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ORIGINAL ARTICLE

Analysis of the Belgian electricity mix used in environmental life cycle assessment studies: how reliable is the ecoinvent 3.1 mix?

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Abstract The current contribution gives insight into the Belgian low-voltage electricity mix, used in environmental life cycle assessment studies and modelled following the attributional and consequential approach. Is the electricity mix for Belgium, as available in the life cycle inventory database ecoinvent 3.1, representative for the current electricity mix and the future developments? Studies on this research topic are missing in the literature, especially for this particular geographical and time frame. In this study, data from the European Network of Transmission System Operators for Electricity and the Federal Planning Bureau have been used to model the historical and future Belgian low-voltage electricity mix. The environmental impact is analysed for different scenarios: attributional and consequential modelling, historic and outlook data, the domestic electricity mix and the extended mix with import from other countries. The life cycle inventory database ecoinvent 3.1 and the life cycle impact assessment method ReCiPe version 1.12 are used. It was found that the historical attributional mixes are well represented by the ecoinvent 3.1 mix. All other scenario mixes significantly differ from the mixes in ecoinvent 3.1.

Keywords Belgium · Low-voltage electricity mix · Life cycle assessment · Attributional · Consequential

Introduction

Life cycle assessment (LCA) according to ISO 14040:2006 is a well-known tool for the assessment of the environmental impact of a product or service, from cradle to grave. All aspects considering natural environment, human health and resource depletion are taken into account and together with the life cycle perspective, LCA aims at avoiding problem-shifting between different life cycle stages or different scenarios (Buyle et al. 2013). Although LCA is an accepted method and useful to provide information to support (policy) decisions, it was found in literature that several studies on similar products, processes or services often yield different results (e.g. the environmental impact of concrete pavements compared to asphalt pavements (Athena Institute 2006; Kicak and Ménard 2009) or renewable (wood) versus non-renewable materials (masonry, concrete, steel) in the construction sector (Cole and Kernan 1996; Gerilla et al. 2007; Mithraratne and Vale 2004).

National, electricity production mixes play an important part in many LCA studies and are one of the aspects that can deviate substantially from one study to another.

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The electricity sector is strongly influenced by governments and consequently developments take place differently compared to other industrial sectors. Environmental and social targets may influence historic and future developments such as decreasing emissions from energy production processes, increasing the share of renewable energy production, safety issues or national electricity self-sufficiency. Another aspect of the complexity in the electricity sector is the increasing liberalisation of the market and thereby the growing interconnection between regions.

Various LCA studies emphasise the importance of the selection of the electricity mix and its influence on the results. Braet (2011) includes a sensitivity analysis for an alternative electricity mix in an LCA case study. The Belgian electricity mix was compared to the continental mix, solely nuclear energy, wind energy, coal energy and natural gas energy. It was found that the preference based on environmental assessment for a specific transport concept in the Antwerp Harbour might turn over from pipeline to road depending on the electricity mix. Also, Buyle et al. (2015) performed a sensitivity analysis to investigate the influence of the electricity mix on the life cycle assessment results. It was found that the electricity mix has a substantial influence on the LCA results. Limited research is available concerning the Belgian grid mix. Rangaraju et al. and Messagie et al. analysed the composition of the Belgian grid mix for the year 2011 on hourly basis (Messagie et al. 2014; Rangaraju et al. 2015). The studies focus more on a detailed temporal resolution in relation with smart grids, rather than on developments on a longer time horizon.

The selection of electricity mixes is often complex and involves economic, operational, social and policy constraints, but methodological modelling choices affect the results to a great extent as well (Masanet et al. 2013). These choices determine which research questions can be answered and can amongst others relate to the definition of system boundaries and time horizon, how multifunctionality is handled and if a retrospective or prospective approach is applied (i.e. use of historical or outlook data) (Buyle et al. 2017). For example, the composition of a regional mix can be different if a consequential (including only marginal technologies) or an attributional approach (representing an average mix) is applied (Lund et al. 2010a; Soimakallio et al. 2011).

Some studies take the effect of different modelling choices into account (Garcia-Gusano et al. 2017; Gibon et al. 2017; Roux et al. 2017). However, most studies use the electricity mixes as defined by existing life cycle inventory (LCI) databases (e.g. ecoinvent) without examining the composition of this mix for compatibility with the real situation or affected suppliers. Ecoinvent is one of the most important LCI databases and accepted as the default LCI database in Europe (Martínez-Rocamora et al. 2016; Wernet et al. 2016). Ecoinvent contains electricity mixes for 71 different non-overlapping regions. Three different system models are available in ecoinvent v3.1: allocation at the point of substitution ('default') and cutoff ('recycled content') for attributional LCA and one for consequential LCA. The choice for a specific system model depends on LCA modelling choices (allocation or substitution, average or marginal suppliers, how assessing by-product treatments, etc.).

In this context, this paper aims to answer the following main research questions:

- Does the data record in ecoinvent v3.1 correspond with the Belgian low-voltage electricity mixes for the different system models?
- What is the effect of the modelling choices on the resulting electricity mixes?
- To what extent the environmental impact of ecoinvent mix compared to the mixes of this study differs?

Only the Belgian electricity mix is analysed in the current contribution, but the methodology can be used for other regions as well. The study is scientifically relevant for all LCA practitioners because verifying life cycle inventory data is essential in order to obtain robust LCA results. Exploring the effect of modelling assumptions also assists to improve the transparency of current LCA practice.

