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LCA MODELLING

Scope-dependent modelling of electricity supply in life cycle assessments

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Abstract
Background, aim and scope Electricity use or substitution is one of the key parameters with regard to life cycle assessment (LCA) results. At the same time, it is often used as an illustrative example to highlight the modelling differences between decision-oriented and descriptive LCA. Three basically different models exist in life cycle inventory analysis: the attributional, the consequential and the decisional model. This paper proposes criteria that help to classify typical LCA questions regarding real business cases and find the most appropriate life cycle inventory (LCI) model. The framework is applied to a case study of an LCA of electricity use and supply within the international operations of an environmental service company with headquarters in France.
Main features Individual decision with comparatively small consequences can be modelled under *ceteris paribus* (other things being equal) conditions. Decision situations with medium to large potential consequences should be modelled under the conditions of *mutatis mutandis* (the necessary changes being made). The key question is how to distinguish between small, medium and large consequences. We recommend using the relative economic size to classify objects of investigation and the LCA goals related to them into three groups to which the most appropriate LCI models are assigned.
Results and discussion The attributional approach is sensible for environmental reporting and product labelling and declaration where the relative economic size of the object of investigation is small. The decisional approach is sensible for LCAs of product and process development, as well as site and supplier evaluation carried out by private companies in case the relative economic size of the object of investigation is medium. The consequential approach is of relevance for policy support of governments and international organisations as well as for strategic decisions of companies, where the relative economic size of the object of investigation is large. The consequential approach is also sensible in product or service comparisons by companies, if they offer products or services that are in line or help to comply with large-scale government policy measures (like for instance promoting renewable fuels). The French attributional and decisional electricity supply mix causes greenhouse gas emissions of 98 and 225 gCO_2-eq./kWh, respectively, whereas the European attributional and decisional electricity supply mix causes greenhouse gas emissions of 554 and 473 gCO_2-eq./kWh, respectively. The volumes of high radioactive waste generated with the French and EU-27 electricity mixes amount to 11 and 3.5 mm^3/kWh for the attributional mixes as well as 3.8 and 0.034 mm^3/kWh for the decisional mixes.
Conclusions The criterion “relative economic size” helps to better decide on the appropriate LCI model to be applied in specific LCA case studies supporting any kind of decisions. Being quantitative, the “relative economic size” criterion is comparable to the criteria used to delimitate the product system (cut-off criteria mass, energy and environmental impact). The delimitation values proposed are still preliminary and still show a certain degree of ambiguity. Nevertheless, it proves to be both a practical and potentially relevant criterion. The case study of the French and European electricity mixes shows that a distinction of different decision contexts is required and feasible. Using official statistical information and published forecasts issued by the relevant

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industrial associations or governmental bodies significantly reduces the potential bias related to the determination of possible change-oriented electricity mixes.

Recommendations and perspectives The relative economic size of the object of investigation is a quantified criterion to decide on the most appropriate modelling approach in life cycle inventory. It is recommended to apply the criterion in the goal and scope phase of any LCA and to apply it on the production volume on the one hand and on purchase volumes on the other. Production and purchase volumes can be expressed in either economic or physical quantities and be related to the totals of economic sectors or political entities such as nations or international organisations. The current paper deals with the appropriate modelling approach illustrated with the electricity mix. The electricity sector is only one of many sectors where the choice of the modelling approach may reveal important differences in the overall environmental impacts. Thus, it is worthwhile to extend the concept presented in this paper to other economic sectors such as agriculture, mining or paper and pulp. This would help to better substantiate or to adjust the delimitation values and to gain more experience with the threshold criteria proposed.

Keywords Attributional · Average · Consequential · Decisional · Electricity · LCA · Life cycle inventory analysis · Marginal · Modelling

1 Background, aim and scope

1.1 Research question and overview

"Being a non-smoker, the poet said, I could smoke for about seven years longer as compared to a smoker."

While it is true that non-smokers enjoy a longer life as compared to a smokers' life, smokers cannot smoke during this longer life without violating the basic condition under which the statement is valid. This statement illustrates one of the most pertinent and difficult problem faced in life cycle assessment studies that are intended to support decisions. Life cycle assessment (LCA) studies that are used for decision support should anticipate the potential implications of the decision and, if required and sensible, include these implications in the life cycle inventory (LCI) models. The scientific community proposes different models and approaches to model the consequences of decisions in LCA. However, a clearly structured analysis and guidance as well as a practical and sensible criterion to choose the appropriate LCI model are still missing. The present paper intends to fill this gap by proposing the "relative economic size" as the quantified criterion to select the most appropriate LCI model. The criterion is illustrated with several real life examples. Furthermore, the different modelling approaches are applied on the French and European electricity sectors.

