Investigation of possible approaches for consequential electricity markets in ecoinvent

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Dokumenttitel och undertitel

Utvärdering av möjliga angreppssätt för modellering av konsekvenselmarknader i ecoinvent

Sammandrag

Version 3 av ecoinvent är den första databasen att erbjuda möjligheten att koppla samman livscykelinventeringar (LCI) utefter olika länkningsalgoritmer. Genom dessa länkningsalgoritmer tar ecoinvent nu fram bakgrundslivscykelinventeringar med både medeldata och långsiktig marginaldata (t.ex. över elmarknader i olika länder). Idealt sett representerar långsiktig marginaldata över elmarknader den ytterligare kraftverkskapaciteten som behöver installeras (installationsmarginal) för att täcka en förändrad efterfrågan av elektricitet inom en specifik marknad. Sådana LCI-data används inom konsekvensLCA (cLCA) och behövs för att korrekt bedöma miljöpåverkan av att ändra ursprung eller produktionssätt i ett produktsystem som använder elektricitet. Den nuvarande sammankopplingen av inventeringar till 'konsekvensbaserade elmarknader' är behäftad med tillkortakommanden genom att exempelvis marknadsspecifika förhållanden inte modelleras, att endast redan producerande tekniker inkluderas, och att el från kraftvärmeverk inte anses vara en del av framtida installationer, vilket resulterar i orealistisk output från framtida installationsmarginaler. Eftersom majoriteten av producerade varor och tjänster i varje sektor av ekonomin till stor del är beroende av elektricitet, behöver angreppsättet för hur konsekvensbaserade elmarknader modelleras förbättras för att stödja relevanta konsekvensLCA-resultat.

I denna uppsats gjordes en litteraturstudie över vilka aktuella angreppsätt som rekommenderas för modellering av eltillförsel i konsekvensLCA. För närvarande är konsekvensversionen av ecoinvent definierad utifrån småskaliga, långsiktiga beslut. Baserat på litteraturstudien ansågs det bästa angreppssättet vara att använda nationella officiella prognoser för elsektorn över perioden 2008-2035. För att bedöma angreppssättets tillförlitlighet tillämpades det på ecoinvents elmarknader för Brasilien, Kina, Indien, Japan, Ryssland och Schweiz. Tillämpningen gav mer diversifierade elmarknadsmixer jämfört med status quo, och kom runt de nuvarande tillkortakommandena. En fortsatt bedömning av angreppssättet gjordes genom att beräkna miljöpåverkan med IPCC 2007 GWP, 100a och ReCiPe 2008 livscykelspåverkananalys (LCIA). Förändringar observerades i alla midpoint-indikatorer, t.ex. en tydlig minskning av global uppvärmningspotential (GWP), partiklarbildning, och försurning, för de studerade marknaderna vars nuvarande konsekvenselmarknad innehåller stor andel fossil tillförsel. Sammanfattningsvis rekommenderas användande av prognoser från datakällor med samstämda bakgrundsantaganden för att förbättra de kvarvarande konsekvenselmarknaderna i ecoinvent. För att möjliggöra modellering av storskaliga beslut kan framtida studier inkludera dataset över fler scenarier och tidsramar för användaren av ecoinvent att välja emellan, såväl som implementering av en dynamisk optimeringsmodell.

Nyckelord

KonsekvensLCA, ecoinvent, elmarknader, långsiktig marginaldata, LCI-modellering, prognoser

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Abstract

Version 3 of the ecoinvent database is the first background database to offer the possibility to link life cycle inventories (LCI) according to different linking algorithms. Using those algorithms, ecoinvent now provides both average and long-term, marginal background LCI data, (e.g. for electricity markets for different countries). Long-term, marginal data for electricity markets ideally represents the additional power plant capacity that needs to be installed to cover a change in demand for electricity in that market. Such LCI data is used in consequential LCA (cLCA) and is needed for an accurate assessment of the environmental impacts of a decision to alter the source or production method of a product system using electricity. The current linking of inventories into 'consequential' electricity markets is associated with shortcomings, e.g. due to the fact that market-specific conditions are not modelled, only already producing technologies are included, and electricity produced in combined heat-and power-plants is considered not taking part in future installations and results in unrealistic output of future build-margins. Because the majority of goods and services produced in every sector of the economy rely heavily on electricity, the modelling approach for the consequential electricity markets must be improved to allow the ecoinvent database to provide relevant results for cLCAs.

In this thesis, a literature study was performed to investigate which approaches are currently being recommended for modelling electricity supply in cLCA. Currently, the consequential version of ecoinvent is defined for small-scale, long-term decisions. From the literature study, the best approach was determined to be the use of nation-wide official forecasts of the power sector covering the time horizon 2008-2035. To determine the reliability of that approach, it was applied to Brazil, China, India, Japan, Russia and Switzerland. The results of these applications demonstrate more diversified mixes for all markets compared to status quo, overcoming the current shortcomings. A continued evaluation of the approach using the IPCC 2007 GWP, 100a and the ReCiPe 2008 life cycle impact assessment (LCIA) methods shows changes in all midpoint indicators, e.g. a clear reduction in Global Warming Potential (GWP), particulate matter formation and acidification for the studied markets with large shares of fossil supply in the current consequential markets. In summation, it is recommended to continue using the forecasts from consistent data sources to improve the remaining consequential electricity markets in ecoinvent. Future work may include using several scenario and time-frame datasets for the ecoinvent user to choose between, as well as implementation of a dynamic optimization model to allow for large-scale decision modelling.

Keywords

Consequential LCA, ecoinvent, electricity markets, long-term marginal data, LCI modelling, forecasts

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Preface

This master thesis was written in 2014 at the Paul Scherrer Institut in Villingen, Switzerland. The work was performed within the Technology Assessment group under the supervision of PSI personnel and academic personnel from ETH Zürich. In 2015, the master thesis was approved and accounted for by Professor Pål Börjesson at the department of Environmental- and Energy Systems Studies at Lund University, as a part of my Master of Science degree in Environmental Engineering. It can be noted that in 2018 the thesis was made a public LU document, as a result receiving a diary number with a later date than when the thesis was finalized. That is also the reason for the two different front pages. With that, I wish you a good read.

Förord

Det här exjobbet skrevs 2014 vid Paul Scherrer Institut i Villingen, Schweiz. Arbetet skedde vid avdelningen för Technology Assessment, under handledning av personal från PSI och akademisk personal från ETH Zürich. 2015 godkändes och tillgodoräknades exjobbet av professor Pål Börjesson vid institutionen för Miljö- och energisystem, Lunds Universitet, som en del av min civilingenjörsexamen i Ekosystemteknik. Det kan noteras att arbetet gjordes till ett publikt LU-dokument 2018 och därför fick ett diarienummer med ett senare datum än när arbetet slutfördes. Det är följaktligen även därför det är två försättsblad. Med det önskar jag en trevlig läsning.

Malin Pettersson,
Lund 2018

PAUL SCHERRER INSTITUT

Investigation of possible approaches for consequential electricity markets in ecoinvent

Master thesis

of

Malin Pettersson

Supervisors: Christian Bauer and Karin Treyer
(Laboratory for Energy System Analysis, PSI)

Supervising professor: Alexander Wokaun
(Head of the General Energy Research Department, PSI)

Date of submission: 16th of December 2014

Abstract

Version 3 of the ecoinvent database is the first background database to offer the possibility to link life cycle inventories (LCI) according to different linking algorithms. Using those algorithms, ecoinvent now provides both average and long-term, marginal background LCI data, (e.g. for electricity markets for different countries). Long-term, marginal data for electricity markets ideally represents the additional power plant capacity that needs to be installed to cover a change in demand for electricity in that market. Such LCI data is used in consequential LCA (cLCA) and is needed for an accurate assessment of the environmental impacts of a decision to alter the source or production method of a product system using electricity. The current linking of inventories into 'consequential' electricity markets is associated with shortcomings, e.g. due to the fact that market-specific conditions are not modelled, only already producing technologies are included, and electricity produced in combined heat-and power-plants is considered not taking part in future installations and results in unrealistic output of future build-margins. Because the majority of goods and services produced in every sector of the economy rely heavily on electricity, the modelling approach for the consequential electricity markets must be improved to allow the ecoinvent database to provide relevant results for cLCAs.

In this thesis, a literature study was performed to investigate which approaches are currently being recommended for modelling electricity supply in cLCA. Currently, the consequential version of ecoinvent is defined for small-scale, long-term decisions. From the literature study, the best approach was determined to be the use of nation-wide official forecasts of the power sector covering the time horizon 2008-2035. To determine the reliability of that approach, it was applied to Brazil, China, India, Japan, Russia and Switzerland. The results of these applications demonstrate more diversified mixes for all markets compared to status quo, overcoming the current shortcomings. A continued evaluation of the approach using the IPCC 2007 GWP, 100a and the ReCiPe 2008 life cycle impact assessment (LCIA) methods shows changes in all midpoint indicators, e.g. a clear reduction in Global Warming Potential (GWP), particulate matter formation and acidification for the studied markets with large shares of fossil supply in the current consequential markets. In summation, it is recommended to continue using the forecasts from consistent data sources to improve the remaining consequential electricity markets in ecoinvent. Future work may include using several scenario and time-frame datasets for the ecoinvent user to choose between, as well as implementation of a dynamic optimization model to allow for large-scale decision modelling.

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A warm thank you goes out to Ms Beatrice Geschwend, and the rest of the PSI and ETH Zürich administrative personnel that has been involved in this master thesis process. Thank you Charlotte Malmgren at the Energy- and environmental engineering department at LTH in Lund for enabling me to perform this thesis abroad.

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A last thank you to my dear friends and family is Sweden and Switzerland. No one mentioned, no one forgotten.

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1 Introduction

1.1 Motivation and background

"Essentially, all models are wrong, but some are useful" - George Edward Pelham Box[1]

Consequential life cycle assessment: assessing the changes in environmental impact connected to a decision

Life cycle assessment (LCA) is a tool to describe the environmental impact associated with the life cycle of a product or service by quantifying the material and energy exchanges to and from the environment. A technical framework for an LCA is standardized in ISO 140 40 and ISO 140 44 (ISO 2006). Different LCA approaches have been developed for different applications and are commonly classified as change-oriented (consequential) or descriptive (attributional) LCA (Rebitzer et al. 2004; Guinée et al. 2011; Finnveden et al. 2009), the latter of which will be important for this thesis. An attributional life cycle assessment (aLCA) uses average data of all processes included in the product system to quantify the exchanges directly associated with the studied product system. Consequential life cycle assessment (cLCA) differs conceptually by including processes, inside and outside the studied product system, that are affected by a change the production output (known as marginal technologies). Only suppliers that are considered unconstrained, i.e. suppliers that will react upon a change in demand, should be included in a cLCA. These suppliers are identified using market relationships, as essentially all goods are assumed to react upon demand and supply signals. The resulting indirect effects can then be connected to the studied product system (Ekvall & Weidema 2004; Weidema et al. 2009). In general, the aim of a cLCA is to answer the question: *what is the total caused environmental impact associated with the decision to change the demand of a product?* A cLCA should be used for decision support and judging the effect of a decision, e.g. the environmental cost of increasing the output of a production line or choosing between different approaches for decreasing energy consumption (Vázquez-Rowe et al. 2014; Ekvall 2002).

In the seminal paper by (Weidema et al. 1999), Weidema asserted that marginal processes are most likely to be affected by a change in the system. A 5-step approach was proposed to identify marginal processes using the time frame and scale of the decision, the general market trend, constrained/unconstrained suppliers and the most preferred technology based on physical, political, economic and social constraints. Over the past years, more ideas and approaches how to practically perform a cLCA has been introduced: equilibrium modelling has become more and more integrated into cLCA to quantify the market effects, while still answering the same questions as in the 5-step approach. (Earles & Halog 2011) described cLCA as the convergence between LCA and economic modelling. (Ekvall & Andræ 2006) developed a model combining a partial equilibrium model and LCA to explore the impacts of a ban of lead solder in the electronic industry.

[1] Box, G. E. P., and Draper, N. R., (1987), Empirical Model Building and Response Surfaces, John Wiley & Sons, New York, NY

(Hedal Kløverpris 2009; Vázquez-Rowe et al. 2014; Dandres et al. 2011) studied the indirect environmental impacts of implementing policy decisions by linking LCA with a Computable General Equilibrium Model, connecting affected markets on a global scale. Other indirect effects, such as positive and negative feedback mechanisms were approached by (Sandén & Karlström 2007).

In summation, the aim of the cLCA methodology is clear (European Commission 2010; Weidema et al. 2009), but the choice of approach used to apply the methodology is unclear and the assumptions and estimations made differ among practitioners, making the results more difficult to compare (Earles & Halog 2011; Ekvall & Weidema 2004; Zamagni et al. 2012).

Modelling of electricity supply in cLCA

Electricity is used as input in most product systems (Treyer & Bauer 2013) and depending on what technologies are contributing to its generation, transmission, and distribution, the environmental performance varies substantially. As a result of increasing population and economic growth, official reports have forecasted a global increase in electricity demand over the foreseeable future: e.g. China projects a demand increase from 4 094 TWh per year (2011) to 8 855 TWh per year in 2035 according to the New Policy Scenario in the World Energy Outlook 2013 (International Energy Agency 2013b) Due to both regulatory measures and new technologies becoming competitive, a shift in technologies being installed to supply this demand is projected (International Energy Agency 2013b). The electricity supply will thus change with time, and its stakeholders must be aware of the associated long-term consequences of decisions involving energy policies to achieve environmental impact reductions (Curran et al. 2002; Hawkes 2014).

Throughout the literature, different approaches are used to define electricity supply in LCA and allocate environmental impacts of production to the consumption of electricity (Unger et al. 2006; Itten et al. 2014). Of these approaches, marginal electricity supply is considered to best reflect the technologies used to cover a change in demand and should thus be used for cLCA studies (Unger & Sköldberg 2008; Curran et al. 2002). How the system boundaries for marginal electricity supply are drawn determines which technologies will be considered affected. Considering time frame, marginal electricity supply can be divided into short- and long term components, where short-term utilizes the existing capacity to cover hourly, weekly and seasonal fluctuations and long-term takes changes in installed capacity (e.g. new power plants) into consideration (Weidema et al. 2009; Lund et al. 2010). Therefore, decisions that are considered long-term should be studied using long-term marginal electricity supply to best determine the related consequences.

Just as in general cLCA methodology, no consistent approach exists for evaluating changes in electricity supply. (Weidema et al. 1999) uses the 5-step approach to determine the relevantly affected long-term marginal technology according to the European energy scenario, but his method fails to consider the dynamics of the energy system and has no metric for the selected choice of technology. Ideally, the long-term marginal supply should instead most likely consist of a mix of technologies depending on technological, political, economic and social constraints (Mathiesen et al. 2009), a mix that is not correctly accounted for in Weidema's model.

Other studies have been performed to assess how demand changes determine the long-term environmental performance of the grid, e.g. investigation of the substitution effect caused by offshore wind electricity in Germany by linking a wind utilization model with Stochastic European electricity market model by (Pehnt et al. 2008). (Hawkes 2014) studied the 'long-run marginal CO2-factors' related to the British electricity grid by combing a dynamic optimization model (a so called Energy system analysis model (ESA)) for predicting possible supply compositions. ESA models have been used with life cycle impact assessment methods in other cLCA studies to investigate the effect of different demand scenarios (Lund et al. 2010; Mathiesen et al. 2009; Unger & Sköldberg 2008). Using long-term marginal electricity mixes modelled by using a ESA model is further recommended for cLCA concerning the energy sector by (Eriksson et al. 2007).

Modelling of electricity supply in ecoinvent v.3.01

In the ecoinvent database, country-specific inventories for electricity generation are used to create 'electricity market' datasets based on current annual production volumes. The linking algorithm, and the resulting composition of the electricity markets, depends on the system model chosen. In version 3.01 of ecoinvent, a whole new database structure was implemented, and two new system models are provided: the allocation, default system model, and the consequential system model. To assess the environmental impacts of a change on a long-term basis is in line with the aim of the consequential life cycle assessment methodology and the modelling approach is thus called 'substitution, consequential, long-term'(Weidema et al. 2013; European Commission 2010). The 'substitution, consequential, long-term' system model uses categorization of technology maturity based on perceived market competitiveness and by-product classification to determine which current technologies which can unconstrainedly supply the electricity. This modelling approach takes no consideration of other constraints or technology developments beyond this point in time. In many markets, the current LCI results thus diverge from expected capacity changes (Treyer & Bauer 2014). If the consequential version of ecoinvent is to be used for modelling electricity markets in the future, a more sophisticated modelling approach is needed to improve predictive quality and reduce the uncertainty in cLCA studies on a worldwide scale.

1.2 Goal and scope of work

Goal

The overall goal of this thesis is to suggest a new modelling approach for consequential electricity markets in ecoinvent. To reach the overall goal, three partial goals must be fulfilled: (1) to find out if one or several approach(es) that satisfy the necessary predictive criteria exists for modelling of electricity supply in cLCA; (2) If such an approach exists, to choose an appropriate one or if it does not, to develop an approach, and (3) to apply the approach to ecoinvent.

Scope of work

As mentioned in previous section, no standard approach exists for determining long-term marginal electricity supply. Therefore, no new modelling approach can be implemented immediately in ecoinvent to provide relevant results. Instead, the 'state-of-the-art" approach must first be identified by mapping out the currently used and most recommended approaches. With an in depth analysis of currently existing solutions, constraints and mechanisms can be identified that should be taken into account when modelling the long-term marginal electricity supply.

To fully understand the need for improvement in the ecoinvent consequential modelling of electricity markets, the current deficits need to be identified. The limitations already presented by (Treyer & Bauer 2014) and according to results found in the 'state-of-the-art' literature review can then be contrasted against the benefits and usefulness of these models. By considering the identified limitations, the structure of the ecoinvent database and the time frame and scope of the thesis, a new modelling approach is suggested and possible ways of implementing the approach is discussed.

To determine the reliability of the suggested approach, appropriate countries are then found for which the approach is then applied. Since ecoinvent v.3.01 consist of 71 different geographies, the time frame of the thesis and the lack of consistent data sets limits on which new datasets can be constructed. The new datasets are then used with the ecoinvent database to estimate their environmental impact and compared to the current consequential supply mixes.

Finally, the results are discussed and an outlook is provided with suggestions on further improvements for the ecoinvent database concerning consequential electricity supply.

2 Key concepts and background

This section describes the development and fundamentals of the concept of life cycle assessment (LCA) in chapter 2.1, the difference between the consequential and attributional LCA approaches in chapter 2.2, and finally how the two different approaches are currently being applied to the modelling of electricity supply in chapter 2.3. Attributional LCA is presented to clarify the differences in application of the two approaches, but the primary focus lies on consequential LCA, as it is the most relevant for the thesis.