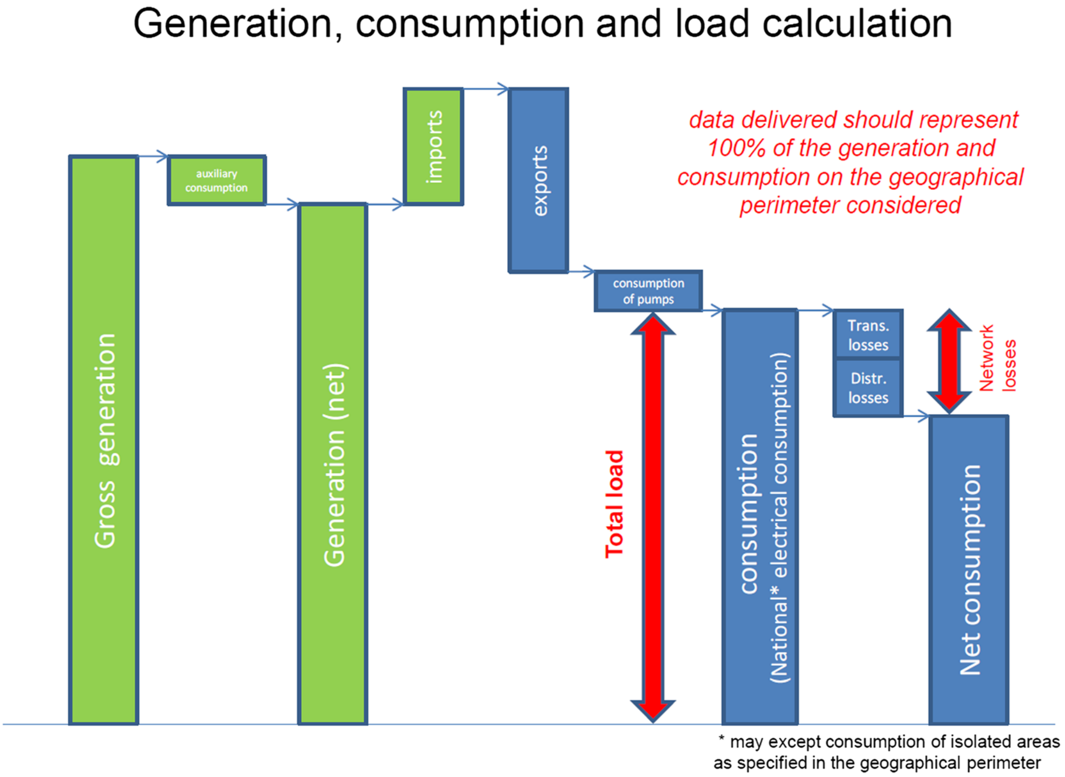
Methodology

General

This study investigates the electricity mix of Belgium by comparing the ecoinvent 3.1 mix with multiple scenarios. These scenarios are built on the findings of the previous section and focus on some of the key modelling choices: LCI modelling approach (attributional or consequential), used type of data (historical or outlook data) and the identification of geographical market boundaries. Following aspects are valid for all included scenarios. The functional unit for the environmental impact assessment is 1-kWh low-voltage electricity as available on the Belgian grid. Transmission, distribution and conversion losses are included. The used life cycle impact assessment method is ReCiPe. ReCiPe implements both midpoint (impact) and endpoint (damage) categories and contains a set of weighting factors to calculate a single score impact. The single score indicator is used in this study for the interpretation of the results. Results of all midpoint impact categories are included in attached Supplementary Information (SI). The default perspective is the hierarchist, which is based on the most common policy principles with regard to time frame and other issues. The hierarchist ReCiPe version with European normalisation and average weighting set was chosen. More information about the chosen LCIA method can be found in literature (Goedkoop et al. 2013; PRé 2013; Sleeswijk et al. 2008).

The approaches to compute life cycle inventories (LCIs) can be subdivided into two main approaches: attributional and consequential. Attributional LCA is defined by its focus on describing the environmentally relevant flows within the chosen temporal window, whilst consequential LCA aims to describe how environmentally relevant flows will change in response to possible decisions (Curran et al. 2005). The specific modelling principles for both approaches are discussed in the "ALCA" and "CLCA" sections.

Data collection was split in two parts: historical data for the period 2006–2015 and data predictions for the period 2010–2030. Historical data were taken from the statistical database of the European Network of Transmission System Operators for Electricity (ENTSO-E). The Belgian figures on the ENTSO-E web pages are related to the Belgian territory and reflect the national figures (including all voltage levels). These figures represent the hourly average of real measurements and estimates. Elia is the Belgian transmission system operator and forwards the relevant information of the Belgian electricity system to ENTSO-E ("Elia Web Page" n.d.). Figures of total load (for definition, see Fig. 1) are


Generation, consumption and load calculation

data delivered should represent 100% of the generation and consumption on the geographical perimeter considered

* may except consumption of isolated areas as specified in the geographical perimeter

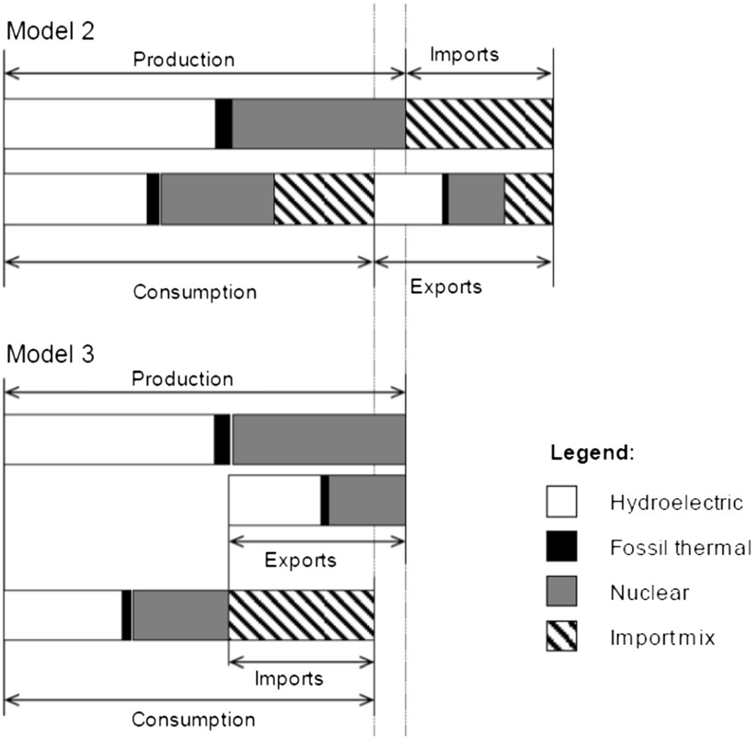
Fig. 1 Definition of generation, consumption and load (Data Expert Group ENTSO-E 2015) used for the composition of the mixes. Total load is calculated from the net generation and accounting for the import and exports according to model 2 of the report by Itten et al. (2012) as presented in Fig. 2 (Itten et al. 2012). Ecoinvent uses the same model for calculating import and export of electricity in the mix.

There are some gaps in the data from ENTSO-E until 2013. The total production of aggregated categories (e.g. fossil fuels) does not always equal the sum of the individual contributing generation types (e.g. coal, oil, gas, lignite). This was corrected by upscaling the values of the individual technologies, but respecting their mutual ratio. Also, the data is subdivided in less categories before 2013 (e.g. subdivision of hydropower in run of river and pumped storage). As much as possible all data was transformed to the categories from 2013 and beyond. If no sufficiently detailed information was available, the original categories were maintained (e.g. solar and hydropower in 2006–2007).

Outlook data for the electricity mix in the period 2010–2030 were taken from the Federal Planning Bureau (Federal Planning Bureau 2014, 2015). The composition of the mix is calculated based on the gross generation and the exchange balance (= import – export). As can be seen in Fig. 1, this differs from the calculation setup used for the historical data but was applied since absolute values of import and export are missing in the report of the Federal Planning Bureau. Besides, the classification of various electricity generation methods slightly differs for the data from the Federal Planning Bureau compared to ENTSO-E. For the outlook data, no detailed information on the distribution of different feedstock materials for biomass and waste was available. It is assumed that the electricity production from industrial (blast furnace gas and coal gas) and municipal waste is constrained since it is dependent on the amount of waste generation (Kuppens et al. 2013). Hence, the absolute electricity production (in GWh) of these types is kept equal in comparison to the data of 2015. The additional electricity production by biomass for 2030 compared to 2015 is associated to the electricity production by biogas and wood chips whilst keeping the ratio between these two constant.

Future predictions are per definition uncertain, so four possible pathways are included that differ in the level of ambition in the field of energy efficiency and renewable energy deployment. An important remark is that these electricity mixes stem from a study on the entire Belgian energy system, including all kinds of energy use (e.g. including transport). For example a fuel

Fig. 2 Model approaches for imports and exports in electricity mixes in LCA (Itten et al. 2012)



shift can result in a reduction of the total national energy consumption, but at the same time induce an increased demand for electricity. The included scenarios are briefly described below (for more details, see Federal Planning Bureau 2014, 2015).