The paper starts with an overview and assessment of the current modelling approaches (Section 1.2 to 1.7). Section 2 classifies the objects of investigation introducing the criterion "relative economic size" (Section 2.2). The practicality of the approach is shown with several real life objects of investigation (Section 2.3). Finally, the link is established between the size of the object of investigation and the most appropriate LCI model (Section 2.4). Section 3 contains the LCA results of the French and European electricity mixes modelled with the different approaches identified relevant in the context of decision making in large, internationally operating companies. The criterion to choose the appropriate model and the modelling approaches are discussed in Section 4. Conclusions are drawn in Section 5, and Section 6 contains recommendations and perspectives related to a broader application of both the recommended criterion and the recommended modelling approaches.

1.2 Evolution of the approaches

More than 10 years ago, the relation between an LCA and the appropriate model was discussed and established during the European Union concerted action LCANET (Frischknecht 1997). This distinction was further refined in Frischknecht (1998).

Whereas the descriptive LCA model is rather undisputed (theoretically founded in Heijungs 1997), the appropriate approach to model the effects of a decision is still subject to debates. Different views exist which result in rather different LCI models and finally LCA outcomes (Frischknecht 2002). The main point of discussion is whether or not actual economic relations are followed to identify the suppliers in the situation after the decision has been taken. Some proponents of the consequential approach (Ekvall et al. 2004; Ekvall and Weidema 2004; Weidema 2001) use market information and price elasticities to identify those suppliers that are affected by the decision and will increase or decrease their production (without necessarily having an economic (contractual) link to the product under study). Others plea for the consideration of the actual (future) suppliers based on factual or anticipated economic business-to-business relationships (Frischknecht 1998).

The revised International Organization for Standardization (ISO) standard 14040 (ISO 2006) mentions the two applications ("consequences of possible changes between two alternative products" on one hand and "the account of the history of the product" on the other) in the informal Appendix A.2. However, the contents of the ISO standards are generally focused on the attributional (average) approach. A recent publication of the UNEP-SETAC Life Cycle Initiative on inventory methods in LCA (Lundie et al. 2007) does not favour any particular approach but highlights properties as well as advantages and drawbacks of the different approaches (attributional, consequential). The international reference life cycle data system handbook of the European Commission (2010) differentiates between three situations; Micro-level decision support (situation A), meso/macro-level decision support (situation B) and accounting (situation C). For the situations A and C, an attributional approach is considered appropriate, whereas for the situation B, they recommend to model processes affected by large-scale changes as a consequence of the decision by long-term marginal processes.

In the following, the three modelling approaches are characterised. The text is partly taken from Frischknecht (2007).

1.3 The attributional approach

The outline of attributional LCI models is described in depth by Heijungs (1997). Attributional LCI models may be used to describe for instance the life cycle of 1 kWh of electricity at grid in France in 2006. It is assumed that this kilowatt hour is part of the total consumption volume of electricity in France (429913 GWh in 2006)[1] and not an extra kilowatt hour. Inputs and outputs are determined based on the average annual production situation for the total amount sold in 2006. The product system of such an attributional analysis comprises for instance all domestic and foreign power plants involved in electricity generation for the French market, all uranium mines supplying the fissile material to the enrichment plants that supply the fuel fabrication plants manufacturing for the nuclear power stations in France, etc.

The result of such an LCI (or LCA) provides information about the environmental impacts of the fuel supply chains, the infrastructure and the operation of the power plants, the electricity transformation and distribution etc. that can be attributed to the consumption of an average kilowatt hour of electricity at low voltage level purchased in France in 2006.

1.4 The consequential approach

The outline of LCI models that describe the changes of a situation caused by a decision, called "consequential approach", has for instance been extensively discussed during an LCA workshop on electricity data in LCI held in Cincinnati, Ohio, USA and during the Internet Life Cycle Assessment—Life Cycle Management (InLCA-LCM) conference in May 2002 (Ekvall 2002). Furthermore, papers have been published by Ekvall et al. (2004) and Ekvall and Weidema (2004) that describe the approach and the procedure about how to establish consequential life cycle inventory models. In the final report of the electricity workshop (Curran et al. 2002), the consequential approach is defined as an attempt to estimate how flows to and from the environment will *change* as a result of a decision. A consequential LCA aims to answer the question "which effect the decision to purchase for instance an additional kWh of electricity has on the electricity market and/or on the environmental impacts". For that purpose, power generation technologies, which will adapt production due to that particular change in demand, need to be identified. Opposite to the attributional approach, actors (power generation technologies), that are not affected by a change in that demand or that are not able to increase their production due to (technical, political, environmental or societal) capacity constraints, are not part of the product system of a consequential LCA.

