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Summary

Nowadays, many countries adopt an active agenda to mitigate the impact of greenhouse gas emissions by moving towards less polluting energy generation technologies. The environmental costs, directly or indirectly generated to achieve such a challenging objective, remain however largely underexplored. Until now, research has focused either on pure economic approaches such as computable general equilibrium (CGE) and partial equilibrium (PE) models, or on (physical) energy supply scenarios. These latter could be used to evaluate the environmental impacts of various energy saving or cleaner technologies via life cycle assessment (LCA) methodology. These modelling efforts have, however, been pursued in isolation, without exploring the possible complementarities and synergies. In this study, we have undertaken a practical combination of these approaches into a common framework: on the one hand, by coupling a CGE with a PE model, and, on the other hand, by linking the outcomes from the coupling with a hybrid input-output–process based life cycle inventory. The methodological framework aimed at assessing the environmental consequences of two energy policy scenarios in Luxembourg between 2010 and 2025.

The study highlights the potential of coupling CGE and PE models but also the related methodological difficulties (e.g. small number of available technologies in Luxembourg, intrinsic limitations of the two approaches, etc.). The assessment shows both environmental synergies and trade-offs due to the implementation of energy policies. For example, despite the changes in technologies towards the reduction of greenhouse gas emissions, only marginal improvements are observed in the climate change mitigation scenario as compared to the business-as-usual. The energy related production and imports are indeed expected to

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increase over time and represent a large contribution to the country's impacts. Interestingly, side effects on other impacts than climate change or fossil resource depletion (e.g. ionising radiation and water depletion) may also occur mainly due to the use of nuclear energy in neighbouring countries.

Keywords: Computable General Equilibrium Model, Partial Equilibrium Model, Energy Policy Life Cycle Assessment, Consequential, Input-Output

JEL Classification: Q40, C67, C68

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Combination of equilibrium models and hybrid *life cycle-input-output* analysis to predict the environmental impacts of energy policy scenarios

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Abstract

Nowadays, many countries adopt an active agenda to mitigate the impact of greenhouse gas emissions by moving towards less polluting energy generation technologies. The environmental costs, directly or indirectly generated to achieve such a challenging objective, remain however largely underexplored. Until now, research has focused either on pure economic approaches such as computable general equilibrium (CGE) and partial equilibrium (PE) models, or on (physical) energy supply scenarios. These latter could be used to evaluate the environmental impacts of various energy saving or cleaner technologies via life cycle assessment (LCA) methodology. These modelling efforts have, however, been pursued in isolation, without exploring the possible complementarities and synergies. In this study, we have undertaken a practical combination of these approaches into a common framework: on the one hand, by coupling a CGE with a PE model, and, on the other hand, by linking the outcomes from the coupling with a hybrid input-output–process based life cycle inventory. The methodological framework aimed at assessing the environmental consequences of two energy policy scenarios in Luxembourg between 2010 and 2025.

The study highlights the potential of coupling CGE and PE models but also the related methodological difficulties (e.g. small number of available technologies in Luxembourg, intrinsic limitations of the two approaches, etc.). The assessment shows both environmental synergies and trade-offs due to the implementation of energy policies. For example, despite the changes in technologies towards the reduction of greenhouse gas emissions, only marginal improvements are observed in the climate change mitigation scenario as compared to the business-as-usual. The energy related production and imports are indeed expected to increase over time and represent a large contribution to the country's impacts. Interestingly, side effects on other impacts than climate change or fossil resource depletion (e.g. ionising radiation and water depletion) may also occur mainly due to the use of nuclear energy in neighbouring countries.

Keywords

Computable General Equilibrium model; Partial Equilibrium model; Energy policy; Life Cycle Assessment; Consequential; Input-Output.

1 Introduction

Nowadays energy supply comprises an essential component of economic, energy and environmental landscape that is exacerbated by the growing scarcity of fossil fuels and societal dependence on these resources. Many countries have developed energy policies to address the global challenge of mitigating current and future environmental impacts due to climate change (IEA, 2013). This concern is particularly important for small and highly developed countries, like Luxembourg, which do not own sufficient energy carriers and primary resources and depend on imported fossil resources to sustain their socio-economic welfare and technological development (Jury et al., 2013).

Luxembourg's greenhouse gas (GHG) emissions profile highlights the significant contribution of the energy sector, covering about 90% of the total GHGs emissions in 2011, and the increase of the emissions from energy-producing industries and transportation as compared to the 1990 levels (UNFCCC, 2013). Moreover, current energy policies in Luxembourg focus on improving the energy efficiency of buildings through the introduction of energy performance certificates (IEA, 2013). To fulfil the 20/20/20 targets set by the European Union in 2009 (EC, 2009), Luxembourg's energy mix should include by 2020 at least 20% of renewable sources, mainly biomass-based (Vázquez-Rowe et al., 2014). Nonetheless, the actual environmental consequences related to the implementation of new energy supply strategies in the country can no longer be evaluated without considering side-effects. For example, in Vázquez-Rowe et al. (2014), the use of maize-based biofuels to reach the 20% of renewable energy in Luxembourg was observed to increase indirect GHG emissions, land use and fossil depletion, also due to important shifts in the import/export of agricultural products.

The latter study was based on Life Cycle Assessment (LCA) (EU, 2010), which is one of the most commonly applied methods to evaluate the environmental impacts of goods and services over their entire supply-chain. In particular, Vázquez-Rowe et al. (2014) applied the consequential LCA perspective, aiming at describing the indirect and direct environmental consequences of (marginal or large scale) changes induced by strategic decisions and actions (Marvuglia et al, 2013), such as those driven by energy policies. Consequential LCA has still not achieved a full methodological consensus, mainly due to the different computational approaches proposed by scholars in the recent years. These have stimulated the development of alternative modelling techniques for impact scenarios and technologies implementation (Earles and Halog, 2011; Marvuglia et al., 2013). In this regard, vast literature already presented cases of evaluation of energy supply scenarios based on LCA. For example, Koskela et al. (2007), Brown et al. (2013) and Dale et al. (2013) focused on the assessment of production technologies for a given country and timeframe (Estonia for 2020, USA for 2055 and Brazil for 2040, respectively). The former authors analysed LCA-based scenarios according to strategic guidelines (e.g. 10% of renewable energy), but without changing the modelling (only adjusting plants efficiency to consider technological improvement). The two latter studies relied on cost optimisation models to determine the effects of electricity supply scenarios on the use of production technologies and the related environmental impacts on air quality and GHG emissions.