- Ref.: evolution of the Belgian energy system under current trends and adopted policies in the field of climate, energy and transport whilst integrating the 2020 Climate/Energy binding objectives. No additional actions to meet, respectively, 2030 and 2050 targets are included.
- Scenario v1: 40 and 80% greenhouse gas (GHG) emission reduction targets in, respectively, 2030 and 2050 are achieved at EU level. No additional energy efficiency policies compared to the reference scenario and no pre-set renewable (RES) target are defined.
- Scenario v2: adds ambitious energy efficiency policies and measures to scenario v1. For example carbon pricing incentivizes fuel shifts, energy savings and non-energy related emission reductions. The 2030 as well as the 2050 GHG reduction target are achieved at EU level. Concerning RES, there is no pre-set target, but energy efficiency policies contribute to higher RES shares as they reduce total energy consumption
- Scenario v3: complements scenario v2 with a binding EU RES target of 30% in 2030. Beyond concrete energy efficiency policies, carbon pricing continues to incentivize fuel shifts, energy savings and non-energy-related emission reductions.

There is a trend of increasing interconnectivity between countries, resulting in more cross-boundary trade. However, since it is not practically feasible to store electricity on a large scale a connected grid infrastructure is needed. Hence, the identification of geographical market boundaries is restricted to surrounding countries. In this research, two possible modelling choices concerning market boundaries are included: taking only domestic production into account and include trade as well. Attributional scenarios represent the average national supply, so scenarios without trade are not included. For the consequential scenarios on the other hand, both the inclusion and exclusion of trade are taken into account. The latter is the default assumption of ecoinvent 3.1, under the assumption that all countries strive for self-sufficiency on the long run (BP Weidema et al. 2013).

Summarising, the included scenarios are listed in Table 1.

In ecoinvent, more detailed information is available per generation type compared to both the historical and outlook data in this study. For example solar, wind and biomass electricity generation are mixes of different technologies. The solar electricity is generated by two types of photovoltaic panels (monocrystalline and multi-crystalline silicon solar panels). Wind energy is divided in four different types of installations, depending on the power and location (onshore or offshore) of the installation. Electricity produced from biomass includes five different feedstock materials: biogas, wood chips, blast furnace gas, coal gas and municipal waste. For calculating the environmental impact per generation type, the ratio of the different technologies is taken from Ecoivent 3.1. Since no other data was available, this ratio was maintained for all scenarios. For each generation type, a relevant process is available in the ecoinvent database, for both attributional and consequential LCA modelling. All electricity datasets in ecoinvent 3.1 were calculated for the reference year 2008 and if applicable extrapolated to the year 2014. Technological evolutions in the generation processes are beyond the scope of the current study and therefore not taken into account. The environmental impacts from the transmission network itself, the transmission and distribution losses, the conversion between different voltage levels and emissions from the electro-magnetic field are not analysed in detail. These impacts are included by applying the values from the ecoinvent database. The full LCI can be found in the attached SI.

Table 1 Included scenarios

Data type	Domestic production only	Domestic production + trade
Historical data	CLCA [H−]	ALCA [H+]
Outlook data	CLCA [F− ref]	ALCA [F+ ref]
		CLCA [F+ ref]
		CLCA [F+ v1]
		CLCA [F+ v2]
		CLCA [F+ v3]

Minus and plus signs refer to small (domestic production only) and large (domestic production + trade) market respectively. “H” refers to “historical” and “F” refers to “future”

ALCA

Ecoinvent 3.1 includes two system models (‘allocation, default’ and ‘allocation, recycled content’) that can be used for attributional LCA modelling. Both system models use the average supply of products. This means that all electricity generation types with a contribution to Belgium low-voltage grid mix are included. Both system models apply allocation to convert multi-product datasets to single-product datasets. The *allocation, default* system model allocates at the point of substitution, based on the market value of the products (economically). The *allocation, recycled content* system model makes a cutoff. This means that the secondary (recycled) materials bear only the impacts of the recycling processes. The *allocation, recycled content system* model is used in the current contribution because this system model is easier to understand and it is aligned to ecoinvent 1 and 2 modelling approach.

CLCA

The concept and methodology of consequential LCA have been described extensively by Ekvall and Weidema in terms of system boundaries, avoiding allocation and data selection and by Weidema related to the identification of marginal technologies (Ekvall and Weidema 2004; Weidema et al. 1999). The presented five-step procedure of Weidema is the most commonly applied approach to identify a marginal technology, taking into account scale and time horizon of the research, market delimitation, market trend, potential to increase capacity and competitiveness (Weidema 2003). Consequential studies typically focus on long-term market trends and how suppliers will change their production capacity in response to an accumulated change in demand. However, short-term changes can be analysed as well, which only affect the currently installed capacity. Previous research applying this five-step procedure can be categorised by whether the simple or dynamic marginal technology was identified (Mathiesen et al. 2009). The first category includes the (long-term) marginal technology without taking into account the possibility to react to an increased demand at any time, e.g. including wind turbines. The second category takes only the (long-term) technologies into account, who always can react at an increase in demand, e.g. conventional thermal power plants. In reality however, a (short-term) marginal technology can change on an hourly basis, depending on time of the day, season and climate conditions. Additionally, an increased production volume of one technology might affect the production volume of other technologies as well, since they are all connected to the regulated grid. So instead of focussing on a single marginal technology, a third approach is defining the complex marginal technology, which consists of a mix of technologies (Mathiesen et al. 2009). Such a mix is described by Lund et al. as “the long-term yearly average marginal (YAM) technology takes into account the fact that a change in capacity has to be adjusted to the existing energy system” (Lund et al. 2010b). The advantages of working with a YAM technology mix are, amongst others, (i) that not only the installed capacity is taken into account but also how this is used and interact with existing capacity, (ii) short-term changes in marginal supply are included and (iii) also non-flexible technologies can contribute if their capacity is increased.

The Belgian consequential mix in this study is modelled according to the principles described in the previous section, working with YAM technologies. In other words, long-term changes in capacity and its utilisation are taken into account, both of flexible as non-flexible technologies. Since the identification of future developments is per definition uncertain, multiple scenarios are developed as described in the “General” section. An important conclusion of the outlook studies with regard to the five-step procedure is related to defining the market boundaries. After the phase-out of the nuclear plants, there will be a structural deficit in production capacity which is covered by imports. On the long-term (2050) however, the share of imported electricity is expected to decrease. The latter results in two scenarios for the market delimitation: (i) domestic production only and (ii) expanding the market by taking into account import and export. To define the boundaries of the market including trade, the ratio of a trade flow compared to the total production volume of the market is applied as main criterion. The criterion to define the countries included in this market is based on the size of individual cross border trade flows compared to the total production volume of the market. If a trade flow is smaller than 3% of the total production volume of the market, it is assumed that the trade connection is not significant and the country is excluded from the market. On the other hand, if a flow is above the threshold of 3%, the market boundaries are extended by including the country into the market. This procedure has to be repeated until all individual cross-boundary trade flows are identified as insignificant and the final market size can be determined. Selecting a threshold value is always an arbitrary choice to a certain extent. However, this does not mean that attributing a value is a priori a meaningless and random decision. Based on a thorough analysis of multiple products, it was found that a threshold value in the range of 2–5% can be interpreted as a market including the most important direct trade partners (Buyle 2018). For more details on this procedure, see Buyle et al. (2017) as well.