In other words, the product system does not comprise the utilities, the national or regional average of electricity generation technologies but the ones that will increase or decrease their production. For instance, the LCA of an additional purchase and consumption of certified green electricity from hydropower may include electricity from hard coal power plants, if the production capacity of certified green electricity from hydropower were constrained and additional electricity demand were supplied by coal power. In that case, a decision to cover an additional demand with certified green electricity instead of conventional electricity leads to increased sales (and production) of coal-based electricity because sales of electricity as a whole increase, but certified power plants cannot supply the additional demand. Hence, the additional kilowatt hour of electricity would then be charged with the environmental impacts of an additional kilowatt hour of coal-based electricity.

We recognise that the consequential approach aims to link micro-economic actions with macro-economic consequences. It requires an LCA that considers market reactions, production volume developments, technology developments, capacity constraints, etc. This information may be delivered by a set of (pre-defined) conditions, by one or several scenarios or with the help of dynamic models. In any case, an embedding in a broader range of socio-economic interdependence is required.

According to the proponents of this approach, the result of an ideal consequential LCI provides information about how an individual (consumption or investment) decision will influence the (global) environment and whether or not the purchase of a supposed environmentally friendly product is likely to lead to a reduction in overall environmental impacts.

[1] http://iea.org/, information retrieved on June 23, 2009

1.5 The decisional approach

An alternative definition of the consequential approach remains on the micro-economic level and is described by Frischknecht (1998). It is called *decisional* approach (Frischknecht 2002, 2006, 2007). In contrast to the interpretation of the consequential approach described above, the decisional approach uses the actual or anticipated financial and contractual relations between economic actors (business-to-business relations) as the main basis of information. Applied on our case study with 1 kWh electricity, the product system would be modelled as follows: A consumer, who chooses to purchase certified green electricity, is entitled (or obliged) to accept the environmental impacts that are economically and contractually related to its production.

As a consequence—and this is one main difference to the consequential approach described above—the LCI of 1 kWh of certified green electricity reflects the environmental impacts of exactly the power plants producing the certified electricity, even if the production capacity of certified green electricity were constrained. Someone else would need to buy regular or unspecified electricity instead.

Particular economic activities, which are linked to the product through economic and contractual relations, are attributed to an individual additional (or reduced) consumption. The consequential approach as defined in the previous subsection links a (consumption or investment) decision to its affected economic activities irrespective of the fact whether these affected activities are actually required for the product consumed or invested in, and irrespective of the fact whether direct economic and/or contractual links to the purchased product exist.

The decisional LCA supports an efficient allocation of scarce environmental resources (similar to the price system that helps to allocate the traditional economic resources labour, land and capital). This alone of course does not reduce environmental pressure. Supporting policy measures need to be established on a macro-economic level. An environmental policy is required that defines reduction targets on emissions and resource consumptions or on environmental impacts (such as climate change). The relative scarcity of the environmental resources (grouped according to human health, ecosystem quality and resource quality) can then be operationalised for LCA with the help of life cycle impact assessment methods.

1.6 Modelling of multifunctional processes and of recycling

According to Ekvall and Weidema (2004), the allocation problem in multifunctional processes and in open-loop recycling is automatically solved with system expansion when applying a consequential modelling approach. Firstly, the co-product of interest of the multifunctional process is determined. Secondly, products or production technologies affected by the change are identified for all other co-products. These products and production technologies are then considered in system expansion instead of assuming average production patterns as is often done in attributional LCAs. The environmental impacts caused by the supply of these affected products and production technologies, respectively, are determined with a life cycle perspective. They are subtracted from the total environmental impacts caused by the multifunctional process.

The affected products are defined as the specific products that are most likely coming to the market if the demand is increasing (or which disappear from the market due to a decreasing demand). The same view can be applied to production technologies. The affected production technologies are defined as the specific technologies that are most likely increasing their production if the demand is increased. Excellent and reliable knowledge on future market developments, price elasticities and market restrictions is necessary when trying to identify these products or production technologies.

One main point of critique is the fact that the environmental impacts caused by these affected products or production technologies are fully attributed in the form of a credit (benefit) to the multifunctional process or the life cycle that supplies materials to be recycled. As it has been pointed out by Frischknecht (1998) and Frischknecht and Jungbluth (2003), the avoided burden approach helps to identify the maximum (or most likely) environmental benefit of co-production. However, it does not avoid allocation because (at least) two parties may claim this environmental benefit: the operator of the multifunctional process on the one hand and the purchaser of the co-products manufactured on the other. The same applies in recycling: the ones that supply and the ones that purchase material to be recycled may claim the environmental benefit. Hence, the total environmental benefit needs to be split between the economic actors involved. The automatism to attribute the entire environmental credit to one of the two leads to an unbalanced view and may even lead to an omission or to a double counting of actually occurring environmental impacts. The avoided burden approach may be useful in national environmental accounts where it is not a matter of attributing environmental impacts to particular products or services but to quantify the annual national impacts in total. Furthermore, the avoided burden concept may help to identify the maximum achievable environmental benefit. However, it does not avoid the allocation step in product LCAs as the credit still needs to be shared among the concerned parties.

