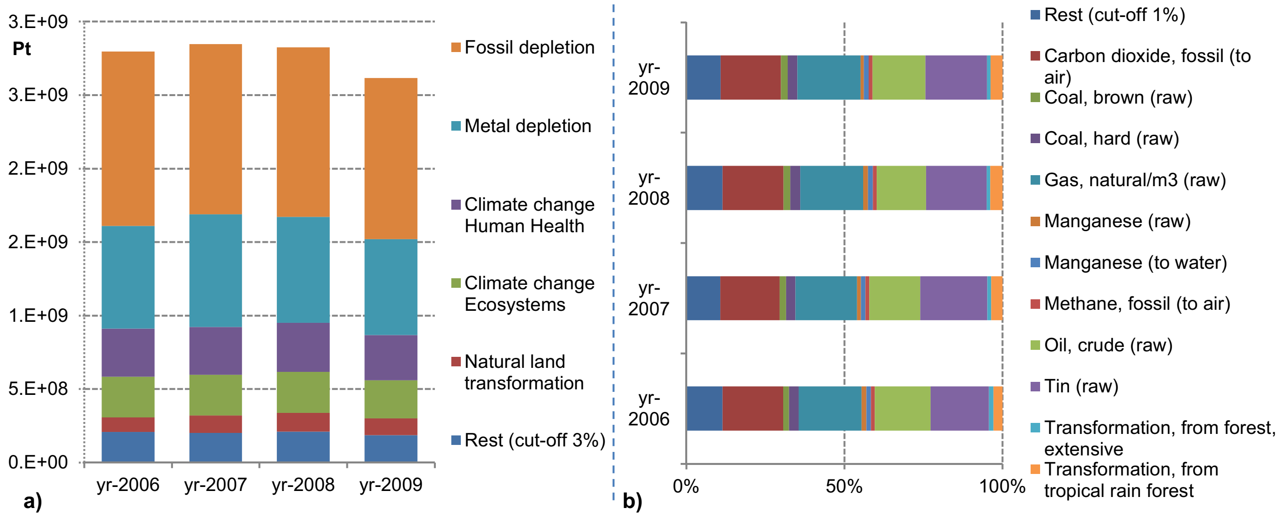

Fig. 3. Historical time-series profile of environmental impact due to Luxembourg's net consumptions using single-score damage assessment (ReCiPe end-point (H) V1.07 / Europe ReCiPe H/A): (a) comparison of impact category score contributions (cut-off indicators in order of influence from lowest, ≈0.001%, to highest, ≈2.7%: Photochemical oxidant formation, Marine ecotoxicity, Ozone depletion, Freshwater ecotoxicity, Freshwater eutrophication, Terrestrial acidification, Ionizing radiation, Terrestrial ecotoxicity, Urban land occupation, Agricultural land occupation, Human toxicity, Particulate matter formation); (b) gravity analysis.

scores recorded in 2006 and 2007, an opposite trend is observed in the second highest impact category, i.e. metal resource depletion (annual contributions always greater than 24%), where instead the final impact scores are slightly increased. The trend observed on fossil depletion is mainly due to a decrease in the use of natural gas to produce electricity and heat in Luxembourg and a slight reduction in the consumption of diesel (both of them being the main cause for the fossil depletion's impact). The effect on metal depletion is in turn explained by an increase (with a peak in 2006) in the imports of metalliferous ores and metal scrap (which mostly contributes to the impact on metal resource depletion, around 70% over time), and, though with minor importance, imports of electrical machinery, apparatus and appliances (around 5–10% contribution to metal depletion over time).

A third impact category worth investigating is climate change, which may have damaging effects both on human health and ecosystem functioning (i.e. species loss). The two indicators resulted in contributions around 12% and 10%, respectively, of the total single-score impact profile due to Luxembourg's net consumptions (see Fig. 3). These climate change scores can be explained by the impact generated to produce electricity and heat in Luxembourg (mainly those natural gas-based production technologies) and, with a minor influence, by the combustion of natural gas for heating in other industrial sectors and also by the indirect impact attributable to the import of electricity from Germany.