A second parameter in the scenarios relates to the selection of marginal technologies. The simplest way is to assume current trends represent future developments, of course taking (future) constraints into account as well. The contribution to the marginal mix can be calculated as the share of the increment in production volume of a supplier over certain period of time compared to the total increase in production volume of the market (see Eq. 1).[1] In this research, it is assumed that the increased production volume is an empirical proof of competitiveness, so no cost data are included. The slope of the linear regression of historical data is used as indicator for the increment (Schmidt and Thrane 2009). Such scenarios are of course only relevant if no fundamental changes in the market structure occur. A more complex way is to model outlook scenarios to identify the changes in production volume. Similar to the historical data, the share of a technology in the marginal mix is the proportion of the change of this technology in comparison with the total change. As pointed out by Mathiesen et al., it is relevant to model multiple possible futures (Mathiesen et al. 2009). The focus of the outlook scenarios is the effect of Belgian policy decisions, so only one scenario is included per neighbouring country, based on the European forecasts up to 2030 (Capros et al. 2013). For the outlook scenarios, 2010 was taken as reference year. These mixes are calculated based on the methods described in this section as well.

$$f_i = \frac{s_i}{\sum s} \text{ and } s > 0 \tag{1}$$

With

f_i share of supplier i in the marginal mix,

s_i slope of linear regression of production time series of supplier i

$\sum s$ sum of all positive slopes of unconstrained suppliers.

Ecoinvent system models

The presented scenarios are based on other data, modelling choices and assumptions than ecoinvent (Wernet et al. 2016). The most important aspects of the applied methodology and the used data described in the "ALCA" and "CLCA" sections and ecoinvent are compared and shown in Table 2. The attributional scenarios and ecoinvent system models rely on a similar methodology, including all technologies and trade. The main differences are the used input data, where ecoinvent relies on extrapolated date from 2008, and this study includes data on multiple years and a forecast up to 2030 as well. In the case of consequential LCA on the other hand, there are substantial differences in modelling approach. In ecoinvent, trade is not taken into account, including only domestic suppliers. Additionally, only technologies with electricity as determining product (constrained by-products) and which are labelled as 'modern' (high voltage) or 'current' (medium and low voltage) are included. Their market shares are in proportion to the annual production volumes. This study is based on the five-step procedure of Weidema and covers a quantitative identification geographical market boundary, takes into account more types of constraints and identifies marginal technologies based on their increment in production volume as indicator for their competitiveness.

Results

Table 3 presents the historical electricity production, and Table 4 presents the forecast of future electricity production. The composition of the market mixes for both ALCA and CLCA modelling were calculated based on these data. If a generation type does not contribute to the electricity mix and so the value is zero, the field is left empty in Tables 3, 4, 5, and 6.

Composition market mixes—ALCA

In attributional LCA, all electricity generation types are included, even when they are a by-product from

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[1] The slope and increment can be computed for a time series or for two data points only. This way, the equation is applicable for both the historical and outlook scenarios.

Table 2 Comparison of the modelling assumptions of this study and ecoinvent

Modelling approach	This study	Ecoinvent
ALCA	• Yearly data from 2006 to 2015 (ENTSO-E), Outlook data up to 2030 (FPB)	• Data from 2008, extrapolated to 2014 (IEA)
	• Including trade	• Including trade
	• Including all supplying technologies	• Including all supplying technologies
CLCA	• Yearly data from 2006 to 2015 (ENTSO-E), Outlook data up to 2030 (FPB)	• Data from 2008, extrapolated to 2014 (IEA)
	• Quantitative identification geographical market boundaries (based on trade and production data) and extra scenarios excluding trade	• Excluding trade
	• Included constraints: policy, natural and by-product	• Included constraints: by-product
	• Identification marginal technologies: trend in production as indicator for competitiveness for all unconstrained technologies	• Identification marginal technologies: only including 'modern' technologies for high voltage and 'current' technologies for low and medium voltage
	• Market shares based on the increment in production volume of a technology compared to the total increase in production volume of the market	• Market shares are in proportion to the annual production volumes (2014) of the unconstrained technologies

another production process, e.g. the heat and power co-generation from biogas or constrained, e.g. nuclear power. The data presented in Table 3 are converted to the electricity mix composition in terms of percentage (for 1 kWh) as presented in Table 5 as the composition of the ALCA scenarios. The national electricity mix of France, Luxembourg, The Netherlands and the United Kingdom from ecoinvent is used to represent the import from these countries. For the single score impact per generation type in Table 5, the weighted average for 2015 was taken if more technologies are available (wind, solar, biomass).

Table 3 Historical electricity production and import (ENTSO-E n.d.-a)

	ENTSO-E									
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Net generation (GWh)										
Coal	1.854	1.225	3.770	3.669	2.796	2.191	2.411	2.555	3.763	3.628
Gas	27.141	28.852	24.933	26.416	28.235	22.665	23.711	21.706	17.171	19.942
Oil	183	102	92	160	50	11	8		34	50
Nuclear	39.704	40.902	39.661	39.105	38.654	39.402	34.891	36.622	30.057	23.421
Hydro	1.445	1.493								
Hydro renewable r.o.r.			370	282	250	166	402	322	249	269
Hydro pumped storage			1.225	1.235	1.142	1.041	1.110	1.185	1.092	1.017
Wind	322	438	576	859	1.088	1.960	2.611	3.211	4.155	5.100
Solar			40	141	468	1.075	1.477	2.185	2.654	2.963
Biomass	2.725	2.894	3.775	4.260	4.603	4.923	2.887	2.831	4.216	5.409
Import (GWh)										
France	9.655	7.579	6.742	1.401	3.203	7.341	6.732	7.898	10.217	9.355
Luxembourg	2.251	1.892	1.507	1.531	1.941	1.581	1.271	641	1.316	462
The Netherlands	5.082	4.784	7.514	4.746	7.768	4.663	7.345	7.084	8.803	12.787
Total load (GWh)	90.362	90.160	90.205	83.805	90.199	87.020	84.857	86.239	83.728	84.403

$\times 10^{-5}$ accuracy needs a nuanced interpretation

Table 4 Forecast of future electricity production in different scenarios (with respect to base level 2010) (Federal Planning Bureau 2014, 2015)

	Federal Planning Bureau				
	2010	2030			
		[F+ ref]	[F+ v1]	[F+ v2]	[F+ v3]
Gross generation (GWh)					
Coal	4.190	1.882	1.882	1.882	1.882
Gas	31.420	36.567	32.550	36.436	30.504
Petroleum production and derived gases	2.164	1.562	722	742	742
Nuclear	47.944				
Hydro renewable r.o.r.	312	395	395	395	395
Wind	1.292	19.926	22.448	20.864	25.313
Solar	560	5.122	5.131	5.291	5.291
Biomass	3.994	6.722	6.686	6.204	7.687
Waste	1.888	2.053	2.053	2.053	2.053
Geothermal		289	289	289	289
Import (GWh)					
France	2.921	10.217	10.063	10.111	10.111
Luxembourg	2.574	5.400	5.318	5.344	5.344
The Netherlands	898	5.000	4.924	4.948	4.948
United Kingdom		400	394	396	396
Total (GWh)	94.315	95.535	92.855	94.956	94.956

$\times 10^{-5}$ accuracy needs a nuanced interpretation

For 2015, the domestic annual production according to ENTSO-E is rather low compared to 2008, the reference year in ecoinvent: a reduction of 6.4% (see Table 3). It can be concluded that the decrease in annual Belgian electricity production is mainly due to the decrease in production by nuclear reaction and gas combustion. The decrease in nuclear electricity production might be explained by (i) problems of little cracks in the steel walls of the reactor vessels (Doel 3 and Tihange 2) since 2012 resulting in temporal closures and (ii) the first phase of the nuclear power phase-out originally scheduled for 2015. Regarding the latter, the current Belgian government postponed the closures of the first phase to 2025. The decrease in electricity production by gas plants is due to the closure of many units in Belgium during the last decade as a consequence of economic and political decisions.