1.7 Synthesis

We have seen that three main modelling principles may be distinguished, namely the attributional, the consequential and the decisional approach. Table 1 shows the main characteristics of the three approaches described above.

All approaches may be applied in a past or future situation. The attributional approach is used in reporting, and the inventory model (the product system) is based on economical and/or contractual relations. The consequential approach is used for decision support (past and future) and the relations are identified, e.g. with the help of computational general equilibrium models. The decisional approach is also used in decision support, but the inventory model is based on future actual or anticipated economic and/or contractual relations. Whereas both the attributional and decisional approaches do not prescribe the allocation approach to be applied, the consequential approach is intimately linked to the avoided burden approach. The environmental impacts related to the product or service under study differ, too. The attributional and decisional approaches try to quantify the impacts caused by the product system supplying the average and extra consumption, respectively. The consequential approach tries to quantify induced impacts, which may have no direct physical or economic link to the product system under study.

After the description and characterisation of the three modelling approaches, the next section deals with the classification of objects of investigation according to their relative economic size and the link between the size of the object of investigation and the most appropriate LCI model.

2 How to choose the appropriate LCI model: the criterion "relative economic size"

2.1 Introduction

The main challenge in decision-oriented LCA lies in an appropriate accommodation of changes in the LCI model. Decisions with small scale effects may hardly be identifiable in the real economy and thus show hardly any empirically identifiable changes neither in the economy nor in environmental impacts. Decisions or policy measures with a regional or even global scope on the other hand may exert influence on the production volume of particular industries or the output of economic sectors and thus indirectly on the impacts observable on the world's environment.

We may compare a decision with a stone hitting the surface of a lake with a moderate swell. Throwing a small pebble will cause ripples, which are very small compared to the size of the swell of the lake. Throwing a boulder into the same lake causes waves that clearly superpose the existing swell. If we throw the same boulder into the stormy Sea, we would hardly observe any change in the pattern of the big swell. Underground earthquakes may cause a tsunami with waves that are likely to even superpose the waves of the stormy sea.

Thus, the selection of the appropriate system model depends not only on the distinction between decision support and description but also on the size of the object of investigation and, by consequence, on the size of the potential effect of a decision.

2.2 Classification of objects of investigation

The economic size of the object of investigation is considered as an important aspect regarding the selection of the appropriate LCI model. During the last months, several governments decided whether or not to avoid insolvency by helping large financial institutes with public money depending, among other criteria, on the economic size of the company. The criterion applied is whether or not a financial institute is considered system-relevant ("too big to fail"). In 2007 Lehmann Brothers contributing some 0.33% to the US American gross domestic product went bankrupt, whereas the Swiss UBS (Parent Bank) contributing some 5.5% to the Swiss gross domestic product in the same year and was rescued by the Swiss government. In the

Table 1 Main characteristics of attributional, consequential and decisional approach in life cycle inventory analysis

	Attributional	Consequential	Decisional
Purpose	Reporting/decision support[a]	Decision support	Decision support
Time	Past or future	Past or future	Past or future
Relations	Economical and/or contractual	Identified via general equilibrium models	Economical and/or contractual
Environmental impacts	Caused by product system supplying average consumption	Induced by decision	Caused by product system supplying extra consumption
Multi-output processes and recycling	Allocation or system expansion	Avoided burden (system expansion)	Allocation or system expansion

[a] In today's practice, most decisions are based on attributional LCAs. Consequential approaches are mainly used by scientists and consultants

context of LCA, the economic size of a company or a commodity may be expressed by monetary indicators such as the consolidated turnover of a company or of certain products or services of a company.

We propose to classify LCA objects of investigations into three classes. There is no scientific evidence of a quantified delimitation though. No such delimitation value seems to exist in econometrics to decide whether to use a static input output table or equilibrium model. We orient ourselves on the two banking institute examples described above. We propose 0.1% and 1% relative economic size to delimitate small, medium and large objects of investigations (Table 2). These preliminary delimitation values show some ambiguity, and more experience is needed to verify or falsify (and eventually adjust) the values proposed. They should not be perceived as being sharp and fixed but rather as a kind of landmark. The examples shown in Table 3 do at least not contradict with our intuitively set delimitations.

We propose to apply a sequence of indicators similar to the sequence of cut-off criteria "mass, energy and environmental impacts" proposed in the ISO standard 14044, clause 4.2.3.3.3. The three classes are defined by the relative share of the contribution of the object of investigation to a total.