These studies show the flexibility and pertinence of LCA in bottom-up analyses. However, detailed datasets are needed to model the life cycle inventory (LCI) of current and future technologies with a significant degree of accuracy. Furthermore, the granularity of the LCA system boundary is usually limited, as process-LCA can fail in providing consistent evaluations of the environmental consequences to other economic sectors beyond energy. To cope with this inventory truncation problem, Dandres et al. (2011) discussed on the potential benefits of linking Partial Equilibrium (PE) or Computable General Equilibrium (CGE) models to LCA and

eventually combining them. They argued that such a link with LCA can improve the accuracy of inventory for specific evolving technologies in LCA, while enhancing the methodology to conduct consequential assessments of energy policies. In this regard, extensive literature demonstrates the feasibility and effectiveness of using CGE or PE models to simulate future environmental burdens, although the proposed analyses were typically limited to the estimate of future carbon emissions without considering a full life cycle perspective (e.g., Bae and Cho, 2010; Chen et al., 2007; Dai et al., 2011; Strachan and Kannan 2008; Thepkhun et al., 2013; Zhou et al., 2013). Interestingly, Input-Output (IO) models were often used in combination with CGE or PE models, either as alternative to LCA or to strength the overall LCI for some specific technologies (see e.g., Dandres et al., 2012; Earles et al., 2013; Lee and Lee, 2008).

Lee and co-authors (2011) and Mischke and Karlsson (2014) comprehensively illustrate the *pros* and *cons* of using CGE, PE, LCA and IO models to predict the environmental impacts at country's scale. On the one hand, CGE models are considered beneficial to provide with information to simulate the response of the full economy to certain policy scenarios, incorporating price changes at the level, for example, of IO tables. On the other hand, PE models can provide detailed data about demand and supply response to shocks in specific economic sector (e.g., energy sector) with possible links to LCA via modification of the LCI datasets. This latter approach typically combines Environmentally-Extended IO (EEIO) modelling for hybridisation with LCA, in order to achieve mutual benefits, among which avoiding system boundary truncation and increasing process evaluation detail (e.g. Tukker et al., 2009; Crawford, 2008, Hertwich, 2005). Despite IO tables may lead to several assumptions and limitations (see e.g. Heijungs and Suh, 2005; Rowley et al., 2009), their flexible and standardised structure may allow several adjustments and extensions, for example using outputs from PE and CGE models.

While it is common practice to use CGE or PE to forecast environmental impacts (in particular with regard to climate change) and assess mitigation scenarios, to the best of our knowledge there are no studies that explicitly address the improvement of consequential LCA by using a combination of CGE and PE. Therefore, the novelty of this paper consists in i) the development of a coupling between CGE and PE models in order to simulate future economic and energy scenarios, which in turn can lead to ii) the implementation of policy effects (changes in the economic/technological structure) in a hybrid LCA framework to assess future environmental impacts. More specifically, the objective is to assess the environmental consequences of an energy policy for GHG reduction in Luxembourg, which is taken as a case study, by looking at the country's *net consumptions* until 2025. A CGE model and a PE model specifically built for Luxembourg are coupled, and their outcomes implemented within a hybrid life cycle framework based on existing EEIO models in time-series. Such a methodological framework allows the consequential LCA of future energy policies benefit the different modelling and assessment tools. The final goal of the analysis is to support local institutional stakeholders in decision-making process related to the elaboration of future energy policy, as well as to understand the strengths and weaknesses of using such an integrated LCA-based approach to assess the environmental effects of long-term energy scenarios.

2 Methods

Figure 1 depicts the methodological approach used to establish the hybrid integrated environmental assessment based on the coupling between the CGE and PE models.

Section 2 (Methods) is structured as follows. First the CGE (LUXGEM) and the PE energy techno-economic (E'TEM) models for Luxembourg are briefly described (section 2.1). Then, their application to the assessment of two energy scenarios (Business-As-Usual - BAU and

Greenhouse Gas emissions reduction - GHGr) are introduced (section 2.2). The hybrid environmental input-output-based framework is detailed in section 2.3. This framework is finally applied to assess the environmental consequences of the GHG emissions reduction (i.e. the difference between the two energy scenarios) on the *net consumption* of Luxembourg taken as the functional unit (described in section 2.4).

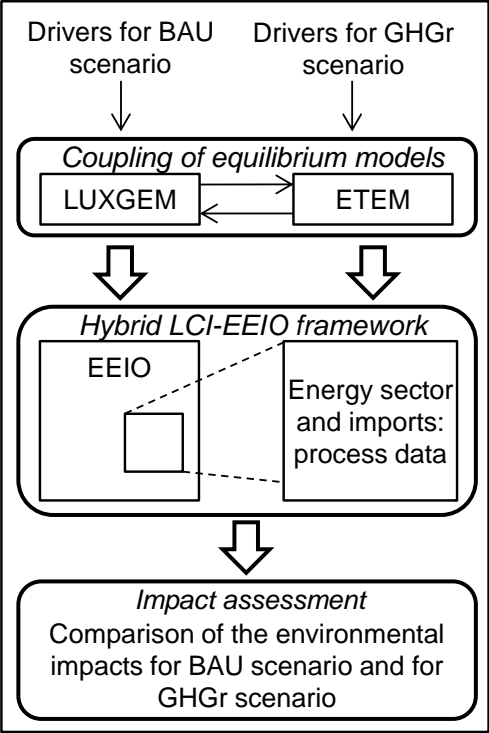


Figure 1 Schematic view of the methodological approach; BAU = Business-As-Usual; GHGr = Greenhouse Gases emissions reduction; LUXGEM = general equilibrium model for Luxembourg; ETEM = partial equilibrium model for the energy system in Luxembourg; LCI = Life Cycle Inventory; EEIO = Environmentally Extended Input-Output.

2.1 Coupling of economic equilibrium models

2.1.1 LUXGEM and ETEM

The CGE model for Luxembourg LUXGEM (Adam et al., 2010) is a sequentially dynamic model with a time horizon of 25 years comprising 16 sectors (following a Capital-Labour-Energy-Materials (KLEM) production function) and 20 commodities (see Table 1), and a single representative household that maximises its utility (Linear Expenditure System) subject to budget constraint.

The trade in LUXGEM is modelled using a *small country assumption*, which uses the Armington function (Armington, 1969) to distinguish between domestic and imported goods. The base year 2005 energy use (TJ) and GHGs emissions (carbon dioxide–CO₂, methane–CH₄ and dinitrogen monoxide–N₂O) are used to calibrate the initial emission coefficients.

Table 1: LUXGEM commodity and sector classification.

N	Commodities	No	Sectors
o			

1	Agriculture, etc.	1	Agriculture, etc.
2	Natural gas	2	Mining and quarrying of energy producing materials
3	Other products of mining and quarrying of energy	3	Manufacture of coke, refined petroleum products, etc.
4	Liquid fuels	4	Manufacturing
5	Fuels	5	Electricity, gas, steam, etc.
6	Other products of coke, refined petroleum, etc.	6	Construction
7	Manufacturing	7	Wholesale and retail trade services
8	Production and distribution of electricity	8	Hotels and restaurants
9	Other gas, steam and hot water supply	9	Transport, storage and communication
10	Construction	10	Financial sector
11	Wholesale and retail trade services	11	Real estate services
12	Hotels and restaurants	12	Business services
13	Transport, storage and communication	13	Public administration
14	Financial sector	14	Education
15	Real estate services	15	Health and social work
16	Business services	16	Other services
17	Public administration		
18	Education		
19	Health and social work		
20	Other services		

The Energy Techno-Economic Model (ETEM) for Luxembourg is a linear programming model that minimises the net present value of all - costs over a time horizon of 26 years in Luxembourg. ETEM for Luxembourg describes the whole energy system from the supply side to the end-use demands for energy services that include transportation, electricity and heat. Over the period 2005-2030, ETEM can select the least costly level of investment and activity of the technologies while satisfying the demands for energy services. The end-use demand sectors are agriculture, industry, commercial and institutional buildings, residential and transportation. The conversion sector includes the renewables and the power plants that produce electricity together with the cogeneration plants that produce coupled heat and power.