2.1 Life cycle assessment

2.1.1 Purpose and development of the concept life cycle assessment

Describing the environmental impact of consumer goods, especially when comparing products against each other, emerged in the 1960s and 1970s. It was seen that for many products a large part of the environmental burden was connected to production, transport and disposal. The importance of studying the life cycle of a product was recognized, which led up to the development of the idea of life cycle assessment (LCA) in the 1980s and 1990s (Guinée et al. 2011). As a method to quantify and evaluate the potential environmental impact of products or services, LCA can be applied to any kind of good or service where the environmental impact is of interest and provide stakeholders involved in the life cycle with basic data and material for decision making. LCA is a tool of importance to help set goals, develop and sustain governmental strategies in order to reduce the environmental impacts related to supply and consumption of products and services (Rebitzer et al. 2004). In many parts of the world, governments now recommend the use of LCA and it has become a core concept for policy making concerning environmental issues, not only for governments, but also for companies and voluntary actions (Guinée et al. 2011).

According to a study on LCA development by Guinée et al. (2011), the field of usage has grown in a creative way to be used in contexts from waste incineration to tourism. With this development, the underlying models also has gotten more sophisticated from proportionally describing activity emissions to be more dynamic and include economic mechanisms and more. In the 1990s, the activities concerning coordination and harmonization of approaches, terminologies and results sprouted. Handbooks and guides were being produced, forums and workshops were being held and scientific papers started to appear. In the process of coordination, the International Organization for Standardization (ISO) developed formal standards for methods and procedures. There are currently two international standards: ISO 140 40 (2006E): 'Environmental management - Life cycle assessment - Principles and framework' and ISO 140 44 (2006E): 'Environmental management - Life cycle assessment -Requirements and guidelines' (ISO 2006). The definition of a standardized methodological framework for LCA was a key result from the process but as described in the standard 'There is no single method for conducting LCA'. The standardized framework for performing a LCA is shown in Figure 1.

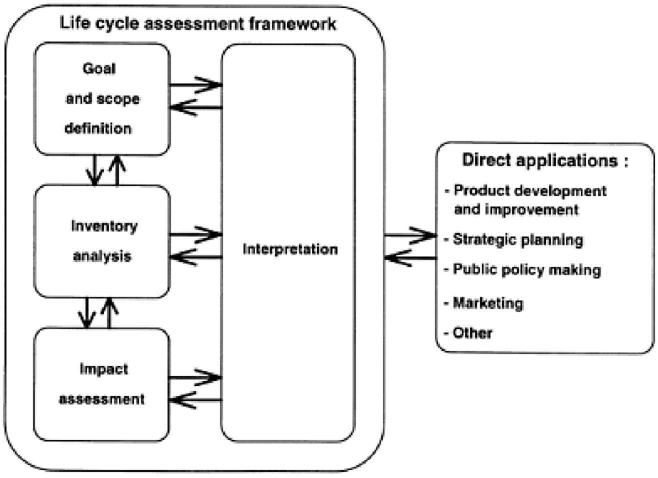


Figure 1 The standardized framework of life cycle assessment according to (ISO 2006).

2.1.2 The structure and components of LCA according to the ISO standard

The ISO 140 40 standard methodological components are Goal and scope definition and Life cycle inventory analysis (required), Life cycle impact assessment and Life cycle interpretation (optional) (ISO 2006).

A summary provided in (Rebitzer et al. 2004), describes each step of the methodology:

The *goal and scope* definition describes the system boundaries and functional unit, which is important to enable e.g. investigation of cradle-to-grave emissions of a product, comparison between other alternative products or services or identifying hot-spots in a product systems for improving environmental performance, and many other field of usage for LCA. The product system under investigation provides a service or fulfills a need, which performance is quantitatively described by the functional unit. The specific flows per produced functional unit are called the reference flow of the product system and can be used for product comparison.

The *life cycle inventory analysis* (LCI) is a step that seeks to quantify the consumption of resources and the waste flows and emissions attributable to the product system. These flows to and from the product system are likely to occur at different times, over different time periods and at different geographical sites which needs to be modelled in order to represent the product system. The model and the inventory will thus represent the exchanges related to the functional unit. A life cycle inventory analysis is basically a model of one or more product systems which are quantified in functional units. All the resources that are required and all the emissions, by-products waste which are associated with the production of one functional unit is calculated within the LCI. The model typically consists of unit processes that describe activities associated with the product system, such as production, transport, and disposal and so on. Every activity gives rise to environmental exchanges which is usually linearly related to the amount of produced function units within the system.

This means a static simulation model in which all the different activities are linked through intermediate flows which are linearly connected to each other and the production.

The *life cycle impact assessment* (LCIA) is the next methodological component and thought to provide indicators that are used to assign possible environmental impacts to the flows described in the life cycle inventory. The result of an LCIA is an evaluation of the product system and how large the environmental impact is based on different categories such as land use, climate change, and noise and so on. Sometimes the categories are aggregated, e.g. into cancerogenic effect.

An *interpretation* of the results is performed at every stage. When comparing a product with an alternative product, purely the result on the consumption of raw material can provide enough information to base a decision on. In other cases more information may be needed, e.g. when a trade-of is to be made between two products which are giving rise to different indicator values for the impact categories.

2.1.3 The role of LCI databases

The system that supplies the functional unit can be divided into a *foreground* and *background* system. The foreground processes can be defined as specifically related to the studied product or service, and actual economic relations about suppliers are usually known. Background processes are e.g. provided via a spot-market and the exact suppliers and purchaser are generally not known (European Commission 2010). LCI databases provide background inventory data, which is helpful since collecting data usually takes a lot of time and many product systems use processes that are common through almost all studies, such as energy supply, chemicals, waste treatment services and materials. Although there are many processes that are subject to global markets which make them very similar, such as steel production in China and oil extraction in the Middle East, there are others that are typically continental, national or regional such as electricity production within a country, agricultural production, and road transport and so on. Databases usually provide data in form of life cycle inventory results, such as aggregated resource consumption, wastes and emissions per kg of material produced. How the data is presented follows an attributional approach in most databases. Even though the data is available on a unit process level, adjustments can be done within the structure of the databases to present more change-oriented LCI data which can be used in a consequential LCI (Rebitzer et al. 2004).

2.2 Attributional versus consequential LCA

The goal of this subchapter is to map out the conceptual difference between consequential LCA and attributional LCA and to provide a deeper understanding for cLCA. Arguments for cLCA along with current limitations and uncertainties connected are presented.

2.2.1 The evolution of two different LCA approaches

Since ISO did not standardize LCA methods, uncertainties emerged how to interpret some of the requirements in the standards. Where to draw the system boundaries and what processes to include are subject to choices and assumptions, which greatly influences the result of an LCA study. Such assumptions and choices are affected by the goal and scope of the study, but it is still a bit unclear exactly *how* they should be made in order to answer which questions (Rebitzer et al. 2004). As a result, diverging approaches have been developed according to system boundaries and allocation methods and more (Guinée et al. 2011).

According to (Rebitzer et al. 2004), the emerged approaches all have a life-cycle basis but differ in the questions that they are trying to answer. There are commonly two distinct categories of goals for LCAs: the first describes the product system and its environmental exchanges and the other is intended to describe how the environmental exchanges change when the actions are taken within the production system, such as increasing or decreasing output. Although these goal distinctions have been made similarly by different authors over the recent years but with slight variations and description names, the first category is usually referred to as *attributional LCA* and the second one which describes expected changes is usually called *consequential LCA*. The distinction of the two LCA approaches has large consequences on how the product system is modelled, why it is important to pay attention to goal and scope of the study when selecting model. There is still further need to clarify how the different approaches differ and which questions they try to answer in order to know which method is appropriate for a certain aim of a LCA.

2.2.2 Differences in purpose and application of the two LCA approaches

2.2.2.1 The purpose of attributional LCA

Attributional life cycle assessments (aLCA) seeks to give an answer to what resource and emission flows that can attributed to a specific amount of the functional unit of a studied product system (Thomassen et al. 2008). The results of the approach can be used to compare the impacts of different products, be used for product labelling and declaration, and to locate hotspots with possibility of emission reduction and efficiency improvements and more (Brander et al. 2009). ALCA accounts for *immediate* physical flows (i.e. resources, material, energy and emissions) involved in the life cycle of a product (Earles & Halog 2011). The directly related emissions and exchanges in the foreground and background systems are allocated to the product. If all the results from all the processes and products in the world would be put together it would lead to the whole world's energy and material consumption (Brander et al. 2009).

ALCA is considered of limited use when it comes to decision support (Frischknecht et al. 2002). The approach is not suitable for studying the eventual consequences that would arise from altering the source or method of production of a product, or a change in the utilization of a service. For example if the load factor on trains increases, the emissions immediately associated with use of rail transport would decrease, but the effects of the modal change from e.g. air or road traffic or the possible impacts of new passengers would not be included in an aLCA. Also, sequential aLCAs does not capture the whole picture, but only provides a part of the impacts (Brander et al. 2009).

2.2.2.2 The purpose of consequential LCA

According to Schmidt et al. (2011), one way to describe the purpose of CLCA is that is strives to answer three questions: 1. What is the consequence of buying this product? 2. What is the consequence of choosing product A over product B? 3. What is the consequence of implementing this new technology? For a decision maker it is not relevant how products has been produced but how they will be produced if we change the demand. One of the strongest arguments for CLCA is that decision makers need to be informed about the consequences of decisions (Curran et al. 2002). The approach claims to describe how physical flows change as a consequence of a change of the demand of a product, includes processes outside the products immediate system boundaries and utilizes economic data to measure the physical flows of indirectly affected processes (Earles & Halog 2011). The results help inform on broader perspectives of decisions/policies which are intended to change the production As stated by (Ekvall & Weidema 2004), the consequences of a decision stretches beyond the studied production system and the can be seen as a stone hitting a water surface and creates a casual effect. The result of a cLCA will show the influence on the global environment as a consequence of the decision of (an individual) consumption or investment.

It can also provide information whether an environmentally friendly product actually lead to an emission reduction or not (Frischknecht et al. 2002). The approach is a poor option for consumption-based emission counting since cLCA estimates the change in emissions in comparison to the most likely scenario and does not seek to quantify the total absolute emissions (Brander et al. 2009).

Weidema (2003) argued that all LCAs in one way aim to provide result for supporting decisions of choosing between two different systems, or substituting one with the other. It can for example be in the form of comparing the environmental benefits from improving the performance of identified hot-spots with the current system. Another decision situation that involves comparison is when a consumer chooses between products with the help of product declarations since the chosen product will be produced at the expense of another. Thus, consequential assessment and consequential modelling is relevant to most all application areas of LCA. A few exceptions concerns studies on a societal level, such as environmental tax schemes, where an attributional approach is better suited to include activities proportionally to their contribution to the taxed activity.

A consequential LCA would be able to answer the question whether a change in demand for the product would change the activity, but it will not assess the current contribution of past events. Thus, studies of such past behavior would best be performed as attributional studies where the activities are included proportional to mass, energy or revenue etc. (Weidema et al. 2009).

2.2.3 The use of average versus marginal LCI data

For an attributional LCI, the environmental exchanges are linearly associated with the production of a specified amount of the functional unit and the processes that are held for contributing significantly to the studied product system are systematically included: Upstream from extraction of raw materials and downstream to disposal or recycling of waste. Full elasticity is assumed upstream of the product system, meaning that the reference flow of energy and materials will not change in if the output of the functional unit changes (Rebitzer et al. 2004). *Average data* is used as input to the life cycle inventory from each included process (Earles & Halog 2011).

Marginal data should be used to describe the exchanges to and from the environment as a consequence to the change. The marginal data represents the processes that are per se those that are actually affected by the decision that is being investigated, depending on the technology and quantity produced (Earles & Halog 2011). An investigated decision could concern for example a small or large output increase, stretching over a short or long time horizon, and the affected processes would change accordingly (Rebitzer et al. 2004). To identify which technologies (and with which quantity) that will react to a change in demand, i.e. the marginal technologies, market information is used (Weidema et al. 1999). The reason for using market mechanisms is that all products can be linked through a market, and though price mechanisms the supply is affected by demand changes (Zamagni et al. 2012).

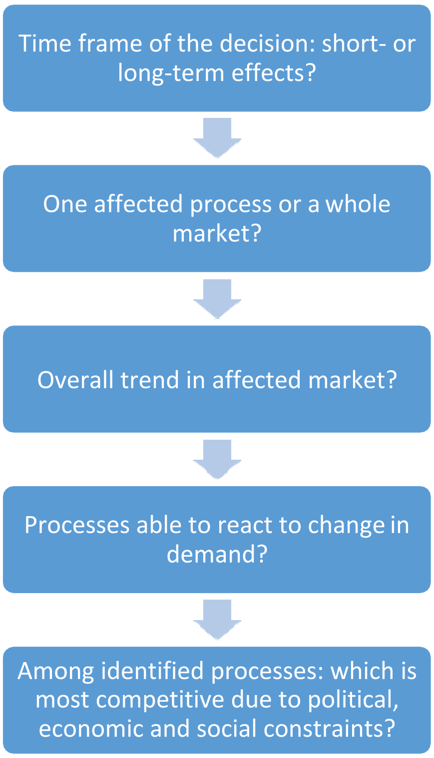
2.2.4 Consequential LCA methodologies

While the methodology for performing an aLCA is commonly accepted, the consequential approach is still clouded in uncertainties and where and how to apply cLCA in a practical way. The modelling principles of aLCA and cLCA are the same and must follow the ISO 140 40 and ISO 140 44 standardization, but the unit processes that are included in the system differ. There is currently no common, wide-spread approach for determining which processes that should be included in a cLCA. This leads to inconsistencies in the results (Zamagni et al. 2012). Up until today, many studies have applied a consequential approach to different allocation problems, e.g. (Eriksson et al. 2007; Ekvall 2000; Hedal Kløverpris 2009; Ekvall & Andræ 2006; Reinhard & Zah 2009; Schmidt 2008; Thomassen et al. 2008; and Zanten et al. 2013) and at this point, it is still hard to reach a consensus on detailed applications for specific situations.

When it comes to modelling of consequential LCI data, the definition of a cLCI model can be put as the linking of unit processes in a product system that are expected to change as a consequence of a change in demand for the product. According to (Weidema et al. 2009), a consequential LCI model is a homogenous, steady-state, linear model that is simply comparing a situation with or without a specific demand and not as a change modelled over time: the unit processes are fixed at a certain point in time. It is possible to apply external, dynamic models to contribute with input data. According to (Earles & Halog 2011) and Marvuglia et al. (2013), two distinct approaches exist to model consequential LCI: a simplified approach using market information, based on rules of thumb, and economic modelling approaches. One type of economic modelling approach is partial equilibrium (PE) models which are adapted to the field of study, and general equilibrium models, which can be precise but inaccurate. Depending on the size of the change studied, the LCI model may be constructed differently such as for a small, marginal change, which is not affecting the overall market situation, or for that of a large, incremental size, which is expected to change the market parameters (Weidema et al. 2009).

2.2.4.1 A 5-step approach

(Weidema et al. 1999) provided a methodology to identify the marginal technologies affected by a decision. The approach was refined in (Weidema et al. 2009), and essentially tries to identify the affected technology by answering the following 5 questions:



According to the first step definition, *short-term studies* may have a durance of up to 5 years while long-term changes stretches further on. When dealing with electricity for example, short-term changes affect e.g. hourly marginal supply while *long-term changes* will induce new capacity to be installed. For electricity markets, that would exclude taking the dynamics of the operation of the energy system into consideration and instead finding a long-term marginal technology by comparison of the investment costs of different electricity generating technologies (Mathiesen et al. 2009).

The second step is to compare the attributes of the products in question in order to identify which of them that are competing on the market. If the studied decision affects a process with a single supplier, that will be the affected technology and will supply the marginal data. But if a process is affected supplied via a market, e.g. electricity supply from the public grid, the marginal supply will have to be identified considering the market situation which is continued to be done in step three:

The third step is to conclude if the general market trend is decreasing or increasing. This is an important step where the technology with the highest marginal cost during a decreasing general market trend will be the affected technology of the change, since it is most likely to be phased out. Further on, the technology with the lowest marginal cost subject to growing market trend will be the most likely to be installed and then considered the affected marginal technology. If the item studied would change the market itself, it cannot be considered a marginal technology and this should be taken into consideration when performing the LCA study.

The forth step analyses which or the affected technologies that are capable of responding to the change at hand. Technical, environmental, market-related and political constraints inhibit some technology to adjust to the demand change and can thus not be considered either a short-term or long-term marginal technology. The constraints may include CO2-quotas, emission limits or the restriction of natural resources. An example of a constrained technology is wind power: not only is the electricity generation subject to wind conditions, but the land area where the wind power plants are to be built will be limited in potential.

Another example is a generic technology subject to CO2-quotas: if the market for the CO2-quotas changes, the market for the technology may change as well. These kinds of changes in constraints are hard to model and therefore the methodology recommends that constraints should be modelled as fixed entities, i.e. do not change over a long-term period. This enables the identification of the marginal long-term technology (Mathiesen et al. 2009).

2.2.4.2 Different ways to use economic tools for modelling cLCI data

CLCA connects economical phenomena with the life cycle environmental modelling of product and technological systems. More and more sophisticated economical models have been integrated compared to the basic models used before, such as partial equilibrium models and computable general equilibrium models, still answering the same questions as the 5-step approach (Earles & Halog 2011), described in the previous chapter.

Partial equilibrium models

Partial equilibrium modelling determines the equilibrium position among one or more markets by maximizing the net social payoff (intersection between the supply and demand curves). This type of modelling is mostly used to analyze the effect of a policy on a market or set of markets. The larger market models stretching across several market sectors are called Multi market PE models or Multi-region PE models (Earles & Halog 2011). By using a PE model, the amounts of decisions on system boundaries that rely on expert opinions (“rule of thumb” approach) are reduced and the uncertainties limited to those beyond the market delimitation (Vázquez-Rowe et al., 2014).

Ekvall (2000) used the concept of price elasticities combined with a two goods PE model in order to determine the indirect effects outside the direct supply chain which instead arises from market mechanisms. Price elasticity of demand quantifies the percentage change in demand for each percent change in price. The same concept is goes for supply elasticities. By examining demand changes and knowing the price elasticities, the supply of substituting products can be estimated and further the associated environmental impacts to these products. (Earles et al. 2013) developed an integrated partial market equilibrium and LCA model to help answer a specified policy question about how governmental incentives would support wood-based ethanol production. The integrated results from the PME and LCA from the study indicate the changes in environmental impacts of alternate policies. The framework integrated the existing PME model U.S. Forest Products Module (USFPM) and LCI data from Ecoinvent and U.S. LCI databases.

Large-scale equilibrium models

Larger multi-market, multi-regional models have been used to estimate the indirect life cycle effects of land use change as a result of change in demand of biofuels (Hedal Kløverpris 2009). MMMR-PE models provide a spatial resolution of production, which is important since the environmental impacts of the same product produced at different locations can have unique environmental impacts due to local environmental or political conditions. Another model class used to estimate indirect effect of a change is Computable General equilibrium models and includes all sectors within the economic system. It is more comprehensive that PE models but typically lack the same sectorial detail level. The output of such models can be soft-linked to LCA to determine the environmental effect a "chock" in policy, demand, supply etc. (Earles & Halog 2011). Considering that CGE models lack customized control for the user to a large extent and the general complexity, a customized soft-linked PE model is proposed to be sufficient for cLCA case-studies (Marvuglia et al. 2013).