Figure 4 shows the relative contributions of each process to generating commodities from the energy sector in Luxembourg, normalized to 1 Euro spent for net consumption of these products in the time series (2006–2009).

The imports play the major role, since their relative influence on the environmental impact is already above 70% only considering imported natural gas (as most directly consumed to produce electricity) and metalliferous ores and scrap (as most indirectly contributing to the energy sector through the inter-linkage with other economic sectors). While their relative contributions slightly decrease or increase, respectively, for 1 Euro net expenditure in energy commodities (Fig. 4), on the absolute scale we observe a general growth of the impact due to the energy sector (in its totality) on

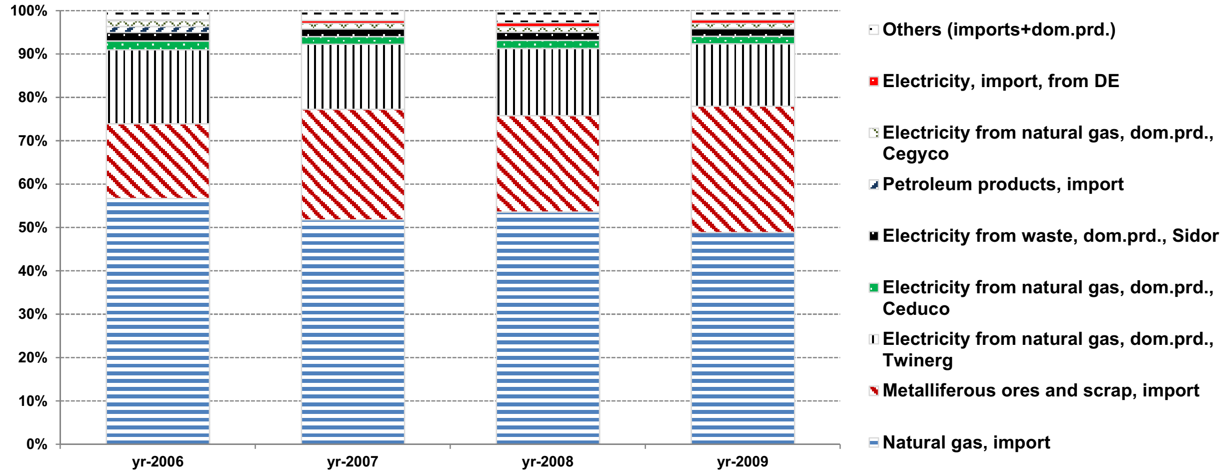

Fig. 4. Historical time-series profile of the relative contribution of imports and domestic production to the environmental impact in the energy sector within the framework of Luxembourg's net consumptions. The single issue impacts (ReCiPe end-point (H) V1.07 / Europe ReCiPe H/A) are normalized to 1 Euro spent in the energy sector to allow a consistent comparison of inputs' contributions by the investigated sector (cut-off 0.5%).

the overall net consumption of the country (i.e. the relative impact contribution of the energy sector increases of 15% from 2006 to 2009, and of 17% in terms of actual money spent to consume energy commodities).

This finding clearly demonstrates the relevance of the energy sector when compared with the impact on the country's economic scale, whereby the impact of net consumptions instead marginally decreases (as outlined in Fig. 3a). In this connection, the hybrid EE-IO model also enabled us to assess the relative impact over time of each technology producing energy. Accordingly, the impact provided by the largest electricity producer in the country (Twinerg, which generates electricity via natural gas) remains quite constant (around 7% of the overall net consumption's impact score and 16% within the energy sector itself), whereas the other domestic energy producers generate only marginal impacts (below 1% of the total impact profile of the Luxembourg's net consumptions).

In contrast, the increasing impacts from the energy sector mainly come from the (direct and indirect) consumption of the above-mentioned imported commodities (i.e. natural gas and metalliferous ores and scrap), for which we recorded increasing trends of impact scores of 2% and 6%, respectively.

2.2 Predicting impacts due to future energy scenarios

In order to provide a reasonable benchmark for future implementation of the integrated EE-IO analysis and assertions in the simulation of impacts from 2010 to 2030, the analysis of the effect of coupling methods between ETEM and LUXGEM is primordial.