The contribution of renewable electricity production to the mix is increasing during the last decade. It is important to note that the energy generation by "other hydro" (pump storage) is smaller compared to the energy consumption by the pumps used for this energy production. Hence, hydropower generation by pump storage plants has some efficiency loss [Reference: e-mail contact with Dries Couckuyt, Belgian correspondent for the ENTSO-E data and market analyst at Elia (Extra High Voltage System Development)]. When the electricity demand is low, energy is consumed to pump water from a lower reservoir to an upper reservoir. When the energy demand is high, the water flows through pressure pipes into turbines, generating electricity. Hydropower production by pumped storage is considered as non-renewable electricity.

A part of the electrical production by fossil fuels still comes from coal and oil with an installed generation capacity of 470 and 190 MW, respectively, in 2015 (ENTSO-E n.d.-b). It was seen from (ENTSO-E n.d.-b) that the power plants Langerlo 1 and Langerlo 2 use hard coal in combination with biomass and natural gas. Fossil oil is mainly used in small electrical power plants for the production during peak hours. Belgium has several turbojet plants using kerosene.

Table 5 ALCA scenarios—composition market mixes and life cycle impact

	Single score impact (mPt/kWh)	Composition ALCA scenarios (%)											
		[H+]										[F+ ref]	ecoinvent 3.1
		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2030	
Generation													
Coal	90.5	2.05%	1.36%	4.18%	4.38%	3.10%	2.52%	2.84%	2.96%	4.49%	4.30%	1.97%	5.23%
Gas	46.8	30.0%	32.0%	27.6%	31.5%	31.3%	26.0%	27.9%	25.2%	20.5%	23.6%	38.3%	23.2%
Oil	87.9	0.20%	0.11%	0.10%	0.19%	0.06%	0.01%	0.01%		0.04%	0.06%	1.64%	0.38%
Nuclear	2.60	43.9%	45.4%	44.0%	46.7%	42.9%	45.3%	41.1%	42.5%	35.9%	27.7%		44.8%
Hydro r.o.r.	0.56	0.37%	0.38%	0.41%	0.34%	0.28%	0.19%	0.47%	0.37%	0.30%	0.32%	0.41%	0.43%
Hydropumped	41.1	1.23%	1.27%	1.36%	1.47%	1.27%	1.20%	1.31%	1.37%	1.30%	1.20%		1.40%
Wind (mix)	3.35	0.36%	0.49%	0.64%	1.03%	1.21%	2.25%	3.08%	3.72%	4.96%	6.04%	20.9%	0.66%
Solar (mix)	14.4			0.04%	0.17%	0.52%	1.23%	1.74%	2.53%	3.17%	3.51%	5.36%	0.07%
Biomass (mix)	24.1	3.02%	3.21%	4.18%	5.08%	5.10%	5.66%	3.40%	3.28%	5.04%	6.41%	9.19%	5.85%
Geothermal	9.27											0.30%	
Import													
FR	10.5	10.7%	8.41%	7.47%	1.67%	3.55%	8.44%	7.93%	9.16%	12.2%	11.1%	10.7%	7.75%
LU	57.6	2.49%	2.10%	1.67%	1.83%	2.15%	1.82%	1.50%	0.74%	1.57%	0.55%	5.65%	1.70%
NL	56.9	5.62%	5.31%	8.33%	5.66%	8.61%	5.36%	8.66%	8.21%	10.5%	15.1%	5.23%	8.49%
UK	56.9											0.42%	
Total impact per scenario (mPt/kWh)		27.3	27.0	29.3	29.8	30.4	26.2	28.2	26.5	28.5	32.5	36.3	29.7

× 10^{-3} accuracy needs a nuanced interpretation

Table 6 CLCA scenarios—composition market mixes and life cycle impact

	Single score impact (mPt/kWh)	Composition CLCA scenarios (%)										Constraints for Belgium
		[H−]	[F− ref]	[F+ ref]	[F+ v1]	[F+ v2]	[F+ v3]	[F+ ref] FR	[F+ ref] DE	[F+ ref] NL	ecoinvent 3.1	
Generation												
Coal	90.9										9.94%	Political
Gas	47.0		16.4%	10.0%	2.28%	9.71%			21.7%			–
Oil	93.1								0.432%	1.56%		–
Nuclear	2.60									3.49%	85.3%	Political
Hydro (mix)	14.6							2.50%	2.06%		3.46%	Natural
Wind (mix)	3.50	50.8%	59.4%	36.2%	42.7%	37.9%	45.7%	76.6%	59.2%	83.0%	1.25%	–
Solar (mix)	17.2	34.9%	14.5%	8.87%	9.22%	9.16%	9.00%	12.0%	11.3%	3.33%	0.07%	–
Biomass (mix)	28.9	14.3%	8.70%	5.30%	5.43%	4.28%	7.02%	7.93%	5.29%	8.59%		–
Geothermal	10.7		0.922%	0.562%	0.583%	0.559%	0.550%	0.920%	0.0382%			–
Import												
FR	9.00			25.5%	26.2%	25.2%	24.8%					–
DE	20.5			5.50%	5.53%	5.36%	5.27%					–
NL	9.04			7.98%	8.11%	7.84%	7.70%					–
Total impact per scenario (mPt/kWh)		13.3	17.8	14.9	11.5	14.5	10.7	9.00	20.5	9.04	14.6	

× 10^{-3} accuracy needs a nuanced interpretation

Belgium exchanges electricity with three neighbouring countries: France, Luxembourg and the Netherlands. The electricity import increased with 43% in 2015 compared to 2008. This trend is especially strong for 2014 and 2015.

The most important differences between the attributional mix for 2015 and the mix for 2030 based on the outlook data of the Federal Planning Bureau are the termination of nuclear production and production by hydro pumped and an increase in electricity production by wind power.

In general, it was seen that there is a strong resemblance between the Belgian Electricity mix as defined in the database 'ecoinvent 3.1, Allocation, Recycled content' and the electricity mix generated based on the ENTSO-E data. For both mixes, the same electricity generation types contribute to the composition and the shares of the different techniques are in the same order of magnitude. The ecoinvent 3.1 electricity mix includes the import of electricity from the same countries as defined by the ENTSO-E data.

Composition market mixes—CLCA

The composition of the market mixes for the different consequential scenarios is calculated according to five-step procedure, based on data presented in Tables 3 and 4. The first step is to define the scale and time horizon of the study. A long-term and large scale is assumed. The latter is in particular true for the future scenarios as fundamental changes in development of the electricity sector are taken into account. The second step is defining the market boundaries. Both the domestic market and an expanded market are taken into account. In this particular case, Belgium is assumed to import substantially from the Netherlands, France and Luxembourg. According to a study of the International Energy Agency (IEA), Luxembourg is a net importer and not planning to increase its capacity. Therefore, it is assumed Luxembourg is only a transit country for German electricity, since it has only a grid connection with Belgium and Germany (IEA 2014). So the included countries in the expanded market are Belgium, the Netherlands, France and Germany. If a smaller threshold is desired, the UK grid could be included. In this case, all trade flows to regions outside the cluster are below 1.5% of the clusters' production volume. Since Belgium has no direct connection with the UK, this would affect the final results only to a small extent. Third, the market trend was determined. The historical data have a stable to slightly decreasing trend, whilst the outlook data take a stable situation into account. Since no sharp decreasing trend is observed, it is assumed that the marginal suppliers should be the most competitive ones. Fourth, the constrained suppliers should be excluded as potential marginal suppliers. Multiple types of constraints occur in this situation: political, natural and by-product constraints. Nuclear generation is the most obvious example of a political constraint due to the planned phase-out, together with the ban on new coal-based power plants. Hydropower has a natural constraint in the Belgian context; no new spots are left to expand capacity. The last group of constraints are the non-determining by-products. Only an increase in demand for the determining product will result in a growing production volume. Energy recuperation at municipal waste incineration plants and other industrial processes are typical examples of technologies that cannot contribute to the marginal mixes. Electricity from combined heat and power generation (CHP) with heat as reference product is another example. The final step is to identify which of the unconstrained suppliers are the most sensitive to a change in demand. Technologies with a decreasing trend are excluded in the mix (e.g. oil); the others contribute to the mix with shares computed according to Eq. 1. In Table 6, all mixes are presented, as well as the ecoinvent 3.1 mix for Belgium.