The indirect environmental effects of a policy decision are limited to marginal changes and for small life-cycles. By using the economic general equilibrium model GTAP combined with LCA, the global economic perturbation of a policy can be predicted. This approach was used by Dandres et al. (2011) to investigate the impact of two European energy policies. The results showed that the combination of GTAP and LCA improves the environmental assessment through using global modelling of economy to study how decisions affect large systems in a time dependent environment. However, the approach also contains uncertainties related to the short time horizon and the geographical resolution of the data.

Other economic modelling tools

Learning effects and experience curves are also economic tools that can have been integrated into CLCA (Sandén & Karlström 2007). A power function is typically used to describe how much cheaper the unit cost gets as the cumulative production gets larger until the curve levels out at a certain cost (the technology is then called mature). CLCA can also give valuable information about rebound effects, which can be highly relevant when calculating environmental effects due to a change in production, so called environmental rebound effects. Rebound effects can be linked to CLCA as they can be seen as a consequence of a decision and are determined using market information (Earles & Halog 2011).

2.2.5 Uncertainties and limitations in consequential modelling

It is very hard to attain completeness in a CLCA, since the marginal effects may cascade down the interconnected product systems (see Figure 2). As the marginal production systems move away from the main product chain, it is fortunately presumable that the consequences on these marginal systems dissipates and becomes a minor source of uncertainty in the final calculations (Ekvall & Weidema 2004). Consequential LCA has also limitations concerning accuracy and relevance. Describing future consequences will always be uncertain since the future itself is inherently uncertain.

With accuracy also limited by various data gaps, CLCA will never be able to describe all the consequences of a change (Ekvall 2002). The uncertainties in CLCA are greater than in ALCA from all the assumptions that are made and from the elasticity of the system boundaries (Ekvall & Weidema, 2004; Vázquez-Rowe et al., 2014). As any study based on long-term predictions, consequential modelling is especially subject to large uncertainties when it comes to the influence of political constraints. It is very uncertain how the regulatory constraints will be designed and to what extent they will act upon the studied product chain (Weidema et al. 2009).

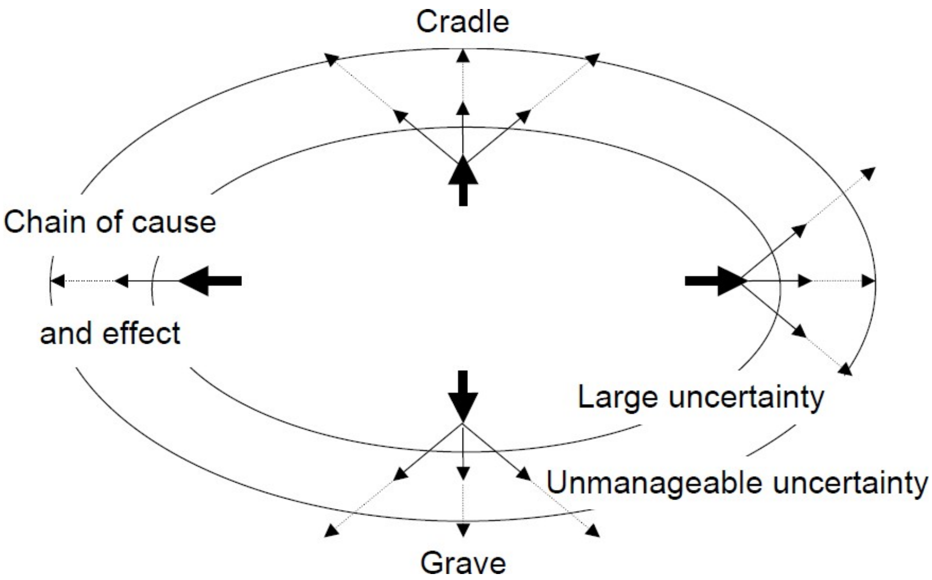


Figure 2 Consequences of action or foreground system spreading through interconnected systems, not only up-and downstream (Ekvall & Weidema 2004)According to textbooks on decision theory, the consequences of a decision need to be provided in order to make a rational decision. (Ekvall & Weidema 2004)

The market mechanisms that should be considered important and when they are important, still needs to be researched to improve the consequential modelling approach. Scenario modelling can help overcoming the uncertainties that arise due to the inconsistencies in assumptions and arguments when identifying affected technologies (Zamagni et al. 2012; Weidema et al. 2009).

2.3 ALCA versus CLCA in the power sector

2.3.1 Related characteristics of the power sector

The electricity sector consists of a complex structure, where thousands of power plants are dispatched using millions of km of transmission and distribution lines with system operators balancing the supply and demand in real time for billions of end-users. The increase in demand for electricity is based on a number of factors such as the growth of the gross domestic product (GDP), population increase, deployment of energy efficient equipment, electricity prices, amount of people with access to electricity supply and the living standard. To meet the demand the power generating plant mix evolves as a consequence of the relative economics of different electricity supplying technologies. The relative economics of the technologies are subject to fossil fuel prices, carbon dioxide pricing, capital costs of power plants, financing conditions, policies to promote or limit the deployment of specific technologies, availability of domestic fuel resources, the age of existing power plant fleet and the overall structure of the power market (International Energy Agency 2013b).

The merit order logic is the basis of how the electricity market faces a demand: the means of production are dispatched according to crescent marginal cost. The electricity mix varies over time, deepening on time of the day, day of the week and season. This creates an annual average composition. On a long term basis the mix also varies as a function of installed capacity, i.e. by which means that electricity can be produced (Gallice & Worbe 2013).

Over the foreseeable future, there is shift in technologies being installed as result of population growth, transportation modal shift, and increased use of air conditioning and so forth which will drive up the demand for electricity around the world. Responses from the energy sectors to supply this increase in demand, in form of political measures and technology development while managing resource availability and security of supply, affects which energy carriers that will be used in the future and subsequently, the associated environmental impact (International Energy Agency 2013b). In Figure 3, the projected electricity generation by source in the New Energy Policies scenario in the OECD and non-OECD countries, by the International Energy Agency (IEA), is shown.

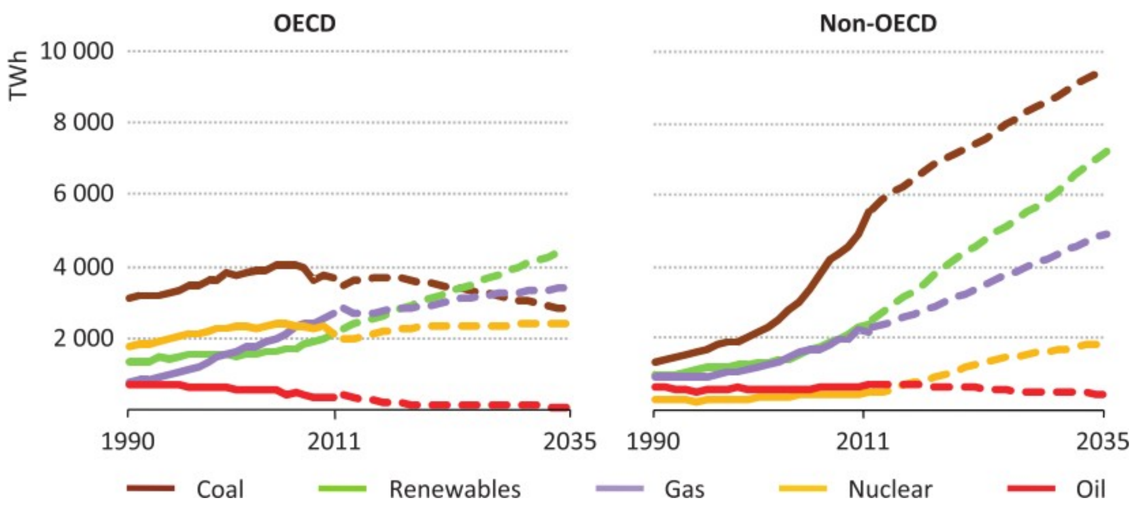


Figure 3 Electricity generation by source in the New Policy Scenario (International Energy Agency 2013b).

It can be seen that the future composition of the electricity supply in 2035 is projected to change compared to today for both OECD and non-OECD countries.

The future net capacity change also depends on the average age of the power plant fleet. This will result in a change in power plant fleet composition even though the demand change in some countries (e.g. in the European countries) is not as significant as e.g. China or India (International Energy Agency 2013b). An example of the projected retirement and addition of capacity in some regions and countries as modelled in the New Energy Policies scenario by IEA up to 2035 can be seen in Figure 4.

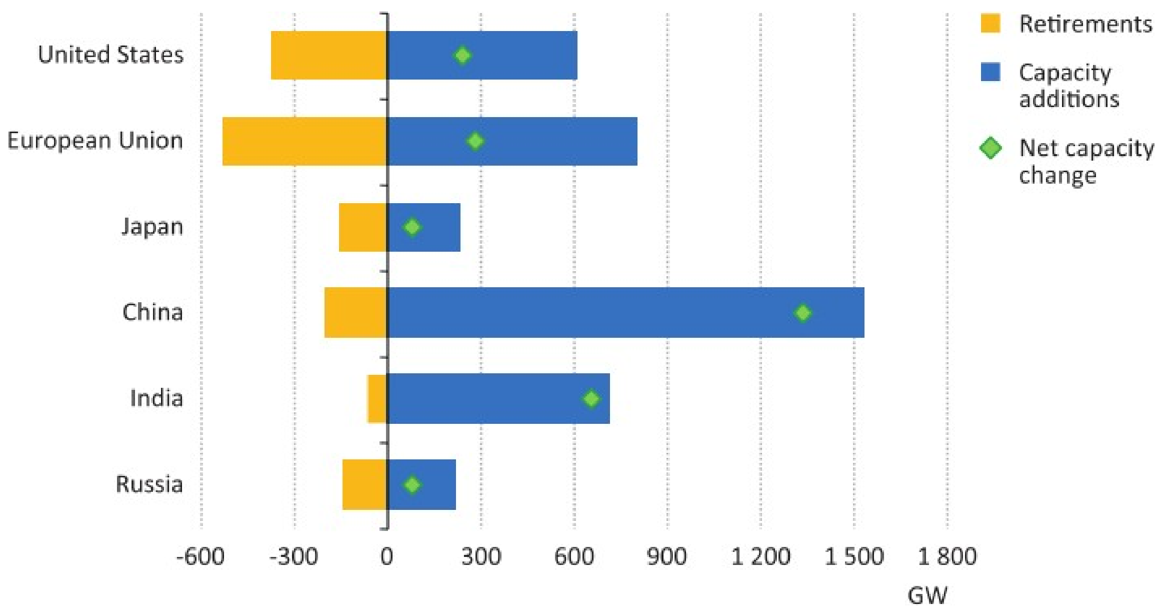


Figure 4 Capacity addition and retirement for some regions and countries in the New Energy Policies scenario up to 2035 (International Energy Agency 2013b).

2.3.2 Assessing the environmental impact of electricity supply

The purpose of cLCA is to ease the process of making informed decisions that directly or indirectly would affect electricity supply. Since electricity is a part of almost every product chain (Treyer & Bauer 2014), almost any decision to change the output of a product will in some way affect the electricity demand. In order to avoid technology and infrastructure lock-in effects that may prohibit realization of long-term decarbonization of the energy system and maximize the greenhouse gas emission reduction, stake holders need accurate and timely advice on how emission reductions can be achieved in the energy system. This can be done by using a life cycle assessment approach (Hawkes 2014).

2.3.2.1 Complexity in choosing the life cycle modelling approach

There are many approaches to determine how the electricity supply is affected by a decision and which approach that is chosen basically depends on the question that the LCA practitioner want to answer (Unger et al. 2006). Depending on how the affected electricity supply is defined, the associated environmental impact with the decision will change (Soimakallio et al. 2011). There are essentially two different time-frames to consider when investigating such a decision: short-term, affecting the already installed capacity, or long-term, affecting the power plant fleet (Weidema et al. 1999). Short-term decisions give rise to variations in the electricity supply on an hourly, weekly, and seasonal basis. Long-term decisions affect new capacity installations which give rise to a change in environmental impact of the grid electricity. Short-term variations in the grid electricity supply can be seen as mere background fluctuations that can be disregarded when comparing to the environmental impact caused by the change in power plant fleet (Mattsson et al. 2001).

The environmental impact of the change in grid electricity can be assigned to the decision that gave rise to it. The already installed capacity that is not affected within the time-frame of the decision can be seen as the effect of another decision prior the investigated decision. The remaining capacity is not part of the long-term marginal mix since it is not contributing to the electricity supply as a consequence of a decision to increase the supply. It is also possible to instead use the long-term average supply mix, but that would instead answer another question: 'What is the future average environmental performance at a given point in time?' The environmental impact associated with the long-term, average supply mix can be seen as the result of many different small-scale decisions giving rise change the electricity demand. An LCA practitioner studying the impact of a decision could argue that using an average, long-term mix is "unfair" since it associates environmental burden to the decision, which is not a created as a consequence of it (Unger et al. 2006).

No common opinion exists today on which approach for estimating the environmental impact of electricity supply that should be used for which situation. The choice of evaluation approach of the environmental impact of electricity consumption seems to be a result of the agenda of the practitioner. Those who speak for reduced electricity consumption tend to use marginal data, while those who propagate a larger use tend to use average data. The choice of data has a large impact on the result of the assessment, especially in the Nordic countries where there is a large difference between average and marginal data (Unger et al. 2006).

An example is the Norwegian electricity supply system, mostly consisting of hydro power plants. However, a small increase (marginal) in the demand of electricity will most probably be supplied by fossil-based electricity production, which is associated with much larger emissions. This is due to the capacity constraint of the hydro power production and the relatively unconstrained and low cost (per kWh) fossil based power production (Earles & Halog 2011).

Since most changes in the electricity supply are long-term and of a large scale, assessments based on the marginal data of the present power system might be insufficient. The perturbation might significantly influence the capacity installations of the power system, which should be taken into account in the assessment, along with the fact that the effect of the perturbation might change over time und thus consist of a mix of contributing technologies (Unger et al. 2006; Mathiesen et al. 2009). Since LCA studies supporting decision-making usually contributes to the accumulated trend of the market and long-term investment within that market, it can be simplified to that only the long-term marginal technology should be used (Mathiesen et al. 2009). The change in supply would more likely consist of a mix of affected production technologies. Fluctuating renewable energy sources and CHP plants installation planning makes the issue even more important (Lund et al. 2010).

The assumption that a perturbation in the electricity supply would affect future capacity installations of electricity is a reasonable approach to assess the environmental impacts of a perturbation. However, the impact results would then depend on computed data of the future energy system from e.g. computer models, and the outcome could be very sensitive to the input assumptions made. One way to handle the uncertainties associated with future scenario projections is to provide a series of computations of the energy system under different assumption, to show the effects a perturbation could have. The user could then choose which input assumptions seem more reasonable according to the goal of the study and for that scenario assess the environmental impact (Unger et al. 2006).

2.4 Existing modelling approaches for electricity supply in CLCA

In this part of the sections a review presents current approaches used to identify the electricity supplying technologies that are affected by a decision. The goal is to see if is exists a widely used, commonly accepted approach, or approaches, for modelling long-term marginal electricity supply that can be used in cLCA context. The review includes, but is not limited to, approaches used in consequential LCA case studies. Studies that are not explicitly a cLCA but model electricity LCI data as a consequence of a decision are also included. The review does not include all studies made, since, as mentioned in previous chapters, almost all change-related LCA studies include electricity as input in the investigated product system. The studies are instead chosen based on commonly cited and referred to studies in literature where the topic of modelling electricity supply in cLCA is discussed, such as in (Frischknecht & Stucki 2010) and (Soimakallio et al. 2011).

The presented studies are divided up according to two main approaches found by (Marvuglia et al. 2013): a simplified approach based on a rule of thumb (chapter 2.4.1) and using economic equilibrium modelling (chapter 2.4.2). Further, the approach of using already modelled data based on future scenarios is presented in chapter 2.4.3.

2.4.1 A simplified approach

Using the 5-step approach for the European energy scenario

Weidema et al. (1999) used the 5-step methodology on the specific context of the European electricity scenario, as described in chapter 2.2.4.1. Many production technologies was considered constrained due to natural capacity constraints, political constraints or lack of market for co-products and the authors mapped out the installation potential for the available technologies. For these potential sources, the production cost per MWh was used to determine natural gas as marginal technology for the Nordic countries and coal condensing power for the rest of Europe until wind power becomes more competitive. According to this methodology, only one technology is considered to be the marginal one and the practitioner will need to map out the constraints acting upon the available technologies.

Using expert judgement and cost of operation to identify marginal electricity supply

(Thomassen et al. 2008) performed a consequential LCA for milk production in the Netherlands. To determine the input of electricity supply, expert judgement along with production costs was used. The most probable technology to be installed to cover an increase in demand for electricity was considered to be natural gas.

The ability of the 5-step approach to identify marginal technologies

Mathiesen et al. (2009) performed a study to evaluate the ability of consequential life cycle assessment to identify marginal technologies by using the 5-step method described by (Ekvall & Weidema 2004; Weidema et al. 1999; Weidema et al. 2009). The expected long-term marginal technologies were identified using the approach from projections made of the Danish energy system and comparing the actual installed marginal technologies. The analysis made shows that the consequential approach for identifying the marginal technology may be too simplified and should instead identify several, fundamentally different technologies, preferably modeled using an energy system analysis model.

2.4.2 Integrating economic modelling tools for energy systems

Identifying long-term yearly average marginal technology for the Danish energy system

A detailed energy system analysis simulation with EnergyPLAN was conducted by Lund et al. (2010) to identify a long-term yearly average marginal (YAM) technology of the Danish energy system, which is based on inputs about the producing marginal technology which change on an hourly basis. The result shows that the environmental consequences of marginal changes in electricity supply cannot always be represented by a long-term change in production capacity which is assumed to be fully utilized to cover marginal changes. A combination of energy system analysis (ESA) and LCA methodology is recommended for identification of a complex set of marginal energy technologies.

Study of the affected CHP technologies with changes in waste incineration

As a part of the study by Mathiesen et al. (2009) evaluate current cLCA approaches concerning heat-and power supply, a case study was conducted, where a 10 % waste incineration increase in Denmark was studied. 10 different future scenarios were modelled in the energy system analysis model EnergyPLAN. The surrounding energy system was modelled by creating two different scenarios: one business-as-usual (BAU) scenario with higher energy consumption than today and one with a high share of renewable energy sources and with lower energy consumption. By changing the parameters in the model for the surrounding energy system, the geographical location or the waste incineration and the distribution in time, the complexity of the system was illustrated. The results were compared to the results from manually using the 5-step approach.