The Luxembourg energy system is calibrated for the base year 2005. The demands for energy services are exogenous, calibrated for years 2005-2010 based on national statistics (Statec, 2013). ETEM has 151 commodities of which only 24 are final demand commodities produced via 622 processes. Therefore, it is a *technology-rich* model. Each process can have one or several input commodities and can produce multiple output commodities including GHGs and other pollutants like Particulate Matter and Non-Methane Volatile Organic Compounds (NMVOC).

Imports and exports of electricity are also represented, amongst the other energy goods.

2.1.2 The coupling process

While LUXGEM is used to evaluate the economic impacts of policy decisions, ETEM computes operation levels for various technologies to meet the demand for energy services at the least cost. The future energy demand and supply in Luxembourg are then harmonised by coupling ETEM with LUXGEM in order to have the same macro-economic variables and energy shares driving both models.

The coupling between LUXGEM and ETEM is a “soft coupling”, i.e. the structure of the general equilibrium model is not changed with respect to the endogenous modelling of technologies (Drouet et al., 2008). The soft coupling is achieved using six common energy commodities (i) liquid fuels (liquefied petroleum gas and residual fuel oil); ii) fuels (biodiesel, bioethanol, gas/diesel oil, gasoline and kerosene); iii) other products of coke, refined petroleum, etc.; iv) production and distribution of electricity; v) other products of mining and quarrying of energy; and vi) other gas, steam and hot water supply) and six common sectors (i) agriculture; ii)

construction; iii) industry; iv) electricity production and distribution; v) transport; and vi) other industries). First ETEM needs drivers to generate demand for energy services, which in turn depend on the energy commodities that transformed inputs into outputs. These values are generated by LUXGEM based on economic interactions. To activate the coupling in LUXGEM, the energy shares are modified to update the energy intensity per value added and to bring the energy consumption as close as possible to ETEM. This iterative process is repeated until equilibrium is obtained, i.e. when the outputs of both models do not change anymore.

2.2 Scenarios development

We run two scenarios: the Business as Usual (BAU) and the Greenhouse Gases emissions reduction (GHGr). In the former, LUXGEM has exogenously specified drivers over time (growth rates, population, GDP), which are used to determine the growth of individual sectors. The forecasted energy demand is, therefore, used by ETEM to determine the mix of energy uses. In the GHGr scenario, a 2.5% cut of GHG emissions each year is imposed in ETEM. This reduction generates a change in the composition of the technology mix (the model chose the best possible technologies to deliver the least costly solution to meet the GHG reduction targets) and a commensurate change in the energy consumption by sector. The change in the consumption of the six energy commodities in these sectors is then fed into LUXGEM, which modifies the energy shares. The system is eventually iterated until no further changes are observed in the drivers, which implies that no additional modifications are possible in the energy consumption profile.

2.3 Hybrid process-EEIO LCI framework

Life Cycle Inventory (LCI) includes the collection of all the exchanges (inputs and outputs) between the technological and the environmental compartments of the studied system (ISO, 2006). LCI is conventionally done through process-based data surveys, where all the materials, chemicals and energy requirements, as well as the waste and emissions flows, directly solicited by the technological system under study, are listed. To this end, foreground data (usually collected on-site) are linked with background data (relative to the upstream and downstream supply-chain). The latter are usually found in process oriented LCI databases such as ecoinvent® (The ecoinvent Centre, 2013). However, an increasing number of LCA studies rely on the use of EEIO models to broaden the scope of their analysis, by including other processes indirectly implicated in the technological system, like e.g. maintenance, services etc. (e.g. Huppel et al., 2006; Kitzes, 2013; Larsen and Hertwich, 2009; Majeau-Bettez et al., 2011; Minx et al., 2009).

Therefore, our objective is to combine process and EEIO inventories in a hybrid LCI approach to strengthen the consistency of the overall inventory model. Energy-technological data from ETEM (after the coupling) are modelled using process based LCI datasets, whereas the economic inter-linkages and sectorial relationships specific for the country are represented by IO data retrieved from LUXGEM (after the coupling). This combination further allows characterising the future *net consumption's* patterns of Luxembourg, as previously outlined in Jury et al. (2013) and Rugani et al. (2014). The analysis is performed along the two scenarios outlined above, i.e. *net consumption* subject to the inclusion (or not) of the energy policy of GHG reduction.

2.3.1 Building the hybrid LCI model for Luxembourg

A set of EEIO tables from 2010 to 2025 are built starting from an existing hybrid model recently built for Luxembourg (Rugani et al., 2014). This model includes World Input-Output Database-WIOD (Timmer, 2012) as the main source of environmental satellite accounts, because WIOD

discloses comprehensive and formerly allocated-by-sector data (3 types of water consumption, 7 types of land use, 8 raw materials extractions and 8 pollutant emissions) in Luxembourg during the time period 1995-2009. WIOD environmental data for Luxembourgish sectors are combined with available IO tables for the country (Statec, 2013), leading to a 43×43 (product-by-product) EEIO model in time-series. The IO tables for imports are built by using the inter-industry transactions share available in the WIOD. The original imports' vector of the IO table (inclusive of 43 industry products) is then disaggregated in 67 imported goods (in physical units) and 15 imported services (in currency units) (Eurostat, 2013), which are associated with the corresponding cradle-to-gate LCI processes to encompass the upstream supply-chain in the rest of the world (LCI data retrieved from Jungbluth et al., 2011). More details about this hybrid LCI model and the data sources utilised are available in Rugani et al. (2014).

To forecast the environmental extensions and the imports coefficients in the hybrid IO-LCI framework from 2010 to 2025, those datasets from 1995 to 2009 are initially averaged and assumed to remain constant over time. Then, two modifications are made on the 43×43 matrix system. First, all the energy-related imports (i.e. coal, coke and briquettes, petroleum, products and related materials, natural and manufactured gas and electricity current) are set to zero, and the environmental extensions associated with the energy sector (namely “electrical energy, gas, steam and hot water”) are removed, to avoid double-counting with data retrieved from ETEM (see Section 2.3.2). Secondly, the 43×43 matrix is aggregated into a 16×16 system to match the current LUXGEM structure (see Table 1), including IO coefficients by sector for intermediate, added value, import, export, final demand and gross capital formation vectors.

Finally, LUXGEM coefficients over time (2010-2025) obtained through the coupling with ETEM are implemented along those vectors allowing the creation of hybrid EEIO models in future time-series for Luxembourg, according to the two energy policy scenarios described in section 2.2.