The variation in the composition of the mixes is noticeable, but a general observation is the dominant share of technologies based on renewable energy sources (RES) both for the historical as the future scenarios. To date, these technologies are growing fast, but they represent only a small part of the total mix. The future scenarios indicate however that the trend is expected to continue, resulting in a significant contribution to the market share. The situation of gas plants is less clear, appearing only in some of the mixes. Gas plants in Belgium produce electricity at a high cost compared to other domestic technologies and imported electricity. This resulted in the last years in a reduced working load of gas plant and even in some closures. However, in future scenarios, gas plants are expected to play an important role as they are able to supply a constant base-load in contrast to most RES technologies. Geothermal production is an expected new technology in the future scenarios. Despite it has only a small contribution in the mixes, it still points out the growing attention for renewable energy sources.

Compared to the presented scenarios, the composition of the ecoinvent 3.1 mix is completely the opposite. Nuclear, coal and hydroaccount for almost 99% of the mix, whilst in this research these technologies are considered to be constrained. On the other hand, technologies based on RES are barely represented in this mix.

Impact assessment

The results are presented in Tables 5 and 6, showing the environmental impact per generation type per kWh, the composition of the electricity mixes for al included scenarios with corresponding impact and the ecoinvent 3.1 mix. The single score impacts of 1-kWh low-voltage electricity by different production types are compared using the corresponding ecoinvent processes. Only the final single scores are included in the tables; more information on the midpoint categories can be found in the SI. An important remark is that due to transmission losses; the final impact per scenario is higher than the combination of the share per technology with its impact.

The results of the environmental impact per generation type show similar trends for both the attributional as the consequential system model. This makes sense since the impact is calculated per process regardless its contribution to a mix or potential constraints. Differences occur due to the modelling assumptions in the background system, but the order of magnitude is the same. It is seen in Table 5 that there is a large difference in environmental impact per kWh electricity depending on the generation type. In general, electricity production based on fossil fuels (in particular coal and oil) causes a large environmental burden. Besides, the cogeneration of heat and electricity with wood chips has an important environmental impact in the category agricultural land occupation (see SI for more details). This results in a high environmental impact for the electricity generation by the biomass mix. In the consequential system model, biomass-based production is modelled with electricity as determining product instead of heat. The electrical production with low environmental impact stems from nuclear reaction (see also the “Discussion” section), wind and hydropower (run of river). In the attributional biomass mix, no environmental impact is assigned to the electrical production by the combustion of municipal waste materials because the system model allocation recycled content is used (see the “ALCA” section). On the other hand, the impact of the imported country mixes differs significantly between the two system models. In this case the differences are caused by the composition of the mixes induced by underlying assumptions of the system model and not by a difference in impact for the same generation type. Identical as for the Belgian mix, in the attributional mixes is worked with the average production (ecoinvent data used), whilst the consequential mixes only include the technologies that can respond to an increase in demand.

As the composition of the attributional electricity mixes changes over time, the environmental impact of these mixes changes as well. It can be seen from Table 5 that the environmental impact is slightly lower in 2006, 2007, 2011 and 2013, whilst high impact per kWh is seen in 2009, 2010 and 2015. The environmental impact of 1 kWh in 2015 is 23% higher compared to the impact of 1 kWh in 2013 and 11% higher compared to the impact of 1 kWh in 2008, the reference year. The lower impacts in 2006, 2007 and 2011 can partly be explained by the low amount of import from the Netherlands (the electricity mix of the Netherlands has a high environmental impact) and a high share of nuclear electricity (with a low environmental impact) in the mix. The low environmental impact in the electricity mix in 2013 is a consequence of an increasing amount of energy produced by wind power, solar and waste incineration; a constant amount of nuclear electricity and import from France and a low amount of import from Luxemburg with a high environmental impact. The high environmental impact of the electricity mix in 2009 and 2010 are caused by a high amount of electricity production from gas with a relative high environmental impact and less import from France. The high environmental impact of the electricity mix in 2015 is caused by the decreased production of nuclear energy with a low environmental impact and the increased electricity from biomass and import from the Netherlands with a higher environmental impact.

The consequential electricity mixes are subject to a large variation in the composition for the different scenarios. This is also reflected in the range of the environmental impacts, going from 10.7 to 17.8 mpt/kWh. The differences in the contribution of gas-based generation are the main reason for the fluctuations in the impact per scenarios. Gas is, together with biomass, the only type of unconstrained fuel that is fully flexible, and which can be used for the base load generation. The production cost per kWh however is higher compared to for example nuclear power. In the [H−] scenario, cheaper nuclear power is still the main base load technology, resulting in reduced share of gas-based generation. In most future scenarios though, natural gas and to a lesser extent biomass are the main domestic base load technologies, resulting in a noteworthy share in the mixes. Solar power has an opposite evolution in comparison with natural gas: it is much stronger represented in the historical mix (35%) than in the future ones (9–15%). This can be explained by strong financial incentives in the last decade for RES technologies, which mainly affected the installation of photovoltaic panels and biomass plants. These incentives have been cut back recently, so the steep increase is not expected to last as can be seen in the future scenarios. Wind power appears to be the leading technology instead in all future scenarios. In the [F+] scenarios, where trade is taken into account, the large share of French import is remarkable. In the reference year 2010, there was a net export to France, whilst in 2030, France is expected to be the main foreign supplier to the Belgian grid. The French consequential future mix is dominated by wind (77%) and solar (12%) power resulting in a reduction of the impact compared to the scenarios with only domestic generation. This reasoning is also valid for import from the Netherlands (83% wind).

Finally, the environmental impacts of the electricity in the different scenarios are compared to the electricity mix in ecoinvent according to the two system models. The scenario ALCA [H+] is compared to the generic data in ecoinvent v3.1 kWh "Electricity, low voltage {BE}|market for|Alloc Rec, U". It is seen that the environmental impact for 1 kWh from the mix of 2015 is 9.4% higher compared to the mix in ecoinvent. Nevertheless, there are similarities in the order of magnitude for the contribution of different generation types in the electricity mix. Despite significant differences between the consequential mixes, the general trend is the large share of renewable energy sources combined with a flexible technology such as natural gas. The consequential energy mix of ecoinvent 3.1 is completely the opposite and is almost entirely composed of constrained technologies. The impact of this mix (14.6 mpt/kwh) fits within the range of the other scenarios, but is not relevant to draw any conclusions based on this mix. The combination of a large share of nuclear energy (low impact) combined with a small share of coal (high impact) is averaged into a realistic values. However, this is rather coincidence instead of a causality.