The total may be defined economically (the total of a certain economic sector) or politically (the total of a country or a region). We propose to use the following indicators:

– Annual consolidated turnover (relative to the annual gross domestic product of an economic and political union such as the European Union 27 or a political entity like France)
– Monetary purchase volume from relevant economic sectors (relative to the annual consolidated turnover of the sectors)
– Physical purchase volume from relevant economic sectors (relative to the physical annual output of the sectors)

Why do we propose to chose the economic size and not, for instance, the "environmental size"? The ultimate goal of any LCA is the quantification of the environmental impacts caused by human activities. The cumulative environmental impacts depend on mainly three aspects:

– The amounts of intermediate goods and services required
– The suppliers of the intermediate goods and services
– The environmental impacts of each individual unit process included in the product system at stake

Table 2 Preliminary classification of the economic size of the object of investigation

Economic size	Relative share
Small	<0.1%
Medium	0.1% to <1%
Large	>1%

The amounts of intermediate goods and services required are the same in a descriptive and a decision-oriented context (given the fact that the same product is being analysed but with different goals). The environmental impacts of each individual unit process are the same, too. The environmental impacts of 1 kWh of electricity produced in one particular power plant are the same in a descriptive and a decision-oriented context.[2] The suppliers of the intermediate goods and services, however, are likely to differ depending on whether the LCA is of attributional, decisional or consequential nature.

Hence, we need to know how the economic relations between the various actors will be affected by a decision. The main question is how the technosphere matrix, which describes the current situation of the supply chain of a product or service (Heijungs and Suh 2002), may change in a decisional or consequential context. The larger the economic size of the object of investigation under consideration, the more likely and distinct are the changes in the economic relations. The environmental size (the cumulative environmental impacts) of the object of investigation does not determine whether or not changes within the economy are likely to happen due to a decision. It is not the cause but a consequence and depends on how the economic relations would be affected. That is why the economic size of the object of investigation is proposed.

2.3 Examples of objects of investigation

Table 3 shows selected examples to illustrate the classification procedure and indicators.

The first objects of investigation are project proposals for a residents' building in the City of Zurich. The LCA results of those projects are used to support an investment decision including environmental aspects. On one hand, the financial project volume is put in relation to the total Swiss investments in the building sector. On the other hand, the annual energy demand for heating is compared with the annual natural gas supply of Erdgas Zürich AG, the supplier of natural gas in the region.

The second object of investigation is the investment in a big new wastewater treatment plant operated in the city of Zurich (assuming there was no wastewater treatment facility before). The results of the LCA are supposed to support the decision-making process. The net annual electricity consumption of the new facility is put into relation of the total annual electricity consumption in the area of the utility of the city of Zurich.

[2] In an attributional LCA, it contributes to the average electricity mix, while it might be the marginal power plant in a decisional or consequential LCA.

Table 3 Examples of objects of investigation and their classification with regard to the relative economic size

Examples	Volume of object of investigation	Reference volume	Relative share	Class
LCA of the investment in a new residence building	90 Mio. CHF[a]	51'881 Mio. CHF[b]	0.17%	Medium
	155 MWh[c]	6,915 GWh[d]	0.002%	Small
LCA of the investment in a new waste water treatment plant (size 670,000 inhabitant equivalents)	7,200 MWh[e]	2,983 GWh[f]	0.24%	Medium
LCA of electricity purchase of Credit Suisse sites in Switzerland (choice of a supplier)	176 GWh[g]	57.4 TWh[h]	0.31%	Medium
Comparative LCA of heating systems in view of a promotion of electric heat pumps in Switzerland	1,000 GWh[i]	57.4 TWh[h]	1.7%	Large
LCA of biofuels to cover a share of 10% in total fuel sales in the EU by 2020	353 TWh	3,530 TWh[k]	10%	Large

Volume of object of investigation divided by the reference volume results in the relative share

[a] Investment volume (BGZ 2009)

[b] Annual purchase in the Swiss building sector (Nathani et al. 2008)

[c] Annual natural gas consumption (SIA 2009)

[d] Annual supply of Erdgas Zürich (2009)

[e] Net annual electricity consumption of wastewater treatment plant (ERZ 2006)

[f] Annual electricity consumption supplied by the electric utility of the city of Zurich (ewz 2008)

[g] Total electricity consumption of all Swiss sites in 2007 (Credit Suisse Group 2008)

[h] Total consumption of electricity in Switzerland 2007 (BFE 2008)

[i] Additional annual electricity demand until 2020 (FWS 2008)

[j] Total consumption of motor fuels in road transport in the European Union 2006 (EUROSTAT 2009)

The third object of investigation is the purchase of electricity by all Swiss sites of the Credit Suisse Group, supposing that the Credit Suisse Group wants to use the LCA results to support a decision whether or not to switch from grid mix electricity to certified green electricity. The relative share is expressed as the ratio between the volume of electricity purchased by Credit Suisse Group in Switzerland and the total volume of electricity consumed in Switzerland.