2.3.2 Implementation of energy process data

As mentioned before, while the monetary exchanges across sectors in Luxembourg are inventoried using the LUXGEM outputs, the environmental extensions and physical energy exchanges between the energy sector and the rest of the economy are modelled using the energy production technologies included in ETEM. This enabled to enlarge the resolution for the energy sector with site-specific data for Luxembourg, creating a mixed physical-monetary IO framework. The energy technologies production (in TJ) are divided by the total economic output of the energy sector retrieved from LUXGEM in order to normalise them to one Euro spent in the energy sector. This allows increasing the consistency of the model as all the transaction flows in the IO can be set in monetary terms according to the outputs from the LUXGEM-ETEM coupling.

ETEM technologies are mapped using corresponding ecoinvent® v2.2 unit processes. ETEM includes 18 domestic energy production technologies, among which 8 multi-output (multi-functional) processes generating electricity and heat (seven from natural gas and one from biogas). However, as ecoinvent® can work only using mono-functional (allocated) processes due to matrix inversion constraints (Frischknecht et al., 2007a), an energy criteria-based allocation is applied to those 8 technologies, obtaining 17 electricity and 9 heat derived processes in total (Table 2). The selected corresponding ecoinvent® datasets are further modified to account for the efficiency ratios and combustion emissions according to the process modules retrieved in ETEM. They are also adapted to avoid double-counting and overlaps between environmental interventions occurring outside and inside Luxembourg (following the EEIO framework).

Indeed, a typical energy production process from ecoinvent® contained inputs and outputs directly linked to the environmental sphere (e.g. energy from wind or emissions of carbon dioxide into air) and other items linked to the technosphere (e.g. consumption of refined materials or waste to a treatment plant). In order to account for environmental impacts of the energy sector only, direct emissions (mainly linked to the fuel combustion) and the land use underlying the production plant are added together with the 26 ecoinvent® processes (*gate-to-gate* perspective). The remaining LCI process flows (e.g. infrastructure, use of water, chemicals, etc.) were removed (except for energy inputs) as they are already taken into account within the EEIO framework through the monetary exchanges and attached environmental extensions. Among the energy inputs, the 5 direct (captured on-site) resources are modelled as elementary inputs and the 11 among fuels and electricity are accounted for as imported commodities (*cradle-to-gate* perspective), using the most pertinent ecoinvent® datasets (see Table 2). These energy inputs related to one Euro spent in each of the 16 economic IO sectors of the model are all retrieved from ETEM and expressed in physical units. For electricity imports, the share between Germany and Belgium needs to be estimated (as it was not given by ETEM) and is averaged starting from the supply mix during the time period 2003-2011 (only 5% of variation among those years).

Table2: Characteristics and types of lifecycle unit processes linked to the ecoinvent® unit processes (i.e. modified according to the assumptions underlying ETEM and then integrated within the hybrid LCI-EEIO system to model the energy supply and demand in Luxembourg). The processes have been chosen to be representative of Luxembourg (LU), or of Europe (RER) and Switzerland (CH) if not available.

Energy type from ETEM	ecoinvent® module of reference	Features
#16 commodities modeled as inputs to the various IO sectors (including the energy sector)		
#5 direct energy resources: (only ecoinvent® elementary flows, if any)		
Air heat potential	-	Used to model domestic inputs (recovered waste and natural, renewable resources); not linked to any unit process
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]	
#11 imported fuels and electricity:		
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-sulphur, at regional storage [RER]	
Imported electricity (mix BE, DE)	Electricity, prod. mix [BE]; Electricity, prod. mix [DE]	
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]	
#26 technologies of electricity and heat production replacing the original energy sector of the domestic IO table		
10* Electricity, from nat. gas	Electricity, natural gas, at power plant [LU]	Included: - Direct resource extraction and emissions as domestically occurring
Electricity, from hydropower	Electricity, hydropower, at power plant [LU]	
Electricity, from	Electricity, production mix photovoltaic, at plant [LU]	

	photovoltaic		- Imported fuel as an LCI input
	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]	<u>Excluded:</u> Other inputs or outputs from the technosphere to avoid double-counting with the IO dataset
3**	Electricity, from wind	Electricity, at wind power plant 600kW [CH]	
7***	Heat, from natural gas	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 1000kW [CH]	

* One plant called Twinerg (the biggest electricity producer in Luxembourg), two smaller ones called CEDUCO and CEGYCO, and seven combined heat and power plants among three with backpressure gas (representative of 2006, 2020 and 2025); ** Wind parks in Kehmen, Heinerscheid and other smaller ones (grouped in one technology); *** Seven combined heat and power plants (see note *)

2.4 Life Cycle Impact Assessment (LCIA)

The conversion from inventory flows to impact results, called Life Cycle Impact Assessment (LCIA), is typically performed via the classification and characterisation of the flows into impact categories, describing cause-effect chain models (ISO, 2006).

The LCIA of *net consumption* in Luxembourg is performed to forecast the potential environmental impacts of final consumers' activities in the country, as *net consumption* equals *domestic production + imports – exports* (Jury et al., 2013; Rugani et al., 2014). The ReCiPe (H,A) method (Goedkoop et al., 2009) is selected. This method includes 18 midpoint impacts, i.e. direct environmental effects like eutrophication or human toxicity, expressed according to a reference substance (e.g. kg CO₂-eq for climate change, kg P-eq. for eutrophication and kg Fe-eq. for mineral depletion). Further assessment is done at the endpoint level, the latter originated from conversion of the midpoints into damages on three areas of protection (AoP): human health (expressed in Disability-Adjusted Life Years, DALYs), ecosystems (losses of species.year) and resources (dollars).

The scores for the three AoP are examined in detail (section 3.2.1) since they are easily comprehensible for stakeholders and policy makers. A focus on three particular midpoints is also made: Water Depletion (WD), Land Use (LU - grouping the categories agricultural land occupation and urban land occupation from ReCiPe) and Climate Change (CC). In addition, the Cumulative Energy Demand (CED; Frischknecht et al., 2007b) is evaluated (section 3.2.2) as inherently associated with the direct and indirect burden related to energy consumption. These four LCIA midpoint indicators are selected due to their appropriateness in emphasising specific environmental issues that are usually of general concern for policy support strategies and for communication purposes.

The full set of hybrid LCI-EEIO models are built in the SimaPro software version 7.3.3. LCIA results are calculated and compared over time and along the two energy policy scenarios BAU and GHGr, considering two different functional units: i) the total *net consumption* of Luxembourg from 2010 to 2025, and ii) one average Euro spent for final energy use by Luxemburgish users in the same timeframe. Accordingly, it is possible to assess the potential annual environmental consequences of the GHGr policy from an overall viewpoint (total *net consumption*) but also analyse in terms of environmental efficiency gains, through the evaluation of intensity metrics (impacts/Euro).

3 Results

3.1 Coupling of equilibrium models

The total energy consumption per sector (sum of the six commodities) obtained for the two scenarios BAU and GHGr are displayed in Figure 2.