Modelling of perturbations in the Nordic energy system

(Mattsson et al. 2001) performed a study with the aim of identifying and understanding the most important mechanisms and effect behind small perturbations in an energy system. The dynamic modelling tool MARKAL was used to investigate the effects in the Nordic power-supply system. The analysis is based on a dynamic, optimizing model: NELSON which follows a bottom-up energy system modelling. It models the development of the whole energy system from fuel extraction and import to end-use. The most cost-efficient solution is produced to supply an external demand taking technical assumptions into account. By modelling changes from an already set reference case (e.g. an increase in long-term demand), deviations the effects of a small perturbation were evaluated, such as a demand increase, and the further installation or decommissioning of specific technologies.

Modelling of perturbations in the Japanese energy system

(Bhattacharya et al. 2012) investigated the future energy system of Japan by analyzing a nuclear phase-out scenario and a replacement with renewable energy sources. To investigate the fossil fuel import volumes, cost of the energy system and associated CO2 emissions, the TIMES Integrated Assessment Model (TIAM-WORLD) was used for a time-frame 2005-2050. TIMES models uses partial equilibrium modelling of the energy and emission markets around the world based on maximization of consumer and supplier surpluses, arrive at a minimum discounted cost for the energy system (Loulou & Labriet 2007).

Using the model results from different scenarios analyzed, insights and policy implications concerning renewable energy supply under a nuclear-phase out scenario and the different pathways to achieve long-term GHG emission reductions in Japan was provided. A number of limitations in the modelling tool were found, including an inability to model regional differences in energy supply, which especially concerns regional renewable energy source installation. Also change in economic growth rates and change in energy prices from regulatory measures or large-scale technology shifts.

Modelling of long-run marginal CO2 emission factors for the British electricity system

(Hawkes 2014) presented the concept of long-run marginal CO2 emission factors. He then determined the long-run marginal CO2 emission factors of the British electricity system by modelling the long-term marginal electricity supply. This was done by building and applying a new energy system model using a TIMES modelling environment. Possible supply scenarios were investigated by modelling different regulatory measures for CO2 emissions. This was done to reduce the uncertainties connected to future developments in the power sector.

2.4.3 Using already modelled scenario data as input

Investigating district heating scenarios with modelled electricity scenarios

(Eriksson et al. 2007) conducted a consequential LCA study by comparing "the environmental consequences of district-heat production from waste and competing fuels in Sweden". The aim was to provide support for policy making in the Swedish energy sector. The subsequent aim of the study was to evaluate the methodological approach of using an energy system analysis model for providing a complex electricity mix and combining it with LCA. Electricity mixes based two fundamentally different scenarios of the Nordic energy system were used, modelled by (Mattsson et al. 2001). It was concluded that building up an energy system model tailored to the study would have provided electricity supply data more relevant to the goal and scope of the study, but would add significantly to the cost of the study.

Using data from the International Energy Agency based on scenarios

(Ekvall & Andræ 2006) performed a study to investigate the consequences of removing the use of lead for solders in the electronics industry. For marginal electricity supply, they used already modelled scenario data from the International Energy Agency from 2001 as input. The average production of electricity on a global level was used for the whole electronics industry.

(Schmidt and Thrane, 2009) used the IEA outlook for the energy sector for 2008 to calculate the expected growth rate of technologies expected to supply the long-term marginal electricity mix. The approach was applied to investigate aluminum smelters in Greenland. This study uses the methodology that is further used in the Energy club, a commercial service provided by 2.-0 LCA Consultants and DuPont to supply consistent consequential LCI data for electricity (Schmidt et al. 2011).

2.5 Conclusion on currently used approaches for electricity supply in cLCA

An overview of the studies used in the literature study is found in Table 1. The identified approaches found in literature range from simplified approaches, customised for the study at hand to approaches using sophisticated economic modelling tools. This is in line with finding made by other authors, e.g. by (Earles & Halog 2011). There seems to exist no commonly accepted, wide-spread approach for modelling long-term marginal electricity supply, but the choice of approach seems to depend on the scope and if the LCA step is prioritized in the study at hand. This is also confirmed by (Mathiesen et al. 2009) when examining the state-of-the-art approaches.

To manually use the 5-step methodology proposed by (Weidema et al. 1999) to determine long-term, marginal electricity supply is considered insufficient by (Mathiesen et al. 2009), who instead recommends to use a mix of different technologies to better simulate the real-life behavior of the power sector. To use a mix of technologies is also recommended by (Lund et al. 2010; Mathiesen et al. 2009; Eriksson et al. 2007; Mattsson et al. 2001) who propose the use of an energy system analysis modelling tool to simulate the power sector behavior under certain scenarios. The same questions are still answered as in the 5-step approach, but with a more sophisticated approach. The resulting installed capacity of different technologies then represent the long-term marginal electricity supply and can be used together with an environmental impact assessment method to determine the impact of the studied decision. This approach is preferable for long-term, large-scale decisions (such as phase-out of nuclear power, large-scale demand increases due to population increase or deployment of electric car fleet, support measures for renewable energy sources etc.) where perturbations are large enough to change the whole energy system. The uncertainties in results connected to modelling future policies and events can be limited by modelling several scenarios.

Constructing an energy system model is not appropriate to model the electricity supply for long-term, small-scale decisions, since such a decision is per definitions not assumed to affect the overall market situation. In such a case, already modelled data, as done by (Eriksson et al. 2007), for the energy system in the study is preferable, since this marginal mix is what would be provided as background LCI data for a long-term, small-scale decision. A small-scale perturbation can be up to 1 TWh in size (Mattsson et al. 2001). When using already modelled data, the background assumptions should be in line with the goal and scope of the study.

The conclusions from the literature review are further used in the discussion in chapter 4.1 to find a suitable approach to be applied in ecoinvent.

Table 1 Overview of literature modelling long-term marginal electricity supply using different approaches.

Study modelling consequential el. supply	Static approach	Integrated dynamic optimization model	Using already modelled data based on scenarios	Methodology for modelling electricity supply
(Weidema et al. 1999)	*X*			Using the 5-step method to find the most likely to be installed technology for the European market.
(Thomassen et al. 2008)	*X*			Investigated marginal milk production in the Netherlands and used natural gas as long-term marginal electricity supply input, after considering production cost and expert judgment.
(Mathiesen et al. 2009)		*X*		Investigated the effects on CHP plant operation as an effect of change in waste incineration in the Danish energy system using EnergyPLAN.
(Pehnt et al. 2008)		*X*		A stochastic energy system model E2M2 was used to simulate the long-term effect of off-shore wind power feed-in in the German electricity market.
(Mattsson et al. 2001)		*X*		Modelled the effects of perturbations in the Nordic energy system using the MARKAL model.
(Eriksson et al. 2007)			*X*	Investigated different district heating scenarios in Sweden, using electricity data of the Nordic energy system, modelled by (Mattsson et al., 2006), to investigate substitution effects from electricity sources.
(Lund et al. 2010)		*X*		Identified long-term yearly average marginal technologies using EnergyPLAN to investigate the effects of perturbations in the Danish energy system.
(Bhattacharya et al. 2012)		*X*		Examined the phase-out of nuclear and its replacement using RES technologies in the Japanese electricity system using the TIMES-WORLD model.
(Ekvall & Andræ 2006)			*X*	Used the global average marginal electricity supply from IEA as input to model consequences of a change to lead-free solders in the electronics industry.
(Hawkes 2014)		*X*		Developed a model based on TIMES modelling environment to model long-run marginal CO2 emission factors of the British electricity system under the influence of different emission regulating policies.
*(*Schmidt and Thrane 2009*)*			*X*	Used IES 2008 data from the World Energy Outlook to estimate the growth rate of supplying electricity technologies for aluminum smelter on Greenland.

3 Current modelling approaches in ecoinvent v. 3.01

This section presents the relevant modelling features of the ecoinvent v.3.01 database for this study, concerning the attributional and consequential version of the database, electricity markets in the consequential version and ultimately the current limitations of the modelling approach of consequential electricity markets with respect to already identified shortcomings in literature and compared to state-of-the-art modelling found in previous section. The features of the ecoinvent v.3.01 database is documented in the ecoinvent data quality guidelines (Weidema et al. 2013). The content of the following chapters concerning main ecoinvent features is based on this documentation and 'the ecoinvent database' refers to version 3.01 unless otherwise stated.

3.1 The ecoinvent v. 3.01 database

The ecoinvent database is built on the methodology for life cycle assessment as standardized by the International Standardization Organization (ISO). The database contains life cycle inventory datasets of human activities and their exchanges to and from the environment. These LCI datasets can also be linked through system modelling to create aggregated LCI datasets. In accordance with the ISO methodology, the database also provides impact assessment methods (LCIA) to allow for guidance on the impact of studied product systems (Weidema et al. 2013).

3.1.1 Datasets

Ecoinvent consists of two types of datasets: activity and impact assessment datasets. Impact assessment datasets consist of impact categories for different impact assessment methods, to which exchanges can be linked to create a list of impacts connected to an activity or product system. The activity datasets represent a unit process and contain data on the associated exchanges to and from the environment, such as emissions and raw materials, and connects exchanges to and from intermediate processes, e.g. other processes supplying the activity and waste, along the product chain. The activity datasets also contain data on which geography they are valid for, along with valid time frame, if it is produced as a reference- or by product, the overall market trend of the product, and technology level (outdated, old, current, modern or new). If a change in demand for a product is expected to affect the production output, then that product is classified as a reference product. These specifications allow the correct activities to be identified and LCI data provided, according to the goal and scope of the study at hand (Weidema et al. 2013).

3.1.2 Market activity and transforming activity datasets

Transforming activities in the ecoinvent database are “activities that transform inputs so that the outputs are different from the input”, such as an oil refinery which transforms crude oil to refined oil products.

Market activities are simply activities that transfer the intermediate product from one transforming activity to another transforming activity which uses this product as input, e.g. the high voltage electricity produced in China from hard coal, wind power, natural gas activities etc.

3.2 Linking of datasets in system models

Market datasets are created by identifying relevant transforming activities by product name and geographical segment and linking the corresponding products as input to the market. This means that when the output of a unit process changes, almost all other unit processes will be influenced and their corresponding LCI results. The influence may yet be negligible, or substantial, depending on the magnitude of the change. These linking rules make the database fully linked upstream: all datasets are linked to their specific supplying activities. The matching of geographical location of the transforming activities and the market activity generally creates one market per geography for each product, e.g. one market for electricity and one for steel etc. The geographical segmentation of the markets are based on the lack of (or constrained) import over a geographical border (Weidema et al. 2013).

The life cycle inventory analysis can be done by two different ways of system modelling: attributional and consequential. The rules deciding how the supplying and consuming activities are interlinked are decided by the system model chosen by the practitioner, according the goal and scope of the study at hand (Weidema et al. 2013). The ecoinvent v. 3.01 is the first background LCI database that models and supplies LCI data for consequential LCA studies (Treyer & Bauer 2014).

In the attributional system models, all the transforming activities that produce the same product within one geography supplies are linked to a market activity. The production volume of a market activity is calculated by summing up the annual production volume of the geographically matching transforming activities. The market output is thus a supply mix of a certain product or service, present with a certain supply volume. For example the production volumes from all the electricity supplying activities for a geography are summed up and used as output from that market. A schematic description of the linking process can be seen in Figure 5.

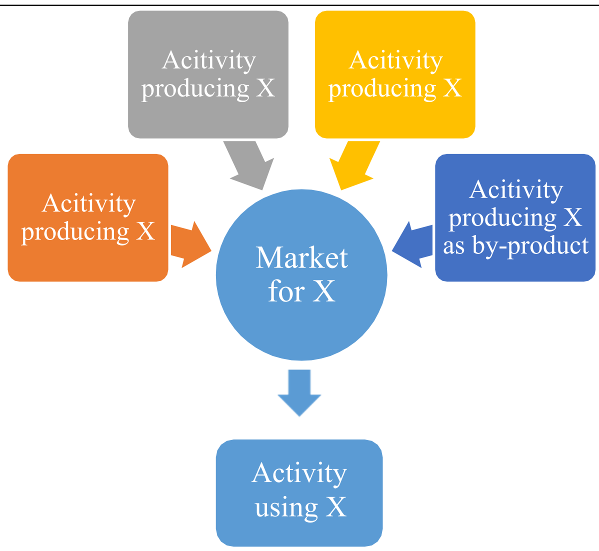


Figure 5 Linking of activities according to Allocation, default system model.

The consequential system model uses production constraints, resulting in an inclusion of unconstrained suppliers only to the market dataset. By-products are per default constrained and their output will only change if the reference product output change. In other words, the production will not react as a consequence of change in demand for the by-product (Weidema et al. 2013). A schematic figure of the linking process, where constrained suppliers are not included, can be seen in Figure 6.

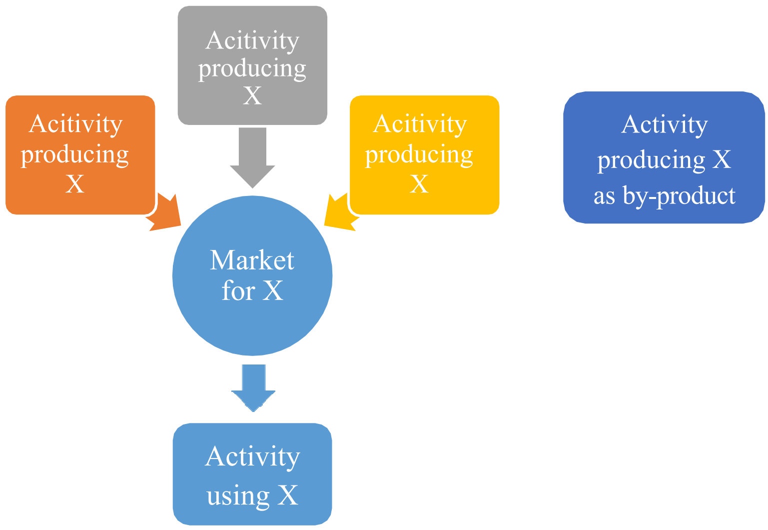


Figure 6 Linking of activities according to consequential system model: only unconstrained suppliers.

3.2.1 The "Substitution, consequential, long-term" system model

This system model intends to reflect the consequences of small-scale, long-term decisions, e.g. changing the output of a process over a longer period of time. This is done by letting constraints act upon the unlinked transforming activities in a way that is intended to reflect the corresponding effects of such decisions on technologies, markets, suppliers and consumers (Weidema et al. 2013). This model is appropriate for “goal situation B for meso/macro-level decision support” in the ILCD handbook (European Commission 2010) and according to the consequential LCA operation in (Weidema et al. 2009). Since the mentioned cLCA operation that lie as methodological basis for the system modelling approach is elaborated in the cLCA methodology chapter (see chapter 2.2.4), it is only briefly recapitulated in this chapter:

The system model is intended to model small-scale decisions, i.e. decisions that are small enough not affect the overall market situation, and only reflects long-term effects, involving new capital investments. Since the overall market parameters are the same, the consequences are assumed to scale linearly to the size of the change. A large-scale decision would in fact change the overall market situation and the consequences would not scale linearly to the change in demand. Ecoinvent does not provide background data for such decisions. The general market trend of the technologies lay as basis for determining the technology level: increasing market trend means modern, competitive technologies are assumed to be preferably installed, and vice versa for a decreasing market trend. Full elasticity of upstream suppliers is assumed (Weidema et al. 2013).

The two modelled market constraints are thus: technology level classification and by-product exclusion. The market shares of activities supplying the consequential markets are calculated based on the annual average production volumes, as in the attributional markets. The constraints are activated via conditional exchanges when the system model is chosen. There is no dynamic equilibrium modelling using elasticity but only absolute exchanges already put into the database. However, there are future possibilities to include market elasticities and more elements of equilibrium modelling into the database via conditional exchanges (Weidema et al. 2013).

3.3 Modelling of electricity markets in ecoinvent v. 3.01

As mentioned, electricity is practically used in every LCA performed and the associated environmental impacts run from high to low depending on where it is produced and how much is being used in the model. It is thus especially important for a LCI database to be able to supply relevant and up-to-date inventories concerning electricity. In ecoinvent, the inventories are linked into electricity markets, depending on the system model chosen, as mentioned above in ’Linking of datasets in system models’. There currently exist 71 electricity markets covering 83 % of the total electricity supply in 2008 (Treyer & Bauer 2014).

3.3.1 Data used for the electricity life cycle inventories

The data used for electricity life cycle inventories in ecoinvent v. 3.01 is based on the report “Life cycle Inventories of Electricity Mixes and Grid” (Itten et al. 2014) and is valid for 2008 (2009 for Switzerland and USA). The annual production volumes for electricity in the report are mainly based on IEA statistics, which is usually the case for LCI data in ecoinvent.

It is provided on a yearly average basis on a high, medium and low voltage level, without taking hourly, weekly and seasonal variations into account. Data on imports and transformation & transmission losses are also provided by the report. Whenever possible, the gross production values were used in the datasets instead of net production values (integral station losses and own use taken into account).

3.3.2 Electricity markets in ecoinvent in general

Market meta-data: geographical delimitation, functional unit and losses

The geographical boundary of the electricity markets in ecoinvent is usually consistent with national borders, since electricity markets are usually subject to regulations concerning production and trade usually within these boundaries. The US and Canada are the only exceptions with markets divided according to NERC regions. The electricity market datasets consist of electricity inputs from domestic production, imports, transmission and transformation infrastructure along with its associated emissions and a functional unit of 1 kWh. Exports are not explicitly taken into consideration since imports into one country is assumed to correspond to the supply mix of the exporting country. The electricity is considered to be exported when it crosses the geographical boundaries of the market and thus is no longer available on the delivering market. Transmission losses on each voltage level are taken into account. The electricity needed to run the pumps in pumped storage hydro plants are accounted for in the producing datasets and is therefore not a part of the general losses in the grid (Treyer & Bauer 2014).

Special electricity suppliers

Electricity processes that produces for internal use (so called auto-producers), which can be the case in large industries for example, should not be a part of the electricity market datasets since are not supplying the public grid. Where their supply has been identified from the overall country supply, they are modelled separately with their own electricity generation and market activities such as for auto-producers in the aluminium industry, coal mining in China and the Swiss Federal Railway in Switzerland (Treyer & Bauer 2014) Label-certified electricity for Switzerland represents green electricity from renewables that the consumer can purchase in order to finance the explicit production of electricity from these renewables. This can be used as input in activities of consumers who purchase this electricity and should not supply the general markets (Treyer & Bauer 2013).

3.3.3 Attributional and consequential electricity markets

As mentioned in the chapter ‘Linking of datasets in system models’, electricity market composition can be adjusted by choosing an attributional or consequential system model, making it possible for the user to adapt the electricity supply mixes suit the goal of the LCA at hand. (Treyer & Bauer 2014)

The attributional electricity markets are supplied by all the transforming activities within its geographical area that has electricity as a reference or by-product, along with imports from neighbouring areas and specific generation technologies. The available annual production volume of each supplying activity determines the market shares. (Treyer & Bauer 2014)

3.3.4 Modelling of consequential electricity markets

Consequential electricity markets are currently modelled using the "substitution, consequential, long-term" system model. Only suppliers who will respond to a change in demand on a long-term basis, so-called unconstrained suppliers, will contribute to the markets (described in the chapter 'The "Substitution, consequential, long-term" system model'). This long-term change in demand does not imply the changes made on an hourly, daily or monthly basis and supplied by already existing capacity, but the change in demand that needs to be covered by further installed capacity in the future. (Treyer & Bauer 2014) How these constraints act upon consequential electricity markets compared to attributional market modelling can be seen in Figure 7.