The fourth object of investigation deals with the policy of the Swiss Federal Office for Energy (SFOE) regarding electric heat pumps. SFOE promotes the use of electric heat pumps for domestic heating purposes. LCA results may be used to evaluate the environmental impacts related to this policy measure. The predicted additional annual electricity demand of heat pumps operated in Switzerland by 2020 is put in relation to the current total annual electricity consumption.

Finally, the fifth object of investigation is the requirement of reaching a 10% share of biofuels in the fuel market of the European Union by 2020.

The relative economic size of all objects of investigation described above and listed in Table 3 are medium or even large, except for the operational energy consumption of the building example, where the economic size is small. The implication of the selection of the appropriate LCI modelling approach according to the relative economic size is described in the next subsection.

2.4 Link between the economic size and LCI models

For any LCA, which documents the environmental performance of an existing product, process, service, production site or company, an attributional LCI model should be chosen. This choice is valid irrespective of the size of the object of investigation, and it is not disputed among experts.

The consequences of a decision depend on the size of the decision but also on the size of the surrounding economic environment. The individual decision of a consumer to purchase a kilowatt hour of electricity from wind power does neither affect the markets of wind mills nor that of coal power plants. In contrast to that, the decision of a major globally acting corporation to purchase exclusively electricity from wind powering all facilities worldwide may lead to a substantial shift in the electricity sector.

While an individual decision with comparatively small consequences is best modelled under *ceteris paribus* (“other things being equal”) conditions, decisions with large potential consequences should be modelled under the conditions of *mutatis mutandis* (“the necessary changes being made”). With the concept of the relative economic size as outlined above, we have an indication to classify objects of investigation into three groups and apply the most appropriate LCI model (Table 4).

Does the consequential or the decisional approach fit better to the *mutatis mutandis* requirement? This clearly

Table 4 Classification of the economic size of the object of investigation and recommended LCI models

Economic size	LCI model	Examples and remarks
Small	Attributional	Support for day to day consumer decisions
		Make sure that the object of investigation and the decision at issue is not part of a policy measure of public authorities or companies with larger consequences
Medium	Decisional/attributional in a sensitivity analysis	Strategic decisions of large companies or industry associations
		Large-scale promotion activities of companies
Large	Consequential/decisional in a sensitivity analysis	Policy measures on the level of nations, regions or multinational companies
		Decisional if consequential information and data are missing

depends on the size of the object of investigation. Medium size objects are better modelled with the decisional approach. It allows companies to explicitly address and include their business policies in the LCAs of their products, services and investments. In an LCA supporting decisions or governmental regulations with large-scale implications, a simplified consequential model is considered more appropriate. It is very important to consider large-scale induced effects in such situations, and it is at the same time easier to predict these effects with the help of scenarios.

3 Illustrative case study

Attributional and decisional LCI datasets of French and European electricity mixes are described in order to show the differences of the environmental impacts depending on the modelling approach selected. No consequential LCI dataset is established due to lack of resources and missing information. Although electricity supply is chosen, the approaches and the findings apply on any other product or commodity as well. The electricity mixes are modelled with datasets of technology specific electricity production according to ecoinvent data v.2.01 (ecoinvent Centre 2007).

Today, the electricity production in France is dominated by the 58 nuclear reactors, which contributed 75.9% to the national electricity supply mix on the average of the years 2006 to 2008. Hydroelectric power accounts for 10.4%, hard coal for 4.8% and natural gas for 3.1%. New renewable energies play so far only a minor role with a production share of 1.4% (see footnote 3).

An annual long-term decisional electricity mix is established by considering the expansion of electricity generation from each energy source. The developments in the electricity generation sector between 2000 and 2030 as predicted by Eurelectric (2006) are used as the basis to establish the decisional mix. In April 2009, the EU directive 2009/28/EC was put into force, which defines an overall share of 20% of energy from renewables by 2020 (European Commission 2009). The illustrative example does not fully correspond to the target shares defined in this directive. On the one hand, the directive covers all forms of energy produced with renewables (thermal as well as electric energy), and on the other, the mixes established in this paper show the changes in the mix from today to 2030 and not the average mix in 2030. The decisional mix constitutes of energy sources from which the electricity generation is predicted to increase in France until 2030. These are nuclear power (27.1%), power from natural and industrial gas (36.1% and 1.3%), wind power (25.5%) and other renewable energies (10.1%).

The decisional LCI model of French electricity mix is established based on future developments of the French national electricity supply and on the best view of country experts of what is likely to occur in each country with respect to plant demand balance, taking into account recent trends and projections of economic, social, environmental and technological developments. This model is applicable as long as no specific information from the supplying electric utility is available or no specific requirements on the electricity mix composition are formulated (such as certified green electricity). Otherwise, the decisional LCI model of the electricity mix may be characterised with a dedicated electricity mix of a particular utility or with an electricity mix composition requested by the company or by the owner or operator of equipment purchased from the company.