Despite the efforts spent to make the outputs of LUXGEM and ETEM converging, it was not possible to obtain a perfect coupling. The explanation for this issue is detailed in Section 4.2.2. The results also show that the outcomes of the two scenarios are very similar. The main differences are observed for the LUXGEM outputs for the construction (8% to 12% lower than ETEM outputs) and the energy sectors (5% to 9% lower). When observing the total energy consumption of the country (by adding up the consumptions by sector), a reduction of about 1% of the GHGr scenario from the BAU scenario is obtained (both in LUXGEM and ETEM). This low improvement in efficiency gained with the GHGr scenario can be explained by the intrinsic limitations of the models. For instance, in ETEM it is not possible to model the technology embedded in the imported energy. Hence, a large fraction of energy imports implies lower degree of freedom over the actual impact than changes in domestic technology have in the energy consumption. We observe that the extent to which the energy consumption in the BAU and GHGr scenarios changes depends on the energy intensity of the industries under consideration. Luxembourg is a service oriented economy and with the reduction in the output of steel, the energy intensity of manufacturing industries is reduced. In contrast, any changes in technology have minor effects on service industries and agriculture. There is no major impact on transportation as the fuel is sold to foreigners and commuters, and local transportation is a small portion of it. Moreover, energy efficient technologies such as hybrid buses and cars have a limited impact. We conclude that the peculiar nature of the small Luxembourgish economy makes the coupling of the two equilibrium models quite challenging.

The lack of an energy intensive manufacturing sector and an excessively large service sector that does not exhibit an elastic energy demand also aggravates the problem. Due to these constraints, few changes are observed in ETEM and the related GHG emissions in 2025 are about 10% lower than in the BAU scenario, when initially a 40% cut was expected.

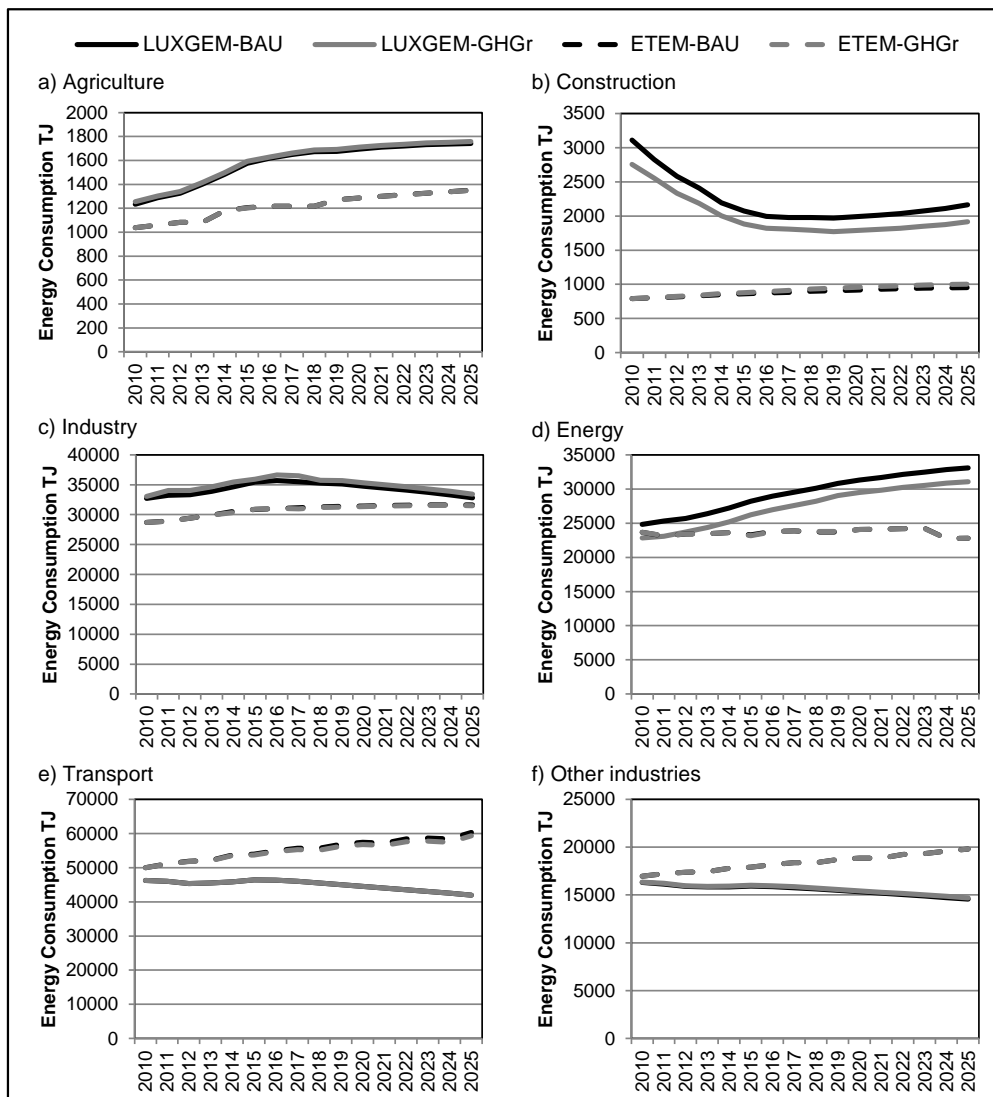


Figure 2 Energy consumption for the six sectors given by LUXGEM and ETEM, obtained with scenario BAU (Business-As-Usual; black lines) and scenario GHGr (Greenhouse Gases emissions reduction; grey lines).

3.2 Life cycle impact assessment

3.2.1 Endpoint assessment

The environmental impacts of Luxembourg's *net consumption* for the two energy scenarios, showing the environmental consequences of the introduction of a policy for GHG reduction, are displayed in Figure 3. To simplify the interpretation, the results are given for every third years. Moreover, a distinction is made between the total impact for the categories “energy production” (to assess the relative *gate-to-gate* contribution of the ETEM technologies to the final impact) and “energy imports” (to assess the relative *cradle-to-gate* contribution of the imported fuels and electricity processes to the final impact).

Regardless the endpoint damage category chosen, the following occurrences are observed: (1) impacts are increasing over time for both scenarios due to the growth of final goods and services demand, (2) the GHGr scenario gives quite stable impact score trends over time and only about

2-3% lower as compared to the BAU scenario, and (3) the difference between the two scenarios for sectors and imports other than energy is very low (less than 0.1%).

For human health and ecosystems endpoint damages (Figure 3a,b), the advantage of implementing GHGr scenario-based strategies over time is on average about 7% for “energy production” technologies (due to lower energy generation from natural gas and municipal solid waste) and about 2% for “energy imports” (due to decreased natural gas imports).

With regard to the endpoint impacts on resources, they all relate to the production of imported commodities, since there is no extraction of non-renewable resources in Luxembourg. By comparing the two scenarios’ trends, better profiles on the “energy imports” are observed with a relatively linear increase over time, from 3% to 7% (due to lowering of natural gas imports) (Figure 3c).