The models have six aggregated sectors in addition to households where the energy demands have to be as close as possible. The process is considered as converged when the drivers for both models do not change from one iteration to the next. For example, when the growth rates of energy efficiency parameters do not change or the demand parameter alphas do not change, the coupling is considered as complete. This is done despite a potential large divergence of the energy consumption between the two models.

The modeling framework suggests that each of the studied coupling approaches has limited efficacy. The equilibrium model showed a limited response to the applied changes, which makes it difficult for energy use between LUXGEM and ETEM to converge (Fig. 5a). As an example, the results of the two models are presented in Figure 5b for the energy demand of electricity by the various sectors. Even if the absolute values are different, similar trends for some sectors such as agriculture or others are observed.

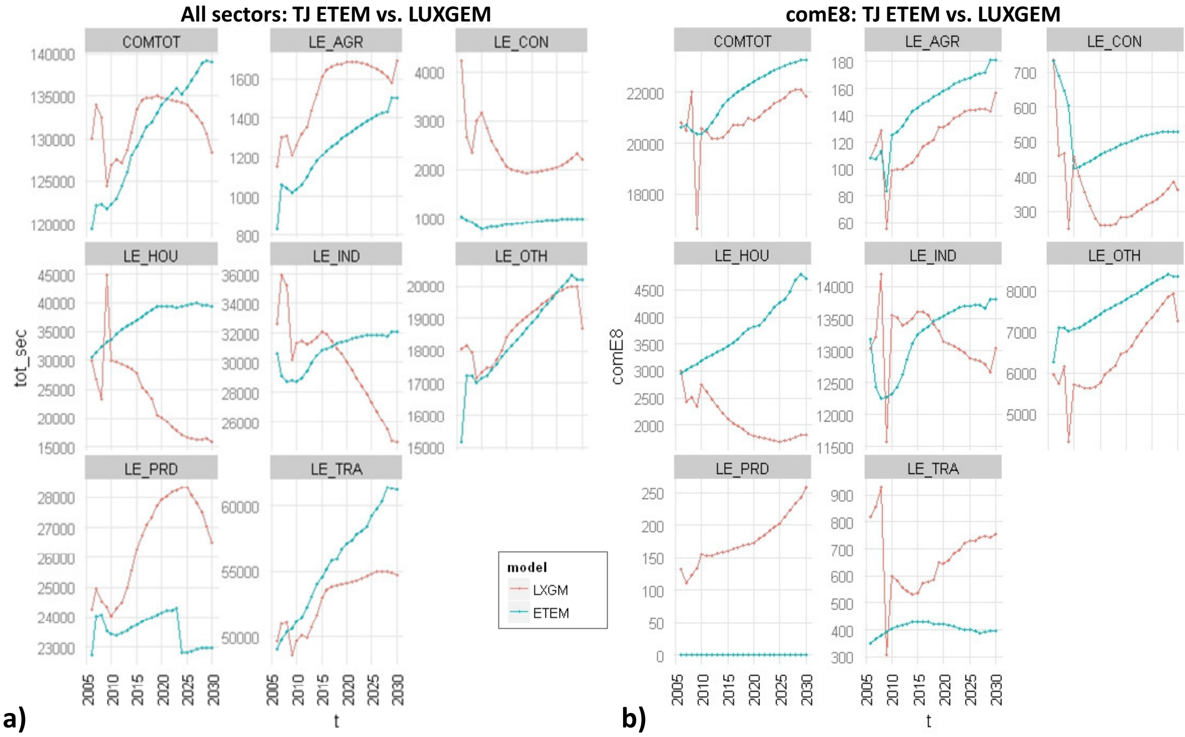

Fig. 5. Comparison of results from LUXGEM and ETEM (in TJ), for (a) all sectors, and for (b) energy demand of electricity (com E8), by the different sectors: COMTOT (total), LE-AGR (agriculture), LE-CON (construction), LE_HOU (households), LE_IND (industry), LE_OTH (others), LE_PRD (electricity production) and LE_TRA (transport).