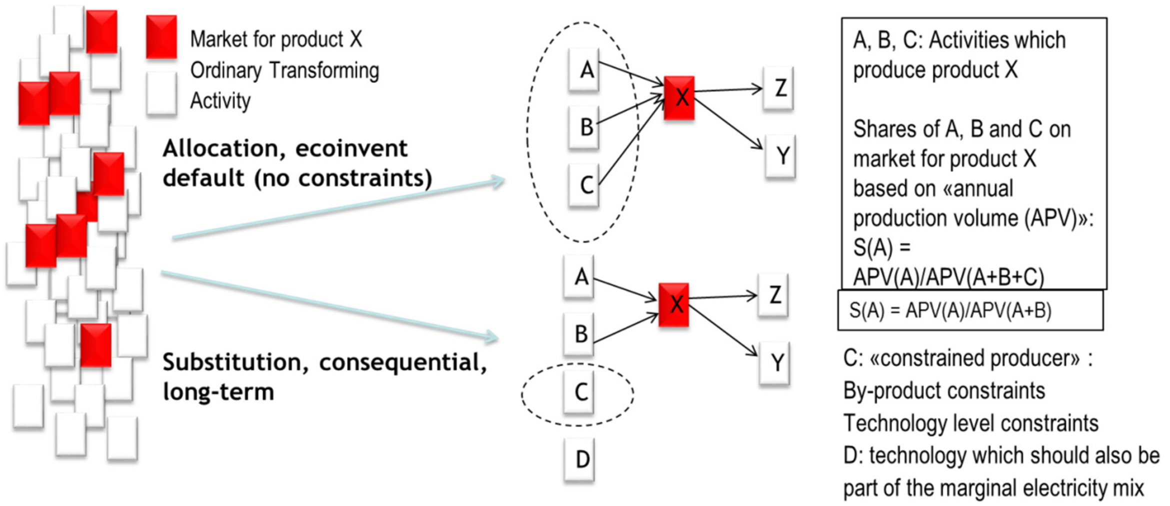


Figure 7 Linking of transforming activities and calculation of market shares in the 'Allocation, default' and 'Substitution, consequential, long-term' system model, respectively. The unconstrained technologies supply the consequential market datasets proportionally to their current annual production volume. (Treyer et al. 2014)

Since by-products are considered constrained, electricity produced in CHP plants (such as natural gas CHP plants) is not assumed to be installed to cover an increasing electricity demand. The co-production will only react to a change in demand for heat and not for electricity.

The other capacity constraint, the technology level, is connected to the long-term economic competitiveness of the technology on the markets and essentially determined by looking at the global overall market trend (with a few market-specific trend exceptions). It can also further be used for other types of constraints, such as environmental or political.

As all electricity markets in ecoinvent v. 3.01 are assumed be increasing or stable, which means that the capacity that will be installed in a long-term perspective will be the most competitive technologies. These technologies are classified as ‘modern’ in the ecoinvent database and are the technologies that in first-hand supply the consequential markets. The other technologies that supply electricity are also classified according to their expected future competitiveness (outdated, old, current and new technologies). The ‘current’ technologies will supply the consequential electricity markets is no ‘modern’ technologies exist. If neither “Modern” nor “Current” technologies would exist then “New” technologies (not yet on the market, but expected to be installed in the future) would be used in their place. However, no such activities exist yet in ecoinvent. All markets are in reality subject to specific conditions which further makes the technology level categorization insufficient since the level is generalised over most markets. (Treyer & Bauer 2014) recommends that in order to overcome the current limitations in the consequential modelling of electricity markets, country-specific conditions need to be taken explicitly into concern in the inventory modelling.

3.4 Identified shortcomings in modelling consequential electricity markets in ecoinvent

The current consequential modelling gives somewhat unrealistic electricity markets in some regions, and for different reasons (Treyer & Bauer 2014). Users are currently recommended to use the results carefully and to further adapt the inventories to more specific information concerning the level of constraints acting upon the technologies. More specifically, the modelled constraints concerning technology level, market shares based on current production volumes and exclusion of electricity produced as by-product act as limiting for the long-term consequential supply mixes. Below, the already identified shortcomings along with further shortcomings found in this thesis are presented:

Known shortcomings identified by (Treyer & Bauer 2014):

- Since only technologies which currently have a production volume in ecoinvent can be used in the consequential linking, technologies for which inventory data does not exist or is not yet available in a certain region will be excluded from the supply mixes, even though some technologies are expected to supply a market in a foreseeable near future.
- The consequential market shares for each technology are calculated using the current annual average supply volumes. This approach excludes any new political, economic or social limitation or incentives that might influence the capacity installation in the future.
- Today, only a rough approach has been applied for technology level classification (not modern=not installed in the future, natural gas conventional power plant=current etc.), based on a decision for all countries instead of geography-specific classification.
- Todays’ state-of-the-art technologies are used for modelling future capacity installations, which means that developments in e.g. energy or flue gas efficiency improvements is also not taken into account.

Further identified shortcomings:

- Electricity produced as by-product, e.g. in natural gas CHP plants, is considered fully constrained. However, this might not hold true for all future situations: the heat demand in colder countries like Russia can be expected to be large enough for the production of electricity to be abundant enough for it to not be constrained as by-product; the demand for electricity is could also be high enough for CHP plants to react to price signals for electricity, which also could be achieved by development in heat storage. Even though electricity produced in CHP plants still cannot be considered fully unconstrained, it can still supply the long-term margin as partially constrained.

- The current consequential version does not allow for modelling different demand scenarios to limit the uncertainties connected to modelling events that has not yet come to pass, which is recommended by (Mathiesen et al. 2009; Mattsson et al. 2001; Lund et al. 2010), among others. Such a feature would enable the ecoinvent user to choose the most feasible future scenario according to user. A dynamic modelling environment would need to be integrated or linked from external databases, as opposed to the current static environment, to provide such data.

A general identified shortcoming *for both consequential and attributional* modelling of electricity, is the definition of electricity supply, i.e. what 1 consumed kWh is assumed to consist of: The geographical delimitation of the supply mixes to include the domestic production and the imports from neighbouring countries could be questioned since there still today exist a discussion on what market limitation that should be used for the consumption of grid electricity, as mentioned by (Weber et al. 2010; Unger et al. 2006). For interconnected transmission grids, as in Europe, determining what electricity production that should be accredited what consumption is not easily done unambiguously. The argument that LCI data should be used for production close to the point of consumption could be questioned when trying to assess the environmental performance of the grid since it is impossible to know what 1 kWh consists of. The origin and volumes of imports in the v. 3 of ecoinvent is assumed to corresponds to the current cross-border trade agreements. This definition indeed covers all electricity production, but for modelling of future supply, the new trade agreements need to be known, which might not be easily done.

Switzerland has been identified by (Treyer & Bauer 2014) as an example on how the shortcomings affect the consequential markets: The governmental Energy Strategy 2050 for Switzerland projects diverse technologies to be installed to cover future demand scenarios. Geothermal and natural gas are expected to be installed in a nearby future, but since these technologies does not yet exist for Switzerland in ecoinvent, only hydro, wind and solar contribute to the consequential dataset. The resulting shares show a future capacity installation of 99 % hydro power, which is not likely (see Figure 8). There are some consequential markets where the market shares are more consistent compared to projections and in line with competitive and promoted technologies, such as for Germany (Treyer & Bauer 2014).

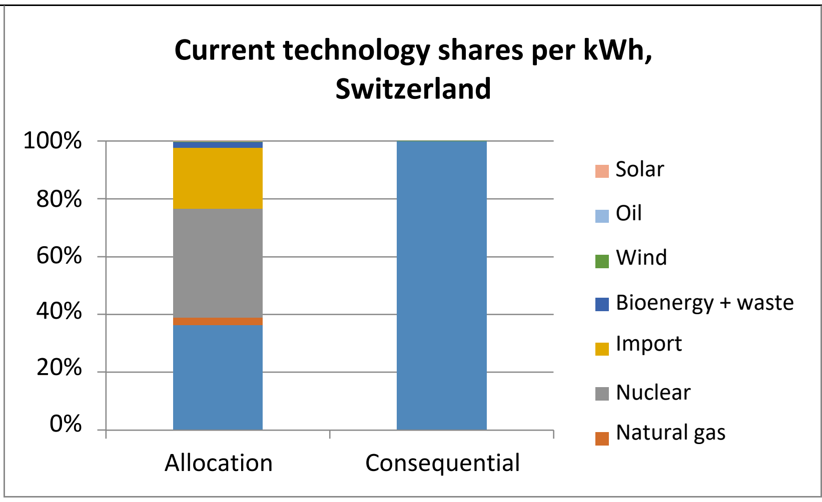


Figure 8 Current composition using attributional and consequential modelling approach for Switzerland.

3.4.1 Conclusions current shortcomings

The current consequential electricity markets do not supply mixes that are consistent with recommendations and currently used modelling approaches and display possibilities for improvements and strengthens the argument for a more sophisticated modelling approach. As stated by (Treyer & Bauer 2014), a more sophisticated modelling approach for the consequential electricity markets should be considered due to the current limitations, if the consequential system models are to play an important role in the ecoinvent database. Such an approach would mainly need to: overcome the shortcomings of classification of electricity as by-products in CHP plants; include future technologies for which inventory data do not exist; reshape the market shares according to political, economic and social constraints, and by including the dynamic behaviour of the energy system where direct and indirect market effects are taken into account. Such an approach could further improve the quality and decreasing the uncertainties of worldwide consequential LCA results.

4 Modelling approach to overcome current limitations in ecoinvent v. 3.01

This section presents a suggestion for a new modelling approach for the consequential electricity markets in ecoinvent.

To reach a choice of a suitable approach, the currently used and recommended modelling approaches for consequential electricity markets (see chapter 2.4) are discussed in chapter 4.1, taking the ability to overcome the current shortcomings in ecoinvent (see chapter 3.4) and the compatibility with the ecoinvent database structure into consideration. A modelling approach then is proposed for this thesis in chapter 4.2, with respect to practical constraints, to supply relevant LCI data for consequential electricity markets.

4.1 Finding a suitable new modelling approach

In an ideal case, the modelling environment in the consequential version of ecoinvent should be such, that all the direct and indirect effects of a decision are identified and quantified in terms of LCI data. For the case of electricity markets, this would mean simulating how the energy sector and other connected sectors would react to a change in electricity demand and quantifying the resulting change in electricity supply. In such a case, the output of the consequential system model in ecoinvent could help making efficient and informed decisions concerning electricity consumption.

Due to time and resource limitations, no altering of the ecoinvent software will be done in this study. At the moment, the database has a homogenous, static modelling environment that scales the consequences linearly to size of the decision. Algorithms for linking external databases containing price elasticities and fuel prices etc. is currently not supported without changing the database features. This also has the result that only one dataset can accessed per geography and system model, i.e. datasets based on different demand and supply scenarios will not be available.

4.1.1 The option of integrating a dynamic optimization model for energy systems

The result from the literature review suggests that there exist no common approach for modelling of electricity supply in cLCA context (see chapter 2.4). However, it is recommended that a mix of affected technologies is identified. The mix of technologies is recommended to be modelled by using an equilibrium modelling environment taking all the important mechanisms of the energy sector into consideration, such as EnergyPLAN or TIMES/MARKAL models. For each market, the country-specific conditions and constraints should be taken into account as a part of a dynamic energy system. Such conditions and constraints includes political measures and policies, resource availability, technological development, market mechanisms, rebound effects and behavioral influences to best model the actual response of an energy system to a change in demand.

Implementing such an equilibrium modelling environment in ecoinvent would allow for large-scale decisions to be modelled, where the overall market trend will be affected. It would provide the user with the option to create an energy system model compatible with the goal of the study and model it using the consequential system model. Linking external databases in an equilibrium environment has also been described as possible for the ecoinvent database as an option for future development in the Data Quality Guidelines for ecoinvent (Weidema et al. 2013).

Such an approach as mentioned above can be seen as long-term idea, but implementing a new model environment into ecoinvent by altering the software structure is not considered a possible task for this study. Also, for providing background LCI data for small-scale decision, which now is modelled in the consequential system model, such a modelling approach would be suitable, since it assumed that every small-scale decision would use the same electricity LCI data as input (in the same market) and the market parameters would not change. Thus, this study does not further investigate how economic equilibrium modelling could be implemented in ecoinvent and suggests an alternative approach with consideration of the current ecoinvent structure.

4.1.2 The option of using a simplified approach

A simplified approach, such as the using the 5-step approach used by Weidema et al. (1999) to manually analyse each market situation and arriving at one or two affected technologies based on e.g. a rule of thumb or expert opinions. Such an approach is not an option since 1. It would be too time consuming to analyse all 71 electricity markets in ecoinvent, and 2. Only arriving at one or two affected technologies is not a sufficient result when it comes to electricity supply, where instead a mix (preferable modelled with an energy system model) of fundamentally different electricity sources should be used, as stated by (Mathiesen et al. 2009). Since ecoinvent already supplies a mix of technologies, it would be a possibility that such an approach leads to more shortcomings in modelling that the ones already identified. The 5-step approach has been developed and refined over part years, such as in (Ekvall & Weidema 2004; Weidema et al. 2009), and is per se not irrelevant for identifying affected electricity technologies. The main drawback is instead connected to the commonly simplified way of interpreting and implementing the approach and arriving at one or two affected electricity technologies. Using partial equilibrium models (such as energy system analysis models) can still be seen as a part of the 5-step approach for answering questions about constrained/unconstrained suppliers and politically, socially most preferred technologies.

4.1.3 The option of using already modelled data based on scenarios as input

Using a dynamic optimization model to construct an energy system model for each market and then manually implementing the data into ecoinvent is not an option for this study since it is too time- and resource consuming. However, using already modelled data for the electricity market could be a possibility.

Eriksson et al. (2007) used modelled electricity supply mixes of the Nordic energy system in their case study on district heating scenarios, based on two fundamentally different scenarios. However, only one set of data based on one scenario can currently be used in ecoinvent. Schmidt (2012) proposed to use data from the International Energy Organization and national forecasts of the electricity sector. This approach was also used in a LCA study on an aluminium smelter in Greenland by (Schmidt & Thrane 2009).

A prerequisite for adopting this modelling approach is that there exists relevant and consistent data for each market. The data should preferably be modelled with consideration of key parameters of the energy sector and take market-specific conditions into account to overcome the shortcomings in ecoinvent concerning only looking at global market trends for technologies etc. Consistency is important to ensure data quality, and exerts requirements on the choice of data source used to supply life cycle inventories to the ecoinvent database. For example, two models that use different pricing on technologies will yield different output when modelling the same electricity market. It is thus preferable to use a single data source for all markets instead of using data sources with different modeling assumptions for each market.

The level of detail of the data used in the models has to be such that relevant country-specific market information is included. Using regional or global projections to calculate average supply for each country should be avoided due to the risk of losing important market-specific information. When no single data source exist covering every market, it would be preferable to use data from different sources that are as consistent as possible. This would also be important in order to enable data comparison.

4.2 Suggested modelling approach based on the current ecoinvent structure

Based on the discussion in chapter 4.1, the best fitting approach in order to keep the current ecoinvent software structure and provide relevant consequential LCI data for electricity markets, is to use already modelled data from *nation-wide official forecasts*. Official data can be defined as information produced, collated and distributed by national governments, their official bodies or the international agencies that link the data. The advantages of choosing this approach is stated out in chapter 4.2.1 and requirements on the acquired data to be compliant with consequential operation in ecoinvent is presented in chapter 4.2.2. The suggested approach will then further be applied in chapter 5.

4.2.1 Advantages of using nation-wide official forecasts

Using data from official projections has generally advantages compared to using other data sets from academic research, independent research institutes and market surveys etc.:

- The scenarios modelled are used to provide decision support for governments and official organizations, seeking to present definite information conformed to international standards or other well-established definitions or classifications.

- Biased projections connected to private interests are likely to be avoided since the assumptions, estimations and model algorithms are usually continuously updated and available to external revision.

- International bodies that provide national data usually base it on national official data source and collect their data in a consistent way.

4.2.2 Acquiring forecasted data consistent with consequential modelling in ecoinvent

There exist many official forecasts of power markets that can be used as data source for the ecoinvent electricity markets. A chosen data source must provide data that is consistent with the operational requirements of the 'substitution, consequential, long-term' system model to provide relevant data for LCA practitioners (see chapter 3.2.1).

However, it is not certain that data is provided on the same level of detail from each included country when secondary sources are used. The level of detail can provide a hint on the quality of the data. How detailed data is supplied for key parameters should be taken into account when choosing data source. Official energy sector projections should preferably model future electricity demand and supply with consideration of country-specific technological, political, economic and social constraints.

Choosing data source for consequential electricity markets according to above could help overcoming the identified limitation in ecoinvent concerning the lack of market specific information when determining the technology level of the transforming activities that supply each market (see chapter 3.4). According to cLCA practice, marginal data should be used for the consequential market datasets. If the projections present future average supply, the current supply can be subtracted to obtain the additional long-term supply (marginal supply).

4.2.2.1 Choice of demand and supply scenario

Since future demand and constraints acting upon the energy sector are hard to predict, most projections model several different scenarios to show the consequences of different policy choices or boundary conditions. As mentioned earlier, the current version of ecoinvent only allows for one set of marginal data per market. When a consistent data source is identified where more than one demand and supply scenario are modelled, projected data based on one of them need to be chosen.

LCA practitioners have subjective opinions on what future scenario that is most likely and no scenario consensus exist between models, which calls for a “generally accepted” market scenario to be used. Further, since the database needs to provide background data for generic cLCA studies, the underlying market scenario needs to fit the purpose of as many studies as possible. Thus, the choice of scenario should comprise a middle path excluding the “extreme” scenarios.

4.2.2.2 Choice of time frame

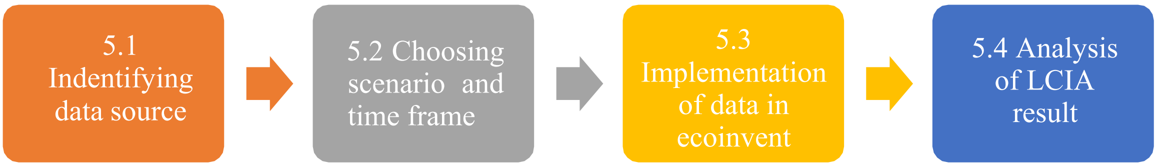
The forecasts must be modelled within a time-frame which is considered *long-term* (includes investment decisions). What is considered to be a long-term change in electricity demand would be such that new power plants will be installed to meet it considering the long capital cycle of investments in the power sector. Although, forecasts become more uncertain the longer into the future one looks, which also should be taken into account when choosing which data to use.