The relative contribution of sectors and commodities is quite similar from 2010 to 2025 across the scenarios studied. The environmental profile of Luxembourg’s *net consumption* is mainly driven by imported commodities (about 70% of the impacts on human health and ecosystems and 100% for resources). This is related to the very high contribution (87% in 2010) of the tertiary sector to the GDP in Luxembourg (Gargano, 2012). All the energy-related processes (production and imports) also influence the environmental profiles with at least 50% of contribution in each endpoint. For human health and ecosystems, this is due to carbon dioxide emissions from combustion of natural gas (domestic impacts), while the damage on resources is mainly driven by the extraction of natural gas and crude oil required to produce the imported natural gas, diesel, petrol and kerosene. The main damages on human health come from the imports of electricity from Germany (10-15%), natural gas (6-7%), diesel (5%) and iron and steel (5%), as well as from the “Twinerg” electricity production plant in Luxembourg (20-25%), powered by natural gas (see footnotes in Table 2 for the plant’s characteristics). For impacts on ecosystems, the main contributors are still due to the “Twinerg” plant (20%), and the imports of electricity from Germany (7-10%), natural gas (5-6%), diesel (5%) and products of coffee, tea, cocoa and spices (5%, mainly imported for agriculture and manufacturing sectors and inducing a transformation of forest). Finally, the depletion of resources is mainly due to the imports of metalliferous ores and metal scrap (25-30%), natural gas (20-25%), diesel (13%) and kerosene (5-10%).

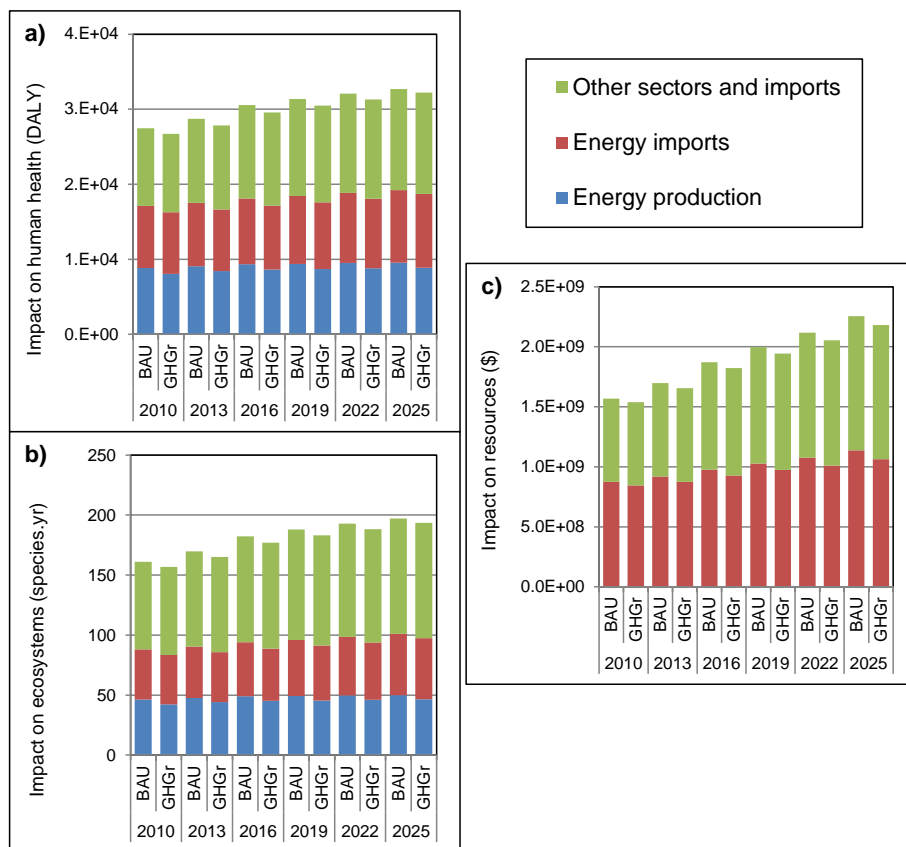


Figure 3 Comparison of Luxembourg's net consumption impacts (with focus on energy-related processes) on a) human health, b) ecosystems and c) resources, which are three areas of protection AoP-endpoint damage indicators modelled with the ReCiPe method; BAU = Business-As-Usual; GHGr = Greenhouse Gases emissions reduction.

3.2.2 Midpoint assessment

When comparing the two energy scenarios at the midpoint level, different trends can be observed. While climate change, ozone depletion, photochemical oxidant formation and fossil depletion are clearly improved with the GHGr scenario (decrease by 3-4%), freshwater eutrophication and ionising radiation show worse trends. The latter usually characterises the impact due to nuclear energy use, and is the most affected in our case as it is 13% higher in GHGr than in BAU. This effect is apparently due to the increase of electricity imports occurring over time, in particular from Belgium, which is going to produce more than 50% of its mix from nuclear energy in our model.

Figure 4 shows the results for CC, LU, WD and CED for the time period 2010-2025. Regardless the energy scenario and the impact category considered, the impacts per Euro spent in the energy sector decrease over time. The latter outcome reflects the enhancement of efficiency expected from the technologies implemented in ETEM.

With regard to CC, the GHGr scenario results in about 3-4% lower impacts than the BAU for the total *net consumption* profile, and about 7% lower impacts for the energy production technologies. The 20% target for the energy sector is not reached, mainly due to the limitations of the coupling (see Section 4.2.2). In fact, the reduced GHG emissions of the energy sector are counter-balanced by the higher imports of electricity from Belgium and Germany to meet the

increasing energy demand. The total *net consumption* generates also lower impacts on CED for the GHGr scenario (about 6%), whereas only 1% reduction on LU and WD is observed.

Concerning the profiles linked to energy intensity (dash lines in Figure 4), the GHGr scenario induces a reduction on CC and CED of about 6-7% as compared to BAU, while the reduction is of 1% only for LU and WD. As a consequence, these impact categories seem less affected by the constraint of reducing GHG emissions. The rationale is that the inventory flows for water and land consumption were not originally included in ETEM and thus did not change with the increase of efficiency in the energy technologies modelled in SimaPro, as no sufficient information was available to modify the LCIs of future energy processes with regard to those flows.

Nevertheless, the increase of WD in the GHGr scenarios observed over the last period (2020-2025) mainly depends on the increased import of electricity (nuclear power plant sourced). This further confirms that addressing the mitigation of one impact category (such as CC) may cause impact trade-offs, potentially affecting other environmental spheres such as freshwater ecosystems.