The ecoinvent electricity mix of the European Union is updated and calculated by adding up the monthly electricity production figures in 2007 of the 27 member states, split up into the different energy sources. Seventeen of the EU States were at that time members of the Union for the Coordination of the Transmission of Electricity (UCTE),[3] which provided such country-specific production data. Denmark, Iceland, Finland, Norway and Sweden were members of the Organisation for the Nordic Transmission System Operators (NORDEL),[4] which provided similar

[3] http://www.ucte.org (accessed in February 2009), http://www.entsoe.eu/index.php?id=52 (accessed in May 2010)
[4] http://www.nordel.org (accessed in February 2009), http://www.entsoe.eu/index.php?id=61 (accessed in May 2010)

Table 5 Synopsis of LCA goals, recommended electricity mix models, their climate change impacts and their radioactive wastes (values include transmission and distribution to medium voltage)

Example	Recommended electricity mix	Climate change impact (g CO_2-eq./kWh)		Volume occupied, final repository for radioactive waste (mm^3/kWh)	
		France	Europe	France	Europe
Reporting of the annual electricity consumption of a company	Annual attributional country or regional supply mixes	98	554	10.8	3.47
Environmental performance of treatment of 1 m^3 of waste water	Annual attributional country supply mix or annual attributional utility's mix (if known)	98	554	10.8	3.47
Investment decision in a new building or a new waste water treatment plant	Long-term decisional supply mix of the respective country or of supplying utility (if known)	225	473	3.83	0.0341
Avoided burdens of 1 kWh electricity from a new waste incineration plant	Long-term decisional supply mix of the respective country or of supplying utility (if known)	225	473	3.83	0.0341

data. Estonia, Latvia and Lithuania were members of the Baltic grid operator organisation BALTSO,[5] which publishes monthly production data of its member states. The British government[6] publishes the monthly electricity production figures of the UK, and data about the Irish electricity production are derived from the statistics of the International Energy Agency (IEA).[7] For Cyprus, only annual production data are available from the IEA statistics.

The general category of hydroelectric power UCTE is split up into hydroelectric power and pumped storage power. The electricity input required by the pumps is converted to electricity produced by the pumped storage hydroelectric power plant with an efficiency factor of 70% (Bolliger and Bauer 2007). Electricity production from "other renewable energies" (renewable energies except hydro and wind power) is split up into waste, biomass, tide, geothermal and solar by applying EU production figures of the year 2006 from IEA.

Today's electricity production in the European Union is dominated by nuclear power (29%), natural gas (22%), hard coal (20%), lignite (11%) and hydroelectric power (11%). With a production share of 5%, renewable energies other than hydroelectric power play so far only a minor role.

In order to determine a long-term decisional European electricity mix, the predicted expansion of electricity production from different energy sources as published in Eurelectric (2006) is adopted. Other publications such as forecasts by the Commission of the European Communities (2008) are used to validate the predictions of Eurelectric (2006).

All considered forecast scenarios predict an expansion of mainly renewable energy sources and natural gas power until 2020. The share of nuclear and coal power in the European electricity mix is expected to decline in the future. Decisional mixes established based on other publications than Eurelectric (2006) include generally higher shares of renewable energies and lower shares of electricity from natural gas. The share of electricity from natural gas is substantially lower when underlying higher oil prices (US $100 instead of 61) and assuming new energy policies favouring renewable energies (see, e.g. Commission of the European Communities 2008).

The annual decisional mix based on the increase in production from today to 2030 is dominated by additional electricity from natural gas (65.6%), wind (15.0%), hydroelectric power (1.9%) and other renewable energies (16.4%). It does not include nuclear, hard coal and oil power plants. Despite the very high share of electricity from natural gas, the decisional mix has lower greenhouse gas emissions compared to the annual average mix due to the lack of electricity from hard coal and lignite.

Table 5 names exemplarily LCA goals and indicates the recommended electricity mixes as well as the climate change impacts and radioactive wastes of the corresponding French and European (EU-27) electricity mixes. It shows that the climate change impact of the French electricity mix raises from 98 to 225 gCO_2-eq./kWh (attributional and long-term decisional mix, respectively) whereas the climate change impacts of the European electricity mix drops from 554 to 473 gCO_2-eq./kWh (attributional and long-term decisional mix, respectively).[8] The volumes of high level nuclear waste generated with the French attributional and decisional mixes amount to 11 and 3.8 mm^3/kWh, respectively, whereas the

[5] http://www.baltso.eu (accessed in February 2009), http://www.entsoe.eu/index.php?id=51 (accessed in May 2010)

[6] http://www.berr.gov.uk/energy/statistics/source/electricity/page18527.html (accessed in February 2009)

[7] http://www.iea.org/ (accessed in February 2009)

[8] The long-term decisional electricity mix does not correspond to the long-term average electricity mix. Furthermore, the emissions are based on a life cycle approach. That is why the climate change intensity of the long-term decisional electricity mix may not comply with the EU target of a greenhouse gas emission reduction of 20% between 1990 and 2020.

volumes of high level nuclear wastes generated with the European attributional and decisional mixes result in 3.5 and 0.034 mm^3/kWh, respectively.