Discussion

In this study multiple scenarios are developed for the composition of the Belgian electricity grid mix according to an attributional and consequential modelling approach. Both a time series of historical data and outlook data were applied. The same source data has been used for both system models, but their goal and underlying modelling assumptions differ. The mixes presented in the "Results" section clearly indicate a growing trend of renewable energy sources in the Belgian power production. This can be directly explained by the European Energy policy, imposing quotas for the share of renewables by 2020 and beyond (European Commision 2014; European Commission 2010). However, the increasing capacity of renewables is reflected differently depending on the approach. In the attributional mix, the share in the total production volume is small in the historical scenarios. At the consequential mixes on the other hand, these technologies are the most important marginal suppliers as they are the only ones with an increment in capacity and production volume. In the future scenarios, renewables are expected to have a much larger share in the total production volume, making the differences smaller between the two approaches.

Both the included scenarios and the ecoinvent system models are based on other modelling choices and assumptions. If the scenarios answer different research questions are, deviations in results should be interpreted with care. The included attributional scenarios and the ecoinvent attributional system models have a similar approach with market shares of the supplying generation types proportional to the annual electricity production volume (Treyer and Bauer 2014). In these cases, the input data has the greatest impact on the results, e.g. historical versus outlook data or the effect of temporal closure of several nuclear reactors in the period 2012–2015. Of course data considerations play a role in the consequential scenarios as well; however, more methodological differences occur as described in the "Ecoinvent system models" section. The ecoinvent consequential system model implies that "electricity markets are not supposed to represent the marginal kWh covering additional power demand [...] with already installed generation capacities, but the additional capacity to be installed in the future for covering increasing (or stable) electricity demand" (Treyer and Bauer 2014, p. 1261). This limitation is acknowledged by ecoinvent as they suggest to "create consequential electricity markets according to more specific information concerning constrained/unconstrained power generation in specific geographical regions" (Bauer 2013, p. 2). The results of this research clearly point out the need for a more detailed analysis of the technologies which will be affected by a change in demand. The choices for the included types of constraints are the main reason for the differences in market composition in the Belgian context. However, defining geographical market boundaries (include trade or not) and using (predicted) production trends instead of an average of a single year can affect the results to a great extent as well. The latter is illustrated by the import from France: nuclear power production has a stable to slightly decreasing historical and forecasted trend, so based on the methodology presented in this study, it is assumed that French nuclear power will not respond to a change in demand and does not appear in the mix. In ecoinvent on the other hand, nuclear power production is considered as a modern technology with electricity as determining product and has a share of over 80% in the mix.

An extensive review of Masanet et al. based on a meta-analysis by the National Renewable Energy Laboratory (NREL), identifying nearly 300 LCA studies of electric power technologies, came to similar conclusions regarding renewable technologies. For example, in most analysed mixes, RES technologies have only a small share in the mixes, but they are growing in importance. Additionally, if future scenarios are taken into account, most analysed studies are restricted to a 'set of scenarios with a priori backgrounds of how the technology might function and are conducted based on understandings of the current or previous technology, costs and market' (Masanet et al. 2013; National Renewable Energy Laboratory 2013). As a result, coal appears often as marginal technology in the few consequential studies.

It is important to note that the current impact assessment analysis does not take into account all environmental issues. It is known that the Belgian power plant Rodenhuize 4 imports 30% of its wood chips from British Columbia (Canada) resulting in very long transport distances (transport by ship) causing an environmental impact which is not included in this comparison (Messagie et al. 2014). Besides, for nuclear power generation safety issues and the radioactive residual waste are not included in the current impact assessment. Furthermore, nuclear energy is politically constrained in the consequential modelling approach, which is an uncertain factor as such decision might be reversed. At the time of writing, the stepwise phase-out is postponed, but the final closing date of 2025 is still the policy target. In future research, these topics could be elaborated more in detail.

The Belgian electricity consumers can influence the environmental impact of the current electricity mix by choosing an energy supplier that invests in the construction of power plants for low-impacting, renewable energy production. As mentioned in the "General" section, technological evolutions in the generation processes are beyond the scope of the current study. Data on these evolutions are not available. The authors of the study recognise that this is a pragmatic limitation of the study. The technological evolutions in the generation processes can be the subject for further research.

Conclusion

The aims of the paper are (i) to verify whether the records in ecoinvent v3.1 correspond well with the Belgian low-voltage electricity mixes for the different system models, (ii) analyse the effect of the modelling choices on the resulting electricity mixes and (iii) how this is reflected in the environmental impact per kWh. The analysed system models are an attributional model ('allocation, recycled content') and the consequential model. Multiple scenarios are included, based on historical statistics or future predictions, and whether trade is included or not. In the case of the attributional model, the scenarios represent the historical and expected average, whilst the consequential scenarios represent the historical and future trend of increasing technologies.

The composition of the historical attributional mixes is fluctuating over time, but the order of magnitude of the different technologies remains the same. These mixes are quite well represented by the ecoinvent 3.1 mix. The future scenario on the other hand is completely different, with a large share of renewable technologies. The analysis of the consequential scenarios is the opposite. Current trends of increasing capacity of renewables are expected to continue in the future, though with a shift of importance from solar to wind power. It was observed as well that the ecoinvent 3.1 consequential mix is composed for 99% of constrained technologies for the Belgian grid mix; however, the other modelling assumptions can play an important role as well. In future research, more attention is needed to take into account the effect of these assumptions on the final results. The proposed procedure for computing consequential electricity mixes is consistent and generally applicable and can serve as starting point for future optimizations.

The impact assessment shows no clear trend and is scenario dependent, especially on the case of future predictions. The attributional scenario shows an increase in impact due to elimination of nuclear power, whilst in the case of consequential scenario, the situation might improve or become worse depending on the base load technology.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Athena Institute. (2006). A life cycle perspective on concrete and asphalt roadways: Embodied primary energy and global warming potential.

Bauer, C. (2013). Electricity markets in different system models of the ecoinvent v3 database. Villigen.

Braet, J. (2011). The environmental impact of container pipeline transport compared to road transport. Case study in the Antwerp Harbor region and some general extrapolations. *The International Journal of Life Cycle Assessment, 16*(9), 886–896. https://doi.org/10.1007/s11367-011-0326-2.

Buyle, M. (2018). Towards a structured consequential modelling approach for the construction sector: The Belgian case. A fairy tale on methodological choices in LCA. University of Antwerp.

Buyle, M., Audenaert, A., Braet, J., & Debacker, W. (2015). Towards a more sustainable building stock: Optimizing a Flemish dwelling using a life cycle approach. *Buildings, 5*(2), 424–448. https://doi.org/10.3390/buildings5020424.

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews, 26*, 379–388. https://doi.org/10.1016/j.rser.2013.05.001.

Buyle, M., Pizzol, M., & Audenaert, A. (2017). Identifying marginal suppliers of construction materials: Consistent modeling and sensitivity analysis on a Belgian case. *International Journal of Life Cycle Assessment*, 1–17. doi:https://doi.org/10.1007/s11367-017-1389-5.

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Papadopoulos, D., et al. (2013). EU energy, transport and GHG emissions: Trends to 2050, reference scenario 2013. Luxembourg. doi:https://doi.org/10.2833/17897.

Cole, R., & Kernan, P. C. (1996). Life-cycle energy use in office buildings. *Building and Environment, 31*(4), 307–317. https://doi.org/10.1016/0360-1323(96)00017-0.

Curran, M., Mann, M., & Norris, G. (2005). The international workshop on electricity data for life cycle inventories. *Journal of Cleaner Production, 13*(8), 853–862. https://doi.org/10.1016/j.jclepro.2002.03.001.