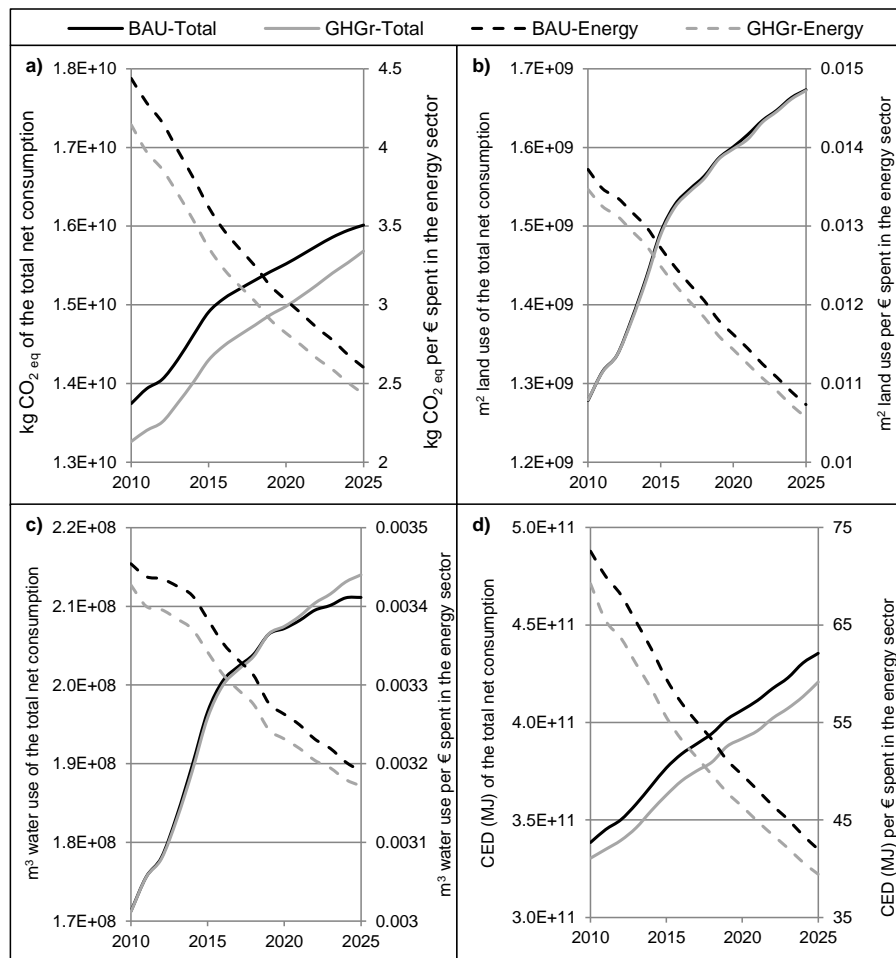


Figure 4 Impacts of the total net consumption of Luxembourg (plain lines, scale on the left) and impacts of one Euro spent in the energy sector (dash lines, scale on the right) for scenarios BAU (Business-As-Usual; in black) and GHGr (Greenhouse Gases emissions reduction; in grey) on a) climate change, b) land use, c) water depletion, and d) cumulative energy demand.

4 Discussion

4.1 Pertinence of the methodology

The current study examined the effectiveness of combining equilibrium modelling approaches with hybrid life cycle-based tools to improve the analysis of energy policies at country scale. The ultimate objective of this study was to contribute to the advancement of knowledge on the development and use of decision-making support instruments in the domain of energy production and consumption, a topic which is of primary importance for the well-being maintenance of current and future generations.

To the best of the authors' knowledge, the development of such an integrated assessment framework has only been sparingly proposed in the context of LCA. Despite the literature offers numerous examples of combined tools, techniques, applications and developments in the field of environmental impact analysis with CGE and PE models (Dandres et al., 2011; Koskela et al., 2007; Brown et al., 2013; Dale et al., 2013), impact categories or issues considered have been usually limited (e.g. assessment of GHG emissions, land use, water use) and economic equilibrium models (CGE and PE) have only been used separately for consequential LCA (Marvuglia et al., 2013, Vázquez-Rowe et al., 2013). Therefore, the coupled use of CGE and PE models focusing on the energy sector, which is highly recalled and directly linked to any other economic sector at country scale, is certainly novel and provides with a mutual enrichment for both LCA and equilibrium-based modelling. Accordingly, while LCA-based models can be improved at the level of forecasting scenario analysis, equilibrium models can benefit from the larger scope in impact assessment of LCA.

In fact, LCA allows accounting for a large number of effects other than e.g. climate change or resource depletion, and this is widely acknowledged by policy stakeholders and other decision-making actors (Wolf et al., 2012). Whereas energy policies are usually narrowed towards the mitigation of a limited range of impacts, as they mostly depend on governmental regulations aimed e.g. at reducing the consumption of crude oil or improving biodiversity status, the use of an integrated and multi-criteria perspective (as incorporated in LCA) can allow the evaluation of a wide spectrum of cause-effect chains that could counter balance possible restricted conclusions and help identifying trade-offs and side-effects. The lifecycle perspective also prevents the unwanted shifting of impacts across the different stages of products. LCA has been recognised as a pertinent integrated approach for decision making support in Europe (COM, 2003 and COM, 2008) and outside Europe (e.g. policy for waste management in Brazil, for energy-using products in China, etc.). LCA can therefore be applied for policy development (e.g. forecasting and analysing the environmental profiles of novel technologies or materials management strategies), and for policy information (e.g. identifying sectors or product groups with high improvement potential).

Moreover, the advanced methodology fits well within the consequential LCA approach, whereby the aim is to assess the consequences engendered by policy (or strategic) decisions in sectors not directly linked to the studied system (UNEP/SETAC, 2011). As already proposed by Dandres et al. (2011), CGE modelling can be used in consequential LCA to assess the environmental impacts of energy policies at large scale. However, Dandres et al. mapped a CGE model (GTAP) with process-data, after conversion of monetary values to mass units. In contrast, the hybrid input-output framework proposed here was modelled according to a different scope, with detailed process data for energy technologies and projected IO coefficients obtained after a sequence of conditioned shocks imposed to the energy sector fully linked with the rest of the economy. The coupling of a (bottom-up) energy model with a (top-down) economic model seems to be a more

realistic approach than basing the analysis on exogenous data, as it would be the case when running the equilibrium models separately. The reason is that potential extremes, possibly arising from policy conditions' imposition, would be limited by the coupling constraints. The relevance of such an integration to reflect climate policy has also been highlighted in Fortes et al. (2013).

4.2 Uncertainty and limitations

4.2.1 Characterisation of uncertainty

As mentioned in section 2.3.1, the future environmental interventions as well as the future demand of imported goods and services (except energy), associated with one Euro spent for each sector, were averaged in the EEIO framework for the period 1995-2009 (EEIO tables originally sourced by Rugani et al., 2014) because they could not be retrieved from the economic coupling or any other source. This approach added uncertainty to the impact results obtained, as future technologies and consumption behaviours will perform differently, in terms of environmental efficiency, than in the last 15 years.

Therefore, the associated uncertainty was characterised as follows: first, uncertainty distributions (from 1995 to 2009) were determined for each environmental and product import flow, assuming either lognormal (specifying the geometric standard deviation) or uniform (specifying the minimum and maximum values) distributions. Then, a Monte Carlo analysis based on 1000 simulations was performed to analyse the range of variation of the impact results for 2010. The analysis was not carried out for other years, since the same average and uncertainty values were applied. Uncertainties from background data (e.g. ecoinvent® unit process for electricity imports) were not included, because the focus was essentially on the assumptions made at the foreground level.