4.2.2.3 Implications for the ecoinvent user

A modelled demand scenario for an entire country usually exceeds what is regarded to be small scale change in the annual electricity demand, which can be up to 1 TWh according to Mattson et al. (2001). Small scale decisions (not affect the overall market situation) can still be modelled using this data since it can be assumed that the modelled demand increase is made up by many small-scale decisions to increase the electricity demand. In other words, a small scale decision to increase the electricity demand in a specific market will be supplied with the same electricity mix as the overall large scale demand increase over a long period of time.

5 Modelling selected electricity markets using new approach

The goal of this section is to provide relevant consequential LCI data for selected electricity markets. This is done according to the methodology flowchart below.



In chapter 5.1 and 5.2, the new suggested approach for modelling consequential electricity markets is used to acquire relevant LCI data for selected markets (see chapter 4.2). In chapter 5.3, the LCI data is implemented in ecoinvent as datasets. Chapter 5.4 presents the methods used to analyze LCIA results of the datasets.

5.1 Identifying data source

5.1.1 Choice of data sources and market delimitation

Since the ecoinvent database currently contains 71 different geographies (i.e. markets) for electricity supply it is not feasible within the time frame of the thesis to find consistent, relevant data and implement it for all of them. Thus, the following official energy sector projections were chosen; The World Energy Outlook (WEO) 2013 (International Energy Agency 2013b) as data source for the markets Brazil, China, India, Japan and Russia. There are more countries and regions presented in the WEO 2013, but data for aggregated regions is not preferable due to the risk of losing market-specific information. The selected markets are generally large producing countries facing an electricity demand and supply shift in a foreseeable future, why relevant cLCI data in ecoinvent is particularly of interest for these markets. Since Switzerland has already been identified as a market supplying unrealistic consequential output (Treyer & Bauer 2014), the Swiss Energy Perspectives (EP) 2050 (Prognos AG 2012) was selected for acquiring data for Switzerland. A detailed description of the data sources follows in chapter 5.1.1.1 and 5.1.1.2.

5.1.1.1 World Energy Outlook 2013

The World Energy Outlook is a published annually by the International Energy Agency and provides medium to long-term energy projections on a global scale and also for selected regions and countries. The projections cover the development up to 2035 and are in 12 countries individually modelled to analyze their trends in demand, supply availability and constraints and international trade and energy balances (International Energy Agency 2013b).

The forecasts are calculated using a large-scale simulation model, the World Energy Model (WEM) which include an energy transformation module for power generation and heat, providing energy flows by fuel etc. as output. The model includes the whole energy system and much of the data on energy supply, transformation and demand and energy prices are obtained from IEA's own statistic databases. The WEM is constantly reviewed and updated by IEA experts and external modelling experts to ensure completeness and relevancy (International Energy Agency 2013a).

The power and heat module in the WEM calculates capacity additions to cover increasing demand and decommissioning of power plants over the projected period. Long-run marginal cost for different technologies is used as basis when investment decisions are needed to supply the demand. The installation and utilization of stochastic energy sources such as wind and PV are based on historical data and the long-run installation potential. The annual generation volumes are based on the variable generation costs of each power plant type, which results in order of merit for dispatch. Figure 9 shows how the module projects electricity generation volumes, which are used to calculate the long-term marginal supply volumes for each market. For the full model description, please refer to (International Energy Agency 2013a).

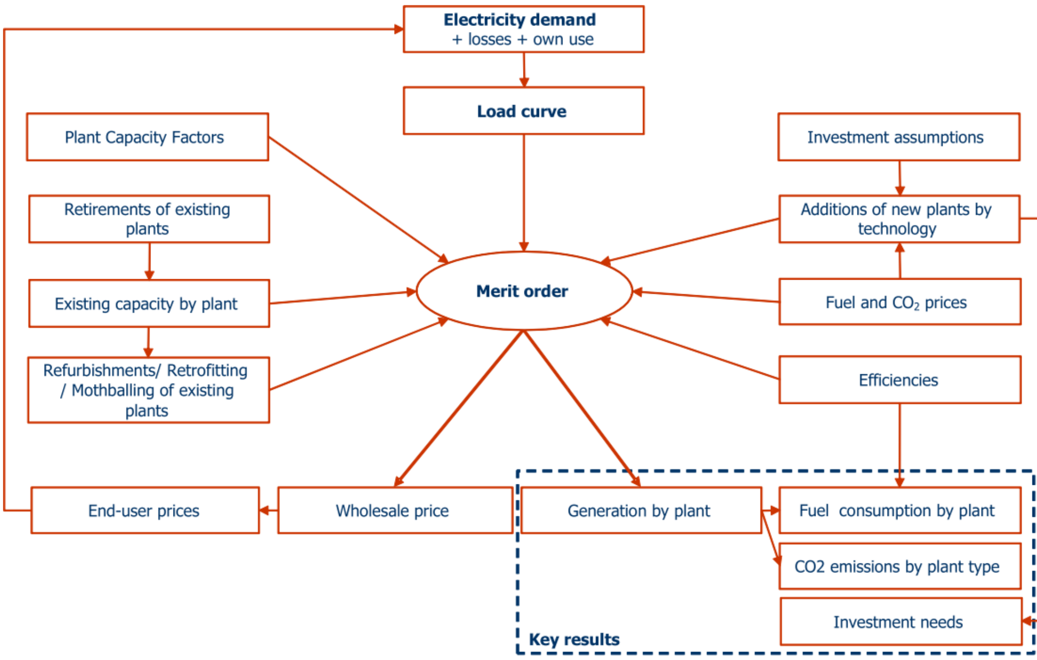


Figure 9. Structure of the power generation module in World Energy Model (International Energy Agency 2013a).

5.1.1.2 Swiss Energy Perspectives 2050

The Swiss Energy Perspectives 2050 'Die Energieperspektiven für die Schweiz bis 2050', is published by Prognos AG, commissioned by the Swiss Federal Office of Energy (Prognos AG 2012).

The long-term development of the Swiss energy sector is investigated by modelling 3 different demand and supply scenarios: ‘Business-as-usual’ with implemented energy and economic policy measures developed in the last years; ‘New energy policy’ where 1-1.5 ton of CO2 emissions per capita is set as goal for 2050, and investigates the measures and pathways to achieve the goal; and the ‘Political measures’, where a package of further energy related policies are implemented and the effect on the energy system investigated. The scenarios are modelled with a bottom-up approach for the demand and supply of energy carriers. The computable general equilibrium model was used to simulate the economic effects and impacts.

The three scenarios are associated with different supply options to construct an energy system that allow for no further refurbishment or installation of nuclear power after 50 years of operation. Optimization of the transmission grid and increase development of energy efficiency is further measures assumed in the investigation. The three supply options modelled are divided into 3 different variants where different deployment renewable energy sources, increased import share and combined cycle power plants: Variant C - Fossil Central; Variant C+E - Fossil Central and renewables; Variant E: Renewables and import.

5.2 Choice of scenario and time frame

Detailed projections for three scenarios are presented in the WEO 2013: the New Policies Scenario, the Current Policies Scenario and the 450 Scenario. The central scenario is the New Policies Scenario where current broad policy measures and announced measures are taken into account to provide a benchmark for the potentials and limitations of the recent development in energy and climate policy. The Current Policies Scenario is based on the policy measures adopted until mid-2013 and the 450 Scenario selects an energy pathway for 50 % chance to limit the average global warming to 2° C (International Energy Agency 2013b). The policies and measures that lay as basis for the scenarios are presented in Table 2. The scenarios presented in the EP 2050 were presented in chapter 5.1.1.2.

Table 2. The policies and measures modelled for the power generation for selected countries in the World Energy Outlook 2013, taken from Annex B in (International Energy Agency 2013b).

Power generation policies and measures as modelled by scenario for selected countries			
	Current Policies Scenario	New Policies Scenario	450 Scenario
Brazil	Power auctions for all fuel types. Guidance on the fuel mix from the Ten-Year Plan for Energy Expansion.	Enhanced deployment of renewables technologies through power auctions.	CO2 pricing implemented from 2020. Further increases of generation from renewable sources.
China	Implementation of measures in 12th Five-Year Plan. Start construction of 40 GW of new nuclear plants by 2015. Reach 290 GW of installed hydro capacity by 2015. Reach 100 GW of installed wind capacity by 2015. 35 GW of solar capacity by 2015. Priority given to gas use to 2015.	12th Five-Year Plan renewables targets for 2015 are exceeded. 70 to 80 GW of nuclear capacity by 2020. 200 GW of wind capacity by 2020. 30 GW of bioenergy capacity by 2020. CO2 pricing implemented from 2020.	Higher CO2 pricing. Enhanced support for renewables. Continued support to nuclear capacity additions post 2020. Deployment of CCS from around 2020.

India	Renewable Energy Certificate trade for all eligible grid-connected renewable-based electricity generation technologies. National solar mission target of 20 GW of solar PV capacity by 2022. Increased use of supercritical coal technology.	Renewable energy support policies and targets, including small hydro. Coal-fired power stations energy efficiency mandates.	Renewables (excluding large hydro) to reach 15% of installed capacity by 2020. Expanded support to renewables, nuclear and efficient coal. Deployment of CCS from around 2020.
Japan	Support for renewables generation. Decommissioning of units 1-4 of Fukushima Daiichi nuclear power plant.	Shadow price of carbon assumed from 2015, affecting investment decisions in power generation. Lifetime of nuclear power plants limited to 40 years for plants built up to 1990 and 50 years for all others. Increased support for renewables generation.	CO2 pricing implemented from 2020. Share of low-carbon electricity generation to increase by 2020 and expand further by 2030. Expansion of renewables support Introduction of CCS to coal-fired power generation.
Russia	Competitive wholesale electricity market.	State support to the nuclear and hydropower sectors; a support mechanism for non-hydro renewables introduced from 2014.	Stronger support for nuclear power and renewables. CO2 pricing implemented from 2020.

The WEO 2013 and EP 2050 projections can be said to contain a business-as-usual, a benchmark and a goal scenario. When it comes to choosing a scenario, it is assumed that more political measures affecting the power sector will be implemented than those decided upon up in the BAU scenarios. The goal scenarios includes many larger changes in the energy system, and it is assumed that not all of these measures will have time to be implemented until 2035, especially due to the capital intensity and long lived infrastructure of the power sector. Thus, it is assumed that a "middle" scenario would be most likely to be realized by 2035, in this case the POM and NP scenario. For Switzerland, datasets were created for all three supply variants. By estimating their associated environmental impact, implications of using different scenarios for cLCA case studies can be analyzed. The projections for 2035 were used for all markets, since this time-frame was considered long-term (new capacity installations are likely within this period).

From the World Energy Outlook for 2013, the annual electricity supply volumes for the countries Brazil, China, India, Japan and Russia statistical supply volume for 2011, the annual additional generation was given, i.e. long-term marginal electricity supply. The marginal data obtained from WEO 2013 for all scenarios is shown in Table 3 (CPS and 450 S shown for comparison). The same method was used for the data for Switzerland, with subtracting the 2010 supply. The obtained marginal data for the three supply variants of the Political measures scenario in the Swiss Energy Perspectives 2050 is shown in Table 4.

Table 3. The marginal electricity supply (TWh) calculated from the World Energy Outlook 2013 for Brazil, China, India, Japan and Russia. Data shown for the New Policies, Current Policies and 450 Scenario, respectively.

Marginal electricity supply 2035 (TWh)															
	Brazil			China			India			Japan			Russia		
	NPS	CPS	450 S	NPS	CPS	450 S	NPS	CPS	450 S	NPS	CPS	450 S	NPS	CPS	450 S
Total generation	553	628	424	5249	6618	3524	2320	2431	1849	174	259	31	468	613	246
Coal	12	18	-10	1755	3653	-1814	1178	1661	47	-5	71	-246	101	110	-45
Oil	-4	-4	-8	-3	-2	-3	-7	-6	-8	-127	-121	-145	-21	-21	-21
Gas	131	190	17	642	520	890	310	294	409	24	81	-59	141	323	-253
Nuclear	15	15	26	867	778	1547	172	141	329	72	72	176	105	94	200
Hydro	247	267	247	717	649	760	237	138	439	25	15	45	75	65	123
Bioenergy	52	50	47	284	240	457	87	50	147	31	25	35	36	21	123
Wind	82	77	85	717	607	1142	185	91	246	62	47	111	15	12	91
Geothermal	0	0	0	13	6	17	2	1	4	23	14	32	15	8	26
Solar PV	12	10	14	201	157	338	142	59	168	67	56	77	1	0	3
CSP	5	4	5	56	10	190	13	0	66	0	0	0	0	0	0
Marine	0	0	1	1	1	2	1	0	1	3	0	6	0	0	0

Table 4. The marginal electricity supply (TWh) for Switzerland as projected in the Swiss Energy Perspectives 2050. The data is shown for the Political measures scenario, supply variants C, C+E and E.

Marginal electricity supply (TWh) , Switzerland, POM Scenario														
	Hydro	Nuclear	Fossil CCPP	Fossil CHP	Imports	PV	Wind Energy	Biomass (Wooden gas)	Biomass (Wood)	Geothermal	Biogas	Wastewater treatment	Domestic waste incineration	Landfill gas
Variant C	5,21	0	19,05	2,92	0	2,44	0,73	0	0,51	0,39	0,43	0,17	0,06	0
Variant C+E	6,48	0	11,63	3,26	0	4,36	1,72	0	1,07	1,43	1,4	0,17	0,4	0
Variant E	6,48	0	0	3,26	11,63	4,36	1,72	0	1,07	1,43	1,4	0,17	0,4	0

5.3 Creating new consequential datasets from selected data sources

Any inherent constraint in the current ecoinvent structure concerning internal linking algorithms and inability to link to external databases is overcome by manually creating the new market datasets. Manual construction would in this case mean taking the forecasted technologies and matching them with current transforming activities in ecoinvent that supply the public markets (no labeled electricity or auto-producers). In ecoinvent, both 'consequential' and 'allocation, default' datasets exist for some transforming activities, where 'consequential' datasets already has consequential input and were used when such existed (the implications on using 'allocation, default' datasets has not been further studied). The new market shares of the projected technologies are calculated from the respective projected supply volume. This way, a new consequential market dataset can be created.

5.3.1 Excluding non-affected technologies

Since all scenarios in WEO 2013 consistently point towards an increase overall electricity market trend (International Energy Agency 2013b), only the technologies that are projected to have an additional generation volume in 2035 are of interest according to cLCA operation. These are the technologies that will contribute to one additional kWh and whose associated impact can be assigned to decisions affecting the electricity demand. The technologies projected to be decommissioned at a faster pace than new capacity is installed were thus excluded in further calculations and their market share set to zero. As can be seen in Table 3, this involves e.g. electricity generation from oil in all enclosed markets in all scenarios.

5.3.2 Matching of projected technologies and ecoinvent transforming activities

There is always the chance that the classification of technologies in the projections does not match the existing transforming activities in ecoinvent. There are mainly two reasons for this: Either **(1)** new technologies are projected for which no dataset yet exist in that specific market, or **(2)** the technology level of the transforming activities is more detailed than in the projections or vice versa (e.g. only aggregated data for 'hydro' available instead of 'run-of-river', 'alpine reservoir', 'pumped storage' etc.). In such cases, the technologies were aligned by finding the most suitable transformation activities. This was done by using the approach described below:

For situation **(1),** similar transforming activities from other markets were used, associated with similar expected environmental impact as the projected technologies. This was mainly done for new technologies, such as PV, Geothermal and Natural gas CCPP. The projected technologies Geothermal and Fossil CCPP do not exist as transforming activities for Switzerland in ecoinvent.

Fossil CCPP refers to natural gas fired CCPP, where corresponding datasets from Germany was used. The only exception where no suitable dataset exists in ecoinvent, was for the category ‘Marine’ in the WEO 2013 projections. Since the contribution to the overall impact was assumed to be small enough on a long-term basis, along with a very small projected capacity addition, the simplifying assumption was made that the contribution is zero, due to data gaps.

For situation **(2),** the different types of technologies utilizing the same type of energy carrier were assumed to supply the new market dataset with the same internal shares as today in ecoinvent. This method was used by (Earles et al. 2013) when integrating economic equilibrium modelling and LCA to investigate the effects of an increase of wood used for ethanol production in the US. The technologies that belong to each category in the WEO 2013 can be found in Appendix I. These definitions lay as basis for the splitting of the WEO 2013 projections. As an example, the category Hydro provided by the forecasts, needed to be split into three transforming activities in ecoinvent according to Figure 10.

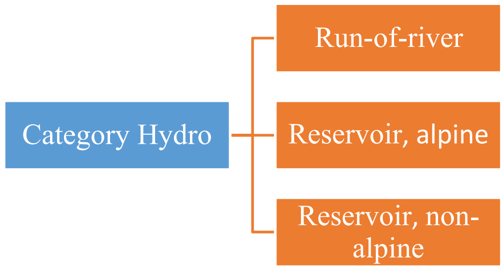


Figure 10 Example: Transforming activities in ecoinvent supplying hydro power.

The new shares (for run-of river etc.) were calculated using the current annual average production volumes according to:

Equation 1. Current internal market share, technology n:

$$Market\ share_{technology,n} = \frac{Annual\ average\ prod.\ volume_{technology,n}\ (kWh)}{Annual\ average\ prod.\ volume_{tech.\ category,\ n}\ (kWh)}$$

Equation 2. New production volume, technology n: multiplying with projected supply volume to get projected market share.

$$New\ marginal\ supply_{\ technology,\ n}(kWh) = Projected\ supply_{\ tech.category,n}(kWh) * Market\ share_{technology,\ n}$$

Equation 3. Normalisation by dividing with new marginal supply with total projected supply.

$$New\ marginal\ market\ share_{technology,n} = \frac{New\ marginal\ supply_{\ technology,\ n}(kWh)}{Total\ projected\ supply\ (kWh)}$$

A special case was made for the **Photovoltaic (PV) supply**: China, Japan and India and Switzerland, many different PV technologies (ca 10 different PV technologies in India and Switzerland) concerning installation, not peak power, is supplying the attributional electricity markets. PV is such a small share compared to e.g. coal and is not expected to significantly change the impact associated with 1 kWh if the projected supply is split among all different PV technologies or only one PV technology is used. Thus, only one PV dataset is used when modelling the LCIA results using Simapro. PV is also the only technology currently supplying the low (none on medium) voltage level for China, Japan, India and Switzerland. In Brazil and Russia, no PV supply currently supplies the attributional markets.

When the projections include *more detailed* technology categories than the ecoinvent transforming activities, the technology categories were merged and added to the best corresponding dataset. No new datasets were made. Concentrated Solar Power (CSP) does not yet exist as a transforming activity in ecoinvent, but is projected to supply some countries in the World Energy Outlook scenarios (see Table 3). The projected volumes for PV and CSP was aggregated and linked to market-specific PV datasets. The categories 'Wastewater treatment', 'Domestic Waste Incineration' and 'Landfill gas', in the EP 2050 were merged to represent the current transforming activity 'treatment of municipal solid waste, incineration' (see Table 4).