Data Expert Group ENTSO-E. (2015). Guidelines for monthly statistics data collection. Brussels.

Ekvall, T., & Weidema, B. P. B. (2004). System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment, 9*(3), 161–171. https://doi.org/10.1007/BF02994190.

Elia Web Page. (n.d.).

ENTSO-E. (n.d.-a). Country data package.

ENTSO-E. (n.d.-b). Transparency Platform.

European Commision. (2014). *A policy framework for climate and energy in the period from 2020 up to* 2030. Communication (COM(2014) 15 final), impact assessment (SWD(2014) 15), energy economic developments in Europe (European economy 1/2014). Brussels.

European Commission. (2010). Europe 2020: A strategy for smart, sustainable and inclusive growth. *COM(2010) 2020 final.* Brussels. doi:https://doi.org/10.1007/s13398-014-0173-7.2.

Federal Planning Bureau. (2014). Het Belgische energiesysteem in 2050: Waar naartoe? - Beschrijving van een Referentiescenario voor België [The Belgian energy system in 2050: where to go? - Description of a reference scenario for Belgium]. Brussels.

Federal Planning Bureau. (2015). 2030 climate and energy framework for Belgium: Impact assessment of a selection of policy scenarios up to 2050. Brussels.

Garcia-Gusano, D., Garrain, D., & Dufour, J. (2017). Prospective life cycle assessment of the Spanish electricity production. *Renewable and Sustainable Energy Reviews, 75*, 21–34. https://doi.org/10.1016/j.rser.2016.10.045.

Gerilla, G., Teknomo, K., & Hokao, K. (2007). An environmental assessment of wood and steel reinforced concrete housing construction. *Building and Environment, 42*(7), 2778–2784. https://doi.org/10.1016/j.buildenv.2006.07.021.

Gibon, T., Arvesen, A., & Hertwich, E. G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews, 76*, 1283–1290. https://doi.org/10.1016/j.rser.2017.03.078.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & van Zelm, R. (2013). ReCiPe 2008 - report I: Characterisation. The Hague, The Netherlands.

IEA. (2014). *Energy Policies of IEA Countries. Luxembourg 2014* Review. Paris, France. http://www.iea.org/publications/freepublications/publication/Luxembourg2014.pdf

Itten, R., Frischknecht, R., Stucki, M., Scherrer, P., & Psi, I. (2012). Life cycle inventories of electricity mixes and grid, (June), 1–229.

Kicak, K., & Ménard, J.-F. (2009). Comparative life-cycle assessment of cement concrete pavement and asphalt pavement for the purposes of integrating energy and environmental parameters into the selection of pavement types. Québec.

Kuppens, M., Umans, L., Adriaens, A., De Greeff, L., Werquin, W., & Vangilbergen, B. (2013). Tarieven en capaciteiten voor storten en verbranden - Actualisatie tot 2012 [tariffs and capacities of landfill and wast incineration - update until 2012]. Journal of chemical information and modeling. Mechelen, Belgium. http://www.ovam.

be/sites/default/files/FILE 138054246784520130930_Tarieven_Capaciteiten2012.Pdf.

Lund, H., Mathiesen, B. V., Christensen, P., & Schmidt, J. H. (2010a). Energy system analysis of marginal electricity supply in consequential LCA. *The International Journal of Life Cycle Assessment, 15*(3), 260–271. https://doi.org/10.1007/s11367-010-0164-7.

Lund, H., Mathiesen, B. V., Christensen, P., & Schmidt, J. H. (2010b). Energy system analysis of marginal electricity supply in consequential LCA. *The International Journal of Life Cycle Assessment, 15*(3), 260–271. https://doi.org/10.1007/s11367-010-0164-7.

Martínez-Rocamora, A., Solís-Guzmán, J., & Marrero, M. (2016). LCA databases focused on construction materials: A review. *Renewable and Sustainable Energy Reviews, 58*, 565–573. https://doi.org/10.1016/j.rser.2015.12.243.

Masanet, E., Chang, Y., Gopal, A. R., Larsen, P., Iii, W. R. M., Sathre, R., et al. (2013). Life-cycle assessment of electric power systems. *Annual Review of Environment and Resources, 38*, 107–136. https://doi.org/10.1146/annurev-environ-010710-100408.

Mathiesen, B. V., Münster, M., & Fruergaard, T. (2009). Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. *Journal of Cleaner Production, 17*(15), 1331–1338. https://doi.org/10.1016/j.jclepro.2009.04.009.

Messagie, M., Mertens, J., Oliveira, L., Rangaraju, S., Sanfelix, J., Coosemans, T., van Mierlo, J., & Macharis, C. (2014). The hourly life cycle carbon footprint of electricity generation in Belgium, bringing a temporal resolution in life cycle assessment. *Applied Energy, 134*, 469–476. https://doi.org/10.1016/j.apenergy.2014.08.071.

Mithraratne, N., & Vale, B. (2004). Life cycle analysis model for New Zealand houses. *Building and Environment, 39*, 483–492.

National Renewable Energy Laboratory. (2013). Life cycle assessment harmonization methodology. http://www.nrel.gov/analysis/sustain_lca_method.html. Accessed 11 May 2016.

PRé. (2013). *SimaPro Database Manual - Methods Library.*

Rangaraju, S., De Vroey, L., Messagie, M., Mertens, J., & Van Mierlo, J. (2015). Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: A Belgian case study. *Applied Energy, 148*, 496–505. https://doi.org/10.1016/j.apenergy.2015.01.121.

Roux, C., Schalbart, P., & Peuportier, B. (2017). Development of an electricity system model allowing dynamic and marginal approaches in LCA—Tested in the French context of space heating in buildings. *International Journal of Life Cycle Assessment, 22*(8), 1177–1190. https://doi.org/10.1007/s11367-016-1229-z.

Schmidt, J. H., & Thrane, M. (2009). *Life cycle assessment of aluminium production in new Alcoa smelter in Greenland.* Denmark: Aalborg. http://lca-net.com/publications/show/life-cycle-assessment-aluminium-production-new-alcoa-smelter-greenland/.

Sleeswijk, A. W., van Oers, L. F. C. M., Guinée, J. B., Struijs, J., & Huijbregts, M. A. J. (2008). Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. *Science of the Total Environment, 390*(1), 227–240.

Soimakallio, S., Kiviluoma, J., & Saikku, L. (2011). The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) - a methodological review. *Energy, 36*(12), 6705–6713. https://doi.org/10.1016/j.energy.2011.10.028.

Treyer, K., & Bauer, C. (2014). Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—Part II: Electricity markets. *The International Journal of Life Cycle Assessment., 21*, 1255–1268. https://doi.org/10.1007/s11367-013-0694-x.

Weidema, B. P. (2003). Environmental project no. *863. Market information in life cycle assessment. Environmental Project No. 863*. Copenhagen, Denmark. http://www2.mst.dk/Udgiv/publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf [accessed 21–8-2017].

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., et al. (2013). Overview and methodology. *Data quality guideline for the ecoinvent database version 3. Swiss Center For Life Cycle Inventories* (Vol. ecoinvent). St. Gallen, Switserland.

Weidema, B. P., Frees, N., & Nielsen, A.-M. (1999). Marginal production technologies for life cycle inventories. *The International Journal of Life Cycle Assessment, 4*(1), 48–56. https://doi.org/10.1007/BF02979395.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *International Journal of Life Cycle Assessment, 21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.