Results showed that the damage scores are very close to the ones calculated with the average values (less than 1% difference), which represents a coherent result. The coefficients of variation (i.e. the standard deviation divided by the mean) are however quite high: 4.7% for ecosystems, 8.2% for human health and 16% for resources. As a consequence, the impact differences observed between the two scenarios (1.9% and 3.6%; see section 3.2) become insignificant when the uncertainty ranges are considered. Hence, based on the uncertainty characterisation performed on the environmental extensions and the imports coefficients, it is not possible to conclude that there are positive environmental consequences on the net consumption of Luxembourg, over time, following the energy policy promoting GHGr reduction. The uncertainty analysis confirms that assessing the environmental performances of our future society is highly challenging.

4.2.2 Limitations underlying the coupling of equilibrium models

Perfect coupling of two equilibrium models driven by different objectives in order to achieve a common goal is possible only if both models have similar data structures. Unfortunately, ETEM and LUXGEM have completely different data structures and modelling methodologies, which eventually led to discrepancies in the coupling trends (see Section 3.1). In order to obtain a common platform, both LUXGEM and ETEM were modified to finally consider a set of six common sectors and six energy commodities. To this end, a problem that had to be faced was the use or absence of a particular energy commodity within a sector. For instance, while the construction sector in LUXGEM used thousands of TJ of fuel per year, this energy commodity was not used in ETEM. The rationale is that the construction equipment was classified under “transportation” and not under “construction”. This peculiarity made the convergence of the

energy use between both models impossible as one cannot set the coefficients in the CGE model to zero. Hence, soft coupling implies that energy prices are not determined endogenously from the CGE model but are exogenously specified.

In order to improve the coupling between ETEM and LUXGEM, a hard coupling strategy similar to that of Böhringer and Rutherford (2007) could be followed, where one would need a large energy sector in the economy wherein it plays a major role in energy supply, especially electricity. Most CGE models employ the *small country assumption*, wherein the import prices are given as fixed and there is a substitution between domestic and imported goods. Electricity is a homogenous commodity and cannot be segregated based on origin, which implies that if the domestic producers produce electricity at competitive rates below import prices, then the entire capacity will be utilised before imports can initiate. Nevertheless, if the situation is reverse with imported electricity being cheaper, then the residual demand will be fulfilled by the domestic suppliers if at all. As a consequence, the assumption underlying the hard coupling approach of Böhringer and Rutherford (2007) would not be feasible in the Luxembourgish case or for that matter any country where the domestic energy sector is small compared to the imports, as the size of imports would be large, thus negating any effects of domestic competition on prices of imported energy. The physical size and the limitations that follow hamper the potential sources of energy generation technologies in Luxembourg and other countries of similar size. The coupling approach to a more technology oriented analysis of energy demand per se is a valid methodology to pursue but in our specific case of Luxembourg, the small size makes it difficult to reap the full benefits.

4.2.3 Limitations underlying the hybrid LCI framework

Evaluating environmental impacts in the future and at macro-scale surely implies adopting a large number of assumptions. The present study relies on the coupling of equilibrium models to model energy supply and demand, as well as the behaviour of a full economy. However, due to the limitations discussed in section 4.2.2, perfect coupling did not occur and the energy demand of each sector differed between ETEM and LUXGEM. The LCA results are therefore biased due to this mismatch. For example, the sum of the energy imports in TJ for one sector may be higher or lower (after conversion to monetary terms) than the predicted value of LUXGEM, but it is unknown which value is the correct one.

The change in sectorial resolution level on the hybrid EEIO models can also underlie uncertainty due to some arbitrary choices in the aggregation of the initial 43 IO economic sectors during the elaboration of the 16×16 IO tables. Moreover, as discussed in section 4.2.1, the environmental extensions and the IO table for imports could not be predicted in this research even if this could have a large influence on the results.

To accomplish comprehensive policy analysis and make consensual assertions, the use of only one LCIA method can be certainly a source of limitation. Thus, to check whether the use of ReCiPe was actually limiting the findings obtained here, another LCIA method was tested, i.e. IMPACT 2002+ (Joliet et al., 2002). The two methods differ in the consideration of climate change as an endpoint (whereby the impact category is translated into damages on human health and on ecosystems in ReCiPe) and the midpoints ‘aquatic acidification’ and ‘eutrophication’, which are not represented at the endpoint level with IMPACT 2002+.

The comparison of the two scenarios with IMPACT 2002+ shows similar results as with ReCiPe, suggesting that the choice of this method was acceptable. The impact of the *net consumption* of Luxembourg decreases in the GHGr scenario by *ca.* 2% on human health, 1% on ecosystems, 3-4% on climate change and 3% on resources. Similar conclusions can also be drawn for the

midpoint analysis with a net advantage on ozone layer depletion, respiratory organics (which evaluates similar effects than with the midpoint photochemical oxidant formation of ReCiPe), climate change and non-renewable energy (equivalent to fossil depletion in ReCiPe), and with significant higher impacts on ionising radiation.

Finally, most of the ecoinvent® processes used either to model the imports or to model the energy production technologies (see Table 2) were not specific to the Luxembourg geographical condition. Process inventories were from average European or Swiss technologies and were not assumed to change over time. An exception was the one of those ecoinvent® processes modified according to the energy technologies from ETEM, having efficiency ratios and combustion emission profiles changing over time. Therefore, the use of appropriate LCI databases for emerging energy technologies is certainly another issue that shall be coped with in the future to enrich the hybrid model proposed in the present paper.

5 Conclusions

This study consisted in the development of an integrated approach combining economic equilibrium models and LCA, giving a broad overview on the potential consequences of implementing energy policy strategies. The application of the novel methodology proposed here matches the requirements of a consequential LCA approach aiming at assessing the effects of large scale changes quantified at the policy (through the use of CGE model) rather than at the production level (like e.g. in Vázquez-Rowe et al., 2014). The coupling of CGE and PE models provides complementary results by detailing the energy supply and demand data by sector and describing the full economy's response to changes in consumption behaviours. To translate these outcomes into environmental impacts over time, a hybrid LCI framework disaggregated and detailed at the level of energy sector has proven to be insightful for consistent application at country scale.

The environmental profile of the *net consumption* of Luxembourg had similar trends between the BAU and GHGr scenarios, with only marginal environmental benefits for the GHGr scenario (3-4% overall considering the average among damage scores). Therefore, the implementation of the GHG reduction policy was found to have quite low influence on the net consumption, even if the energy related production and imports represent a large contribution to the country's impacts. The results were validated through the comparison of two different methods (ReCiPe and IMPACT2002+). However, these suffer from large variations when applying uncertainty ranges on the prediction of environmental extensions and detailed imported data per sector.

The environmental assessment of future scenarios is a complex exercise and the proposed methodology still needs further developments. For instance, possible solutions to limit the mismatch between CGE and PE models should be investigated for a better consistency of the results. The environmental modelling can also be improved by forecasting more inventory data. Overall, however, the proposed integrated modelling approach is original and flexible enough to perform the analysis of future scenarios at any sectorial scale, while able to disclose straightforward environmental recommendations for policy support.

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