4 Discussion

The classification of the objects of investigations in life cycle assessments used to support decisions allows for an explicit attribution of the relative economic size of the object of investigation to the most suited LCI model. It turns out that the decisional model is suitable in most of the business cases on a company level such as investment decisions, choices of suppliers and the like. The consequential modelling is limited to cases with predicted large impacts on economy (and ultimately on the environment) and thus mainly useful in policy making by national, regional or global governmental bodies. The attributional model is applied on descriptive LCAs (such as environmental reporting) and where decisions with small scale effects are involved such as product comparisons. If however an LCA on a product level with small scale implications is intended to support a corporate environmental strategy of larger consequences, the decisional approach should be applied on such an LCA. Usually, the business plan related to the market introduction of a product contains the necessary market figures.

The case study of attributional and long-term decisional electricity supply mixes shows considerable differences in the amount of environmental impacts per kilowatt hour depending on the underlying type of model. The choice of the most appropriate type of model is therefore crucial. Furthermore, in applying a long-term decisional or a consequential electricity mix, the resulting share of different energy sources depend on predictions of how the electricity market will develop. In the case of the European Union, most predictions agree that the electricity increase will be covered by power plants based on natural gas and renewable energies. This is mainly due to the high flexibility regarding natural gas electricity on one hand and the more prominent role of new renewables in the European and national energy policies. However, depending on various factors such as national and international policies, the shares of electricity from natural gas and the split up of the different renewable energy sources differ considerably. Furthermore, one has to acknowledge the inherent and possibly large uncertainties related to long-term forecasts.

5 Conclusions

This paper proposes a practical approach to decide on the basis of a limited amount of information on which model to apply in a particular LCA. The relative economic size turns out to be a sensible criterion to classify objects of investigation into three groups to which the most appropriate LCI models are assigned and to delimitate the three classes on the relative sizes of 0.1% and 1%, respectively. The criterion provides a good insight into the size of potential consequences of a decision, being applied on the consolidated turnover of the product, or the purchase volume (physical, economic) of selected inputs required to manufacture the product under investigation, and being related to the size of a political entity (such as a community, a nation or an regional political body) or to the size of relevant economic sectors. It gets easier to identify the "necessary changes to be made" in decision-oriented LCAs based on the criteria established as proposed in this paper.

Being quantitative, the "relative economic size" criterion is comparable to the criteria used to delimitate the product system (cut-off criteria mass, energy and environmental impact). At this point in time, the delimitation values (0.1% and 1%, respectively) are based on a rather small sample and thus show a certain ambiguity. More experience on the basis of case studies is required to verify or falsify (and adjust) the delimitation values proposed in this paper. Nevertheless, the concept proves to be both a practical and relevant criterion. The case study of the French and European electricity mixes shows that a distinction of different decision contexts is required and feasible. Using official statistical information and published forecasts issued by the relevant industrial associations or governmental bodies significantly reduces the potential bias related to the determination of possible change-oriented electricity mixes.

6 Recommendations and perspectives

The relative economic size of the object of investigation is a quantified criterion to decide on the most appropriate modelling approach in life cycle inventory. It is recommended to apply the criterion in the goal and scope phase of any LCA and to apply it on the production volume on the one hand and on purchase volumes on the other. Production and purchase volumes can be expressed in either economic or physical quantities and be related to the totals of economic sectors or political entities such as nations or international organisations.

The delimitation values 0.1% and 1.0% are defined based on a very limited set of cases of the financial sector. Thus, more experience is needed to confirm or eventually adjust the delimitation values. Furthermore, the limits should not be applied too strictly (0.11%, decisional; 0.09%, attributional) but with a certain flexibility. Flexibility would mean in this context to perform the LCA using two approaches in case of an ambiguous relative economic size of the object of investigation.

The present paper deals with the appropriate modelling approach illustrated with the electricity mix. The electricity sector is only one of many sectors where the choice of the modelling approach may reveal important differences in the overall environmental impacts. Thus, it is worthwhile to extend the concept presented in this paper to other economic sectors such as agriculture, mining or paper and pulp. This would help to continuously build up a decisional LCI database that contributes to more appropriate LCI models used in decision support in industry and public administration.

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