To illustrate the matching approach, an example is shown for the matching of Japan, see Table 5. The current transforming activities (TAs) that are supplying electricity for Japan in ecoinvent are listed in column A. Column B shows the corresponding annual average production volumes (AAPV) (kWh). The projected technologies (see Table 3) for Japan are matched according to which transforming activities that best fit the technology category in column D. The projected technologies for which no transforming activity exists today in ecoinvent are listed in column C. The projected marginal data (TWh) is taken for each scenario and matched according to equation 1 and 2. Only the additional supply is use, no decommissioned capacity (market with a '-'). The decommissioned volumes are added to the sum of the matched technologies. 'Marine' is predicted to be installed, but since no datasets was found that were matching, nor was any new dataset created, the contribution was set to zero.

Table 5 Matching process of the projected Japanese marginal electricity supply.

Tranforming activities (TA) in ecoinvent	AAPV (kWh)	No TA match	Technology matching	Ecoinvent complying supply mix (TWh)		
				NPS	CPS	450 S
electricity production, hydro, pumped storage	6,99E+09		Hydro	2,12	1,27	3,81
electricity production, oil	1,24E+11		Oil	-	-	-
treatment of blast furnace gas, in power plant	2,25E+10		Coal	-	5,75	-
treatment of coal gas, in power plant	7,72E+09		Coal	-	1,97	-
electricity production, wind, >3MW turbine, onshore	3,51E+08		Wind	8,36	6,34	14,97
treatment of municipal solid waste, incineration	6,87E+09		Bioenergy	10,12	8,16	11,43
electricity production, wind, <1MW turbine, onshore	2,00E+08		Wind	4,77	3,62	8,54
electricity production, wind, 1-3MW turbine, onshore	1,99E+09		Wind	47,51	36,01	85,05
electricity production, wind, 1-3MW turbine, offshore	5,71E+07		Wind	1,36	1,03	2,44
electricity production, nuclear, pressure water reactor	1,06E+11		Nuclear	31,40	31,40	76,76
electricity production, nuclear, boiling water reactor	1,37E+11		Nuclear	40,60	40,60	99,24
electricity production, hydro, reservoir, alpine region	1,51E+10		Hydro	4,58	2,75	8,24
electricity production, hydro, run-of-river	6,04E+10		Hydro	18,31	10,98	32,95
electricity production, geothermal	2,64E+09		Geothermal	23,00	14,00	32,00
heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control	1,42E+10		Bioenergy	20,88	16,84	23,57
electricity production, hard coal	2,48E+11		Coal	-	63,28	-
electricity production, natural gas, at conventional power plant	2,66E+11		Gas	24,00	81,00	-
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted			Solar PV	67,00	56,00	77,00
-		Marine		0,00	0,00	0,00
SUM				304,00	381,00	*476,00*

5.3.2.1 *Import datasets*

The same approach as above was applied to the imports from neighboring markets, where it is assumed that the origin of the imports will be the same and the internal shares will be same as currently assumed in the attributional electricity markets. However, consequential datasets will be used for the composition of the imports in the consequential version of ecoinvent. The only exception concerns Russia, where imports currently supplies the attributional market, but is assumed not be a part of the marginal supply in the future. Since it is impossible to trace from where electricity is produced in an interconnected transmission network, as mentioned by Weber et al. (2010), there is a difficulty in correctly defining what the supply mix consist of and subsequently the imports to a market. Even if an the marginal supply mix for an interconnected grid is assumed to be better suited for the purpose of a cLCA study, e.g. a European supply mix, the current approach to use import datasets still need to be used due to the current inability to aggregate electricity markets to a larger geographical region in ecoinvent, e.g. aggregating the whole of Europe. As for the above example with the Japanese market (Table 5), imports were not applicable.

5.3.2.2 Complementary qualitative analysis of included transforming activities

It should be noted, that the aligning approach suggested above may result in including transformation activities that are not expected to contribute to a long-term marginal supply: every electricity supplying transforming activity in the attributional version can be included. However, some technologies can be considered an outdated technology or to have small further installation capacity. A complementary, qualitative analysis was done for each market dataset to exclude such activities from the new datasets. Peat was not considered to play a role in further capacity installments and was not included in the new Russian market. It is not specified in the projections which specific plant technology that will be installed to supply the capacity addition of natural gas PP for which market. As for Japanese example above (Table 5), conventional cycle plants are currently supplying the attributional market, but this transforming activity was changed to combined cycle plant dataset in the new consequential dataset, since this technology is most expected to be installed.

5.3.2.3 Normalized market shares

When all projected technologies for a market have been connected to a transformation activity (or several), the new production volumes should be normalized by dividing by the total projected marginal supply volume according to equation 3. By adding the normalized market shares to the datasets, a new consequential dataset is created. The resulting new consequential datasets are presented below in Table 6 to 13. The matching of projected technologies and ecoinvent transforming activities for the respective markets are shown in Appendix II together with the resulting new conseq. supply volumes.

Table 6 New consequential electricity market dataset for Brazil.

Transforming activities, new consequential electricity market, Brazil	Share/ kWh
Electricity, high voltage {BR}| electricity production, hard coal | Conseq, U	0,00053
Electricity, high voltage {BR}| electricity production, hydro, reservoir, tropical region | Conseq, U	0,44424
Electricity, high voltage {BR}| electricity production, lignite | Conseq, U	0,01124
Electricity, high voltage {BR}| electricity production, nuclear, pressure water reactor | Conseq, U	0,02698
Electricity, high voltage {BR}| electricity production, wind, <1MW turbine, onshore | Conseq, U	0,02138
Electricity, high voltage {BR}| electricity production, wind, >3MW turbine, onshore | Conseq, U	0,01947
Electricity, high voltage {BR}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U	0,10663
Electricity, high voltage {BR}| ethanol production from sugar cane | Alloc Def, U	0,00461
Electricity, high voltage {BR}| cane sugar production with ethanol by-product | Alloc Def, U	0,02448
Electricity, high voltage {BR}| treatment of coal gas, in power plant | Alloc Def, U	0,00294
Electricity, high voltage {CL}| electricity production, natural gas, combined cycle power plant | Conseq, U	0,23561
Electricity, high voltage {BR}| heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control | Alloc Def, U	0,06443
Electricity, high voltage {BR}| treatment of blast furnace gas, in power plant | Alloc Def, U	0,00687
Electricity, low voltage {IN}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U	0,03058

Table 7 New consequential electricity market dataset for China.

<table>
<tr><th>Transforming activities, new consequential electricity market, China</th><th>Share/ kWh</th></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, hard coal | Conseq, U</td><td>0,33145</td></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, hydro, reservoir, non-alpine region | Conseq, U</td><td>0,10237</td></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, hydro, run-of-river | Conseq, U</td><td>0,03412</td></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, nuclear, pressure water reactor | Conseq, U</td><td>0,16505</td></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, wind, <1MW turbine, onshore | Conseq, U</td><td>0,03317</td></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, wind, >3MW turbine, onshore | Conseq, U</td><td>0,04204</td></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, wind, 1-3MW turbine, offshore | Conseq, U</td><td>0,00082</td></tr>
<tr><td>Electricity, high voltage {CN}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U</td><td>0,06047</td></tr>
<tr><td>Electricity, high voltage {CN}| treatment of blast furnace gas, in power plant | Alloc Def, U</td><td>0,00185</td></tr>
<tr><td>Electricity, high voltage {CN}| treatment of coal gas, in power plant | Alloc Def, U</td><td>0,00079</td></tr>
<tr><td>Electricity, high voltage {CN}| heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control | Alloc Def, U</td><td>0,05406</td></tr>
<tr><td>Electricity, high voltage {KR}| electricity production, natural gas, combined cycle power plant | Conseq, U</td><td>0,12222</td></tr>
<tr><td>Electricity, high voltage {RU}| electricity production, geothermal | Conseq, U</td><td>0,00247</td></tr>
<tr><td>Electricity, low voltage {CN}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U</td><td>0,04892</td></tr>
</table>

Table 8 New consequential electricity market dataset for India.

<table>
<tr><th>Transforming activities, new consequential electricity market, India</th><th>Share/ kWh</th></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, hard coal | Conseq, U</td><td>0,48886</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, hydro, pumped storage | Conseq, U</td><td>0,01253</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, hydro, reservoir, alpine region | Conseq, U</td><td>0,07851</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, hydro, run-of-river | Conseq, U</td><td>0,01081</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, lignite | Conseq, U</td><td>0,01610</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, nuclear, boiling water reactor | Conseq, U</td><td>0,00505</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, nuclear, pressure water reactor | Conseq, U</td><td>0,06886</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, wind, <1MW turbine, onshore | Conseq, U</td><td>0,03517</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, wind, >3MW turbine, onshore | Conseq, U</td><td>0,01393</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U</td><td>0,03040</td></tr>
<tr><td>Electricity, high voltage {IN}| treatment of coal gas, in power plant | Alloc Def, U</td><td>0,00127</td></tr>
<tr><td>Electricity, high voltage {IN}| electricity production, natural gas, combined cycle power plant | Conseq, U</td><td>0,13322</td></tr>
<tr><td>Electricity, high voltage {IN}| heat and power co-generation, wood chips, 6400kW thermal, with multicyclone emission control | Alloc Def, U</td><td>0,03739</td></tr>
<tr><td>Electricity, high voltage {RU}| electricity production, geothermal | Conseq, U</td><td>0,00086</td></tr>
<tr><td>Electricity, low voltage {IN}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, laminated, integrated | Conseq, U</td><td>0,06661</td></tr>
</table>

Table 9 New consequential electricity market dataset for Japan.

Transforming activities, new consequential electricity market, Japan	Share/ kWh
Electricity, high voltage {JP}| electricity production, geothermal | Conseq, U	0,48886
Electricity, high voltage {JP}| electricity production, hydro, pumped storage | Conseq, U	0,01253
Electricity, high voltage {JP}| electricity production, hydro, reservoir, alpine region | Conseq, U	0,07851
Electricity, high voltage {JP}| electricity production, hydro, run-of-river | Conseq, U	0,01081
Electricity, high voltage {JP}| electricity production, wind, <1MW turbine, onshore | Conseq, U	0,01610
Electricity, high voltage {JP}| electricity production, wind, >3MW turbine, onshore | Conseq, U	0,00505
Electricity, high voltage {JP}| electricity production, wind, 1-3MW turbine, offshore | Conseq, U	0,06886
Electricity, high voltage {JP}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U	0,03517
Electricity, low voltage {JP}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U	0,01393
Electricity, high voltage {KR}| electricity production, natural gas, combined cycle power plant | Conseq, U	0,03040
Electricity, high voltage {JP}| heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control | Alloc Def, U	0,00127
Electricity, high voltage {JP}| electricity production, nuclear, boiling water reactor | Conseq, U	0,13322
Electricity, high voltage {JP}| electricity production, nuclear, pressure water reactor | Conseq, U	0,03739
Electricity, high voltage {JP}| treatment of municipal solid waste, incineration | Alloc Def, U	0,00086

Table 10 New consequential electricity market dataset for Russia.

Transforming activities, new consequential electricity market, Russia	Share/ kWh
Electricity, high voltage {RU}| electricity production, geothermal | Conseq, U	0,07492
Electricity, high voltage {RU}| electricity production, hard coal | Conseq, U	0,00690
Electricity, high voltage {RU}| electricity production, hydro, reservoir, non-alpine region | Conseq, U	0,01491
Electricity, high voltage {RU}| electricity production, hydro, run-of-river | Conseq, U	0,05963
Electricity, high voltage {RU}| electricity production, lignite | Conseq, U	0,01553
Electricity, high voltage {RU}| electricity production, nuclear, boiling water reactor | Conseq, U	0,02724
Electricity, high voltage {RU}| electricity production, nuclear, pressure water reactor | Conseq, U	0,00444
Electricity, high voltage {RU}| electricity production, wind, <1MW turbine, onshore | Conseq, U	0,15474
Electricity, high voltage {RU}| electricity production, wind, >3MW turbine, onshore | Conseq, U	0,21824
Electricity, high voltage {RU}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U	0,07818
Electricity, high voltage {RU}| treatment of municipal solid waste, incineration | Alloc Def, U	0,06801
Electricity, high voltage {RU}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Def, U	0,13224
Electricity, high voltage {RU}| heat and power co-generation, wood chips, 6400kW thermal, with multicyclone emission control | Alloc Def, U	0,10229
Electricity, low voltage {CN}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U	0,03297

Table 11 New consequential electricity market dataset for Switzerland, Variant C.

Transforming activities, new consequential electricity market, Switzerland ,Variant C	Share/ kWh
Electricity, high voltage {CH}| electricity production, hydro, reservoir, alpine region | Conseq, U	0,09134
Electricity, high voltage {CH}| electricity production, hydro, run-of-river | Conseq, U	0,07193
Electricity, high voltage {CH}| electricity production, wind, <1MW turbine, onshore | Conseq, U	0,00368
Electricity, high voltage {CH}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U	0,01919
Electricity, low voltage {CH}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U	0,07647
Electricity, high voltage {CH}| treatment of municipal solid waste, incineration | Alloc Def, U	0,00188
Electricity, high voltage {CH}| heat and power co-generation, biogas, gas engine | Alloc Def, U	0,01348
Electricity, high voltage {CH}| heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal, with extensive emission control | Alloc Def, U	3,29E-11
Electricity, high voltage {CH}| heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal | Alloc Def, U	3,29E-11
Electricity, high voltage {CH}| treatment of digester sludge by municipal incineration, future | Alloc Def, U	0,00533
Electricity, high voltage {CH}| ethanol production from wood | Alloc Def, U	1,64E-06
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 1MW electrical, lean burn | Alloc Def, U	0,03469
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 200kW electrical, lean burn | Alloc Def, U	0,01977
Electricity, high voltage {CH}| heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control | Alloc Def, U	0,01598
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 500kW electrical, lean burn | Alloc Def, U	0,01979
Electricity, high voltage {CH}| heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | Alloc Def, U	0,01727
Electricity, high voltage {DE}| electricity production, geothermal | Conseq, U	0,01222
Electricity, high voltage {KR}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Def, U[2]	0,59699

Table 12 New consequential electricity market dataset for Switzerland, Varian C+E.

Transforming activities, new consequential electricity market, Switzerland , Variant C+E	Share/ kWh
Electricity, high voltage {CH}| electricity production, hydro, reservoir, alpine region | Conseq, U	0,11357
Electricity, high voltage {CH}| electricity production, hydro, run-of-river | Conseq, U	0,08944
Electricity, high voltage {CH}| electricity production, wind, <1MW turbine, onshore | Conseq, U	0,00868
Electricity, high voltage {CH}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U	0,04521
Electricity, low voltage {CH}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U	0,13659
Electricity, high voltage {CH}| treatment of municipal solid waste, incineration | Alloc Def, U	0,01253
Electricity, high voltage {CH}| heat and power co-generation, biogas, gas engine | Alloc Def, U	0,04386
Electricity, high voltage {CH}| heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal, with extensive emission control | Alloc Def, U	6,51E-11
Electricity, high voltage {CH}| heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal | Alloc Def, U	6,51E-11
Electricity, high voltage {CH}| treatment of digester sludge by municipal incineration, future | Alloc Def, U	0,00533
Electricity, high voltage {CH}| ethanol production from wood | Alloc Def, U	3,25E-06
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 1MW electrical, lean burn | Alloc Def, U	0,03871
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 200kW electrical, lean burn | Alloc Def, U	0,02206

[2] Natural gas, combined cycle power plants with electricity production only would most likely be installed in the future in Switzerland instead of the activity heat and power co-generation, natural gas, combined cycle power plant used in this dataset. For implementation of the dataset in ecoinvent, this activity can be changed. The difference in using one or the other is not assumed to be large for the LCIA results.

Electricity, high voltage {CH}| heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control | Alloc Def, U	0,03352
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 500kW electrical, lean burn | Alloc Def, U	0,02208
Electricity, high voltage {CH}| heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | Alloc Def, U	0,01927
Electricity, high voltage {DE}| electricity production, geothermal | Conseq, U	0,04480
Electricity, high voltage {KR}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Def, U	0,36435

Table 13 New consequential electricity market dataset for Switzerland, Variant E.

Transforming activities, new consequential electricity market, Switzerland , Variant E	Share/ kWh
Electricity, high voltage {CH}| electricity production, hydro, reservoir, alpine region | Conseq, U	0,11357
Electricity, high voltage {CH}| electricity production, hydro, run-of-river | Conseq, U	0,08944
Electricity, high voltage {CH}| electricity production, wind, <1MW turbine, onshore | Conseq, U	0,00868
Electricity, high voltage {CH}| electricity production, wind, 1-3MW turbine, onshore | Conseq, U	0,04521
Electricity, low voltage {CH}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U	0,13659
Electricity, high voltage {CH}| treatment of municipal solid waste, incineration | Alloc Def, U	0,01253
Electricity, high voltage {CH}| heat and power co-generation, biogas, gas engine | Alloc Def, U	0,04386
Electricity, high voltage {CH}| heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal, with extensive emission control | Alloc Def, U	6,51E-11
Electricity, high voltage {CH}| heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal | Alloc Def, U	6,51E-11
Electricity, high voltage {CH}| treatment of digester sludge by municipal incineration, future | Alloc Def, U	0,00533
Electricity, high voltage {CH}| ethanol production from wood | Alloc Def, U	3,25E-06
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 1MW electrical, lean burn | Alloc Def, U	0,03871
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 200kW electrical, lean burn | Alloc Def, U	0,02206
Electricity, high voltage {CH}| heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control | Alloc Def, U	0,03352
Electricity, high voltage {CH}| heat and power co-generation, natural gas, 500kW electrical, lean burn | Alloc Def, U	0,02208
Electricity, high voltage {CH}| heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | Alloc Def, U	0,01927
Electricity, high voltage {DE}| electricity production, geothermal | Conseq, U	0,04480
Electricity, high voltage {CH}| import from AT | Conseq, U	0,00793
Electricity, high voltage {CH}| import from DE | Conseq, U	0,07343
Electricity, high voltage {CH}| import from FR | Conseq, U	0,06766
Electricity, high voltage {CH}| import from IT | Conseq, U	0,03678
Electricity, high voltage {CH}| hydro, reservoir, import from France | Conseq, U	0,00836
Electricity, high voltage {CH}| hydro, run-of-river, import from France | Conseq, U	0,04366
Electricity, high voltage {CH}| nuclear, import from France | Conseq, U	0,11069
Electricity, high voltage {CH}| natural gas, import from Germany | Conseq, U	0,01434
Electricity, high voltage {CH}| wind power, import from Germany | Conseq, U	0,00150

It should be noted that the datasets are constructed using existing ecoinvent activities but is not implemented as a part of the database. No database software alteration was performed during this thesis, but should instead be done by ecoinvent software administrators.

5.4 Evaluation of suggested modelling approach using LCIA results

As mentioned in chapter 2.1.2, Life cycle impact assessment (LCIA) methods can be used as a tool to estimate the environmental impact of a products life cycle. Since the associated environmental impact of LCI data is what actually is used in LCA to evaluate a studied system, results from LCIA methods are used to give implications on what effect using the new market mixes has on LCA results, compared to status quo. Status quo is this case means using the current 'Consequential' or 'Allocation, default' market mixes.

5.4.1 Life cycle impact assessment methods

The new consequential electricity market datasets were used with the commercial LCA software Simapro v.8 and the ecoinvent v. 3.01 background database to estimate the related environmental impact. Many different impact assessment methods are currently available in Simapro v.8. For this study, the IPCC 2007 GWP, 100a (IPCC 2007) and ReCiPe 2008 (Goedkoop & Huijbregts 2012) were chosen. A deeper description of the chosen LCIA methods and their relevance for electricity production impact are presented in chapter 5.4.1.1 and chapter 5.4.1.2.

5.4.1.1 IPCC 2007 GWP, 100a

In this LCIA method, the different emissions caused by the production of 1 kWh of electricity are characterized according to their global warming potential (GWP) and aggregated in the impact category 'climate change'. The global warming potentials published by the Intergovernmental Panel on Climate Change (IPCC) are used in the method as characterization values for the greenhouse gas emissions. By using this method, LCIA results are obtained in the unit kg CO_2-eq/kWh, i.e. the various GHG emissions (converted to CO_2 equivalents) assigned to the production of 1 kWh of electricity. If the result is 1, the global warming potential would be equivalent to that of a release of 1 kg CO_2 per kWh produced. For policy makers GWP has proven a convenient measure to compare the climate impact of different emissions and subsequently different production chains. (Hischier et al. 2010) Global warming associated with greenhouse gas emissions is considered one of the most negative effects of electricity production. (Alves & Uturbey 2010) Since the GHG emissions associated with electricity production can be expected to be influenced by a change in market composition (due to change in e.g. fossil-fueled power plant utilization), it is of interest to study and compare the estimated GWP of the different electricity markets mixes.

5.4.1.2 ReCiPe 2008

ReCiPe is an LCIA method that categorizes environmental impact on a midpoint and endpoint level. The midpoint level consist of 19 different impact indicators (For full overview of the midpoint categories and indicator units, please refer to Table 2.1 in the ReCiPe 2008 report (Goedkoop & Huijbregts 2012)), which can be multiplied with a damage factor and aggregated into three endpoint categories:

Damage to human health (measured in Disability Adjusted Life Years, DALY), damage to ecosystem diversity (measured in Loss of species during a year) and damage to resource availability (measured in increased cost). (Goedkoop & Huijbregts 2012) The general representation of the ReCiPe methodology is shown in Figure 11.

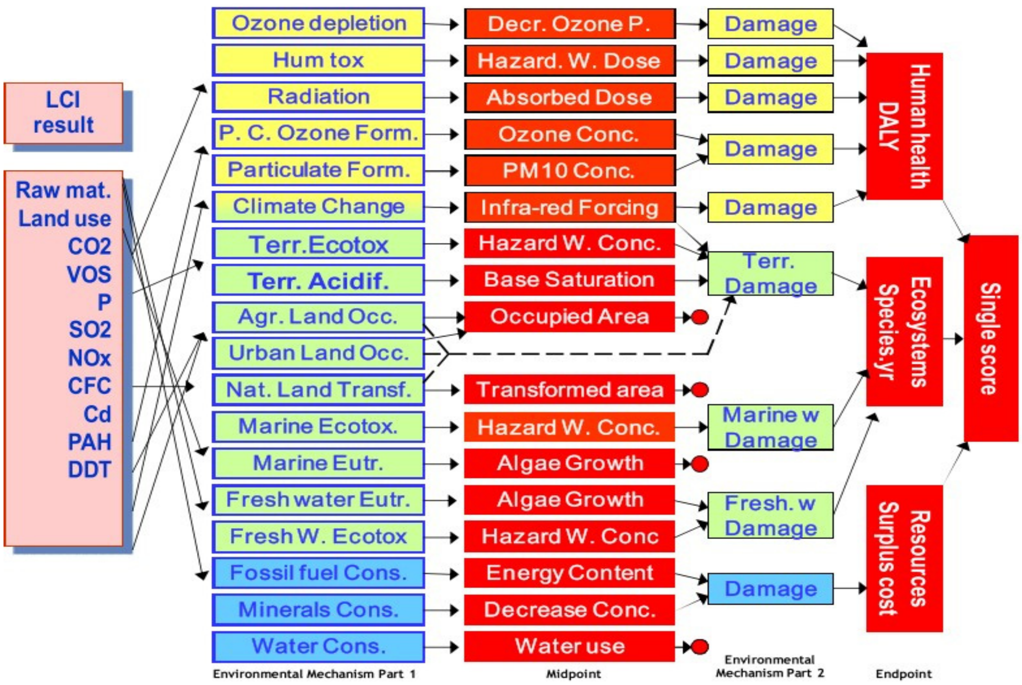


Figure 11. The general methodology of the ReCiPe. Indicator values from the LCI result analysis is represented at a midpoint level and weighted damage analysis result is represented at an endpoint level (Goedkoop & Huijbregts 2012).

Due to uncertainties in environmental mechanisms and the damage factors, value choices can be made depending on cultural preferences. The uncertainties are grouped together into three scenarios: Individualist (I,A) – Short-term, based on proven, undisputed effects; Hierarchist (H,A) - Based on intermediate time frame and decided from common policy principles; and Egalitarian (E,A) – A precautionary scenario with the longest time frame, including effects with minimum scientific proof. The (H,A) scenario can be considered the middle path to use between a scenario based on a technology salvation perspective (I,A) and the worst case scenario (E,A). The LCIA results at the endpoint level are associated with larger uncertainties than on the midpoint level since endpoint categories are categorized using weighting and contain value choices (Bare et al. 2000). Also, characterization of environmental impacts according to the method leading up to the midpoint level is consistent with the ISO 14040 standard.

Electricity supply is associated with a diversity of utilized technologies, which in turn can be assumed to cause damage through different impact categories (see Figure 11). However, not all indicators are expected to be equally influenced by electricity production and some key indicators are more important to study than others.

Terrestrial and aquatic acidification can be expected to contribute to the ecosystem damage endpoint category through precipitation of acidifying compounds (i.e. SO_2 and NO_x), originating mainly from the combustion of fossil- and biomass-fueled power plants (Dincer 2000).

When investigating the damage on human health from electricity production, particulate matter (measured in 10 µm PM diameter equivalents) formation is an interesting indicator to study since air pollution from PM emissions is considered one of the most negative effects associated with electricity production (Alves & Uturbey 2010). Particulate matter formation is divided up between primary and secondary PM formation. Primary PM formation, originating from direct emissions, causes health problems when inhaled. Secondary PM10 aerosols are formed in the air from SO_2, NH_3 and NO_X among others, also causing different health problems when inhaled (Goedkoop & Huijbregts 2012). While coal and biomass-fired power plants are associated with emissions of primary and secondary PM. Electricity from natural gas fired power plants does not form direct particulate matter let out in the flue gas, but forms secondary particle matter from NOx and NH3 in the atmosphere. (Alves & Uturbey 2010)

A change in electricity supply can be expected to affect many different impact indicators. For this reason, it is interesting to use this method to study electricity markets supplied by technologies with different market shares. For this analysis, the method ReCiPe (H/A) was used at the midpoint level. Since most countries in this study are located outside Europe, the 'World' normalization is chosen for the datasets.

6 Results and discussion of case study on selected markets

In this section, the new consequential markets are compared with status quo in chapter 6.1, along with an analysis. The LCI data result for each country is presented in 0 followed by a discussion on the inventory results in chapter 6.1.2. The results from the life cycle impact assessment are presented and analyzed in chapter 6.2. Associated indicator values results are presented and analyzed in 6.2.1 (Global warming potential), 6.2.2 (Particulate matter formation) and 6.2.3 (Terrestrial acidification). A general discussion on the implications of using the suggested approach, based on the case study results, is done in chapter 6.3.

6.1 Life cycle inventory results

The selected electricity markets modelled according to the attributional, current consequential and new, suggested consequential approach are shown in Figure 12. The numbers behind the new consequential market tiles can be found in Tables 6-13. The attributional and current consequential market tiles are based on the annual average supply volumes found in table 14-19 in Appendix III. The activities that marked with (*) are the activities that are supplying the consequential markets. How the activities included in the consequential markets were selected, is described in Table 2 in (Treyer & Bauer 2014), and the reader is referred to this table for more thorough description.

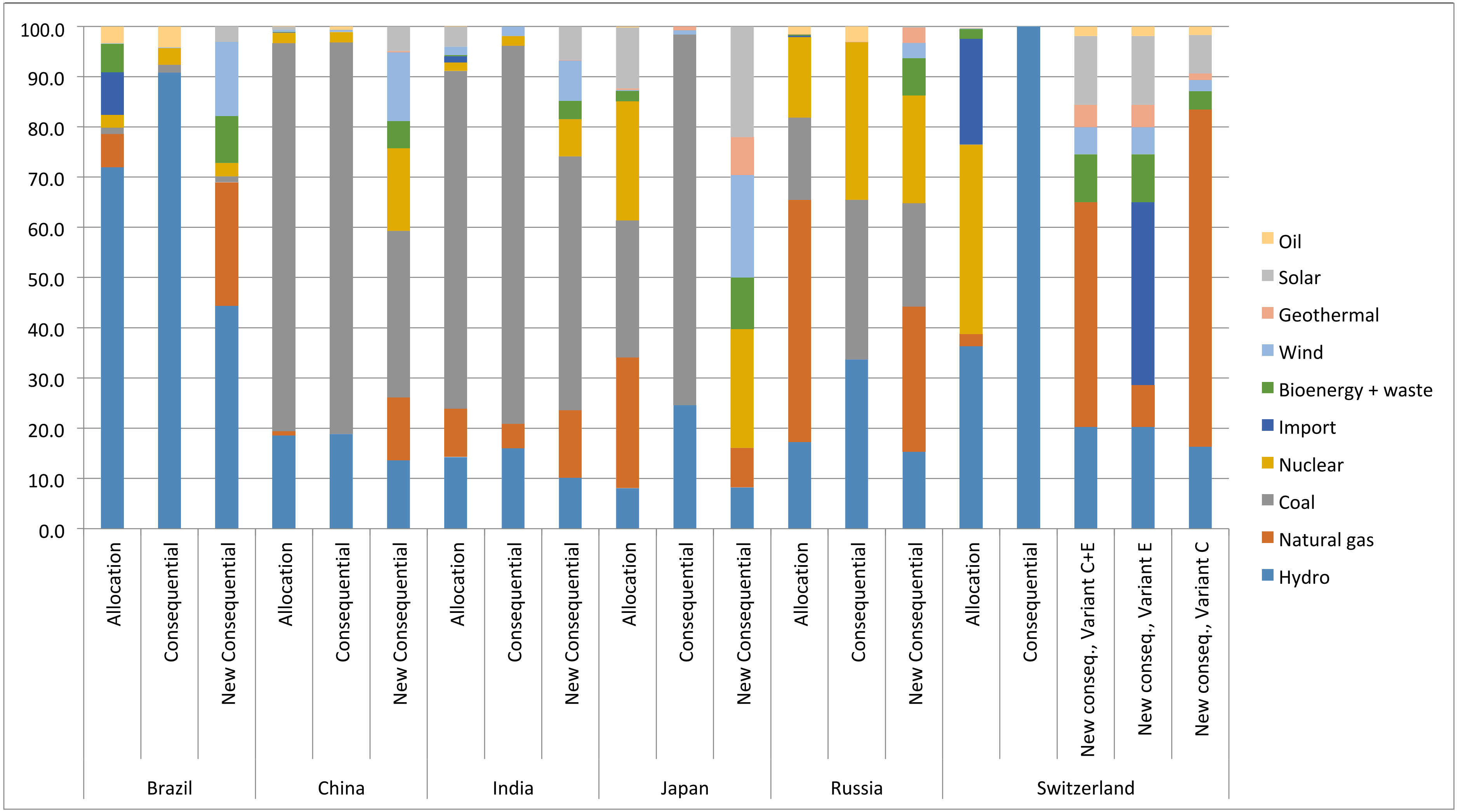


Figure 12 Electricity markets modelled according to the attributional, current consequential and new, suggested consequential approach. The 'New consequential' market mixes are based on WEO 2013, NP scenario, 2011-2035 (Brazil, China, India, Japan and Russia, and EP 2050, POM scenario, 2010-2035 (Switzerland).

6.1.1 Country-specific results

For ***Brazil***, the attributional market consist of 72 % hydro, 8.5 % imports, 6.5 % natural gas produced in conventional power plants, 5.7 % bioenergy, 3.3 % oil power plants, 2.5 % nuclear and 1.3 % coal. The current consequential market consists of almost 91 % hydro, accompanied by smaller shares of nuclear, coal, oil and wind, since imports are not considered to supply the long-term capacity addition and electricity from bioenergy is produced as by-product. Electricity produced as by-product is included in the new approach, and projected electricity from bioenergy therefore supplies the new consequential market with 9.4 %. New technologies are projected to be installed in form of 25 % natural gas CCPP, 15 % wind, 3 % solar power. The same shares of coal and nuclear as in the attributional markets is included. The additional supply from hydro is projected to be around 43 %. This development can be related to the modelled policy measure in the New Policy scenario (see Table 2. The policies and measures modelled for the power generation for selected countries in the World Energy Outlook 2013, taken from Annex B in (International Energy Agency 2013b). to increase the deployment of renewable energy sources through power auctions. According to (Alves & Uturbey 2010), the trend for the Brazilian electricity market is also projected to include more diverse sources: Concerning the Brazilian continuous exploitation of hydro power, the remaining potential is located in especially rich biomes, like the Amazonas, and is associated with the risk of power outages from water supply shortages. Balancing the electricity sector development in Brazil in accordance with environmental, social and economic sustainability goals is therefore particularly challenging and diversification of the market composition is expected.

The composition of the current consequential market and attributional market in ***China*** is quite similar (77 % coal power plants, 19 % hydro, 2.1 % nuclear and oil each), which can be related to the fact that technologies (such as natural gas CHP) that are considered constrained only supplies the attributional market with small shares. Ergo sum, the shares are calculated to be the similar in the current consequential market. China is expected to further install nuclear power to cover increase in electricity demand as a policy measure to increase to 70 to 80 GW nuclear capacity by 2020 in the New policies scenario (see Table 2). The policy measure modelled in the WEO 2013 results in an expected long-term marginal nuclear power share of almost 17 %. The current consequential modelling approach does not take this policy measure into account. The policy measure of having 200 GW of wind capacity and 30 GW of bioenergy capacity by 2020 (see Table 2) results in a long-term marginal share of 13.6 % from wind sources and 5.4 % from biomass (no waste supplied this category for China). The larger deployment of the new technology natural gas CCPP and renewables can also be related to the modelled assumption that China has CO2 pricing in 2020.

For ***India***, the same reasoning can be made as for China concerning the composition of the attributional and consequential electricity market since they are similar: The attributional market consist of 67 % coal, 14 % hydro and 9.5 % natural gas. Wind, imports and nuclear supply with ca 1.7 % each. In the current consequential market, coal power plants have a share of ca 75 % and hydro 16 %. There is still supply for natural gas (4.8 %) since the attributional market already is supplied by both conventional and combined cycle power plants. The remaining capacity consists of 2 % nuclear and wind each since imports are considered constrained.

In the New policies scenario, policies and targets for support for renewable energy sources is modelled (see Table 2), which can be correlated to the larger share of renewable energy sources in the new consequential market: 10 % hydro, 6.5 % solar and 8 % wind power. There is also an additional supply from natural gas power plants forecasted of 14.5 %, which is modelled with a combined cycle power plant dataset.

The attributional electricity market for ***Japan*** is relatively diversified with large contribution from non-renewable technologies: nuclear (24 %), coal (29 %), gas (24 %) and oil (12 %). Since most of these technologies are considered constrained (nuclear as well due to expected phase-out), the build-margin is calculated to consist of 74 % coal power and 26 % hydro power according to the ecoinvent modelling approach. The projected build-margin however, modelled with increased support for renewables generation (Table 2), consist of many fundamentally different technologies with large supply shares from mainly renewable energy sources (22 % solar, 7.5 % geothermal, 20.5 % wind, 10 % biomass + waste, and 8 % hydro). Nuclear is projected to contribute with 24 % to the long-term margin, and is not subject to phase-out, but nuclear power plants instead have a limited lifetime in the NPS (50 year from plants built after 1990). Coal and oil is not supplying the long-term margin, but natural gas CCPP supplies with 8 %. It should be noted that according to (International Energy Agency 2013b), a possible policy decision concerning a phase-out of nuclear is not yet reached, but might be in the future.

The ***Russian*** attributional market is being supplied by 42 % natural gas CHP (along with 17.3 % hydro, 16 % nuclear and 16% coal. Oil supplies with 1.6 %), which is considered constrained as by-product according to the status quo consequential modelling approach. This results in a current consequential market supplied by one third each of nuclear, coal and hydro power (oil supplies with 3 %). Continued installation of natural gas power plants, modelled state support for nuclear and hydro power, and a support mechanism for non-hydro renewable energy sources after 2014 (see Table 2) results in a new consequential market with 29 % contribution from natural gas and 3.1 % geothermal, 7.4 % biomass + waste and 3.1 % wind. The natural gas is modelled with combined cycle power plant datasets, with and without CHP, since it can be assumed that the heat demand in Russia allows for a partially unconstrained supply of electricity produced in CHP plants.

The current consequential market for ***Switzerland*** consist of almost 100 % hydro power since nuclear is modelled as constrained in due to political decision to inhibit further investments in nuclear power (Prognos AG 2012), imports are not expected to unconstrained react to a long-term change in demand, since imports depend on the overall market situation in the interconnected countries. Natural gas, wood chips and biogas are fuelling heat- and power plants, why these technologies are classified as by-products and not expected to react to price-signals for electricity. Technologies using waste, such as domestic waste incineration, is not expected to be able to react to a price signal for electricity but is rather generating electricity depending on when there is supply of waste.

Depending on supply variant, the internal shares in the new consequential mixes are projected to differ as a result of different political measures. Natural gas-fuelled combined cycle power plants are projected to be installed. Biogas and wood fuelled power plants are projected to supply the long-term marginal mix. Geothermal does not yet supply the attributional electricity market is included as new technology in the new conseq. mix. Wind and hydro is still supplying the new consequential market but with new shares:

Wind is projected to increase and hydro will supply with ca 20 % in all variants. Photovoltaic is increasing in supply in the new consequential mixes compared with small shares in the attributional market. The 'Fossil, central' variant (variant C), has the largest projected marginal share of natural gas CCPP of 67 % and 7.6 % photovoltaic along with smaller shares of geothermal, bioenergy+waste and wind. The 'Fossil central + renewables' variant (variant C+E) consists of 50 % natural gas CCPP, 13.5 % solar, 4.5 % wind, 5.5 % geothermal and 9