For other sectors the behavior of the curves is completely divergent, like for households. These simulations were carried out for the five other energy commodities (coal, liquid fuels, fuels, gas and hot water, and other productions of coke or refined petroleum) as well, leading to similar conclusions. The ETEM and LUXGEM models basically answer differently to the drivers, which can lead to huge discrepancy in the corresponding energy demand (see Fig. 5a for all sector trends).

Additional lines of reasoning can be given with regard to the efficacy of each coupling approach. By changing demand parameters (alphas), the expenditure on energy commodities in LUXGEM was found to be not very high to begin with and neither was the amount of committed consumption as a share of the total consumption in the Linear Expenditure System (LES)[3] of each commodity. Hence, the changes in alphas marginally affect the demand for energy consumption in households.

The changes in the growth rates of energy intensity affect the value added, which in turn are the drivers for ETEM. However, in cases where the energy use in LUXGEM is lower than that of ETEM, the growth rates in energy intensity can at the most be zero (they are negative so as to have lower energy intensity corresponding to improved energy efficiency over time) and thus it makes it difficult to bring LUXGEM close to ETEM.

In order to further reduce the divergence between the two models, one could modify the production function share parameters. Thus, LUXGEM would have a different set of parameters for the production function for each time period. These parameters would be calibrated based on the data from ETEM and this approach would hopefully achieve a better level of convergence than the existing one.

Another possibility is to harmonize the levels of investments between the two models. However in our specific case, this approach had to be ruled out as the investment in ETEM exceeded that of LUXGEM in the electricity sector. Since LUXGEM has a more

[3] For details on LES refer to [30].

smooth investment profile, there is a limited potential for increasing investment in a particular sector. In ETEM the investment is lumpy, implying that the harmonization between LUXGEM and ETEM can potentially take place only where the investments are of a similar scale.

From a policy perspective each of the methods used for coupling would have different implications in terms of public spending or taxation. Incentives or taxes could be levied to change the behavior of households and industries in order to achieve a different basket of energy goods. This in turn would result in impacts generated, e.g., by greenhouse gas emissions. From a reverse thought process, in order to achieve a pre-defined level of emissions, one needs to choose a set of energy technologies that would be compatible with the emission levels. This, however, would come at a price. What that price is the economy would have to pay would be given by LUXGEM, while what can be achieved at that price and income level is given by ETEM. In the end, one hopes that the incentives would be strong enough to bring about the desired change to reduce emissions.

Conclusion

The present paper first aimed at presenting the results of the coupling of partial and general equilibrium models to predict future energy demands for the time horizon 2006–2030. The currently used approaches showed non-satisfactory results. This is due to fundamental differences in the behavior of the two models ETEM and LUXGEM. However, the authors are currently attempting to change the share parameters in the production function, which could lead to more reasonable results.

Accordingly, potential environmental impacts might be modeled for the future scenarios (2010–2030), since the second aim of the paper was to propose a framework for environmental assessment which could integrate the coupled outputs from the LUXGEM economic model and the ETEM energy technology model. The types of flows coming from the two models, expressed in monetary and physical units, respectively, were considered in a hybrid LCA combining EE-IO and process-based LCA. The corresponding structure was specifically built for Luxembourg in a large time frame (25 years, from 2006 to 2030) and could be adapted for other countries.

Although it was not possible to integrate results from the coupling of future scenarios, an assessment was carried out using historical data. The hybrid LCA enabled us to perform a deeper analysis of the results in the energy sector, allowing us to observe the technological change and the sectors' consumption, as well as to give an overview of the entire Luxembourg economy. For the years 2006–2009, we found that most of the impacts came from imported commodities (natural gas, metalliferous ores and metal scrap). The main energy production technology was the combined-cycle gas turbine plant "Twinerg", which represents almost 80% of the domestic electricity production in Luxembourg. In the hybrid EE-IO model, this technology contributed to around 7% of the total impact of the country's net consumption.

Further analyses will focus first on the completion of the models' coupling and its application to the defined scenarios. Then, an effort will be made to integrate the derived results within the EEI-IO to provide a consistent model for environmental assessment of the Luxembourg energy sector in future years, by modifying parameters of environmental extensions, domestic production and imports in time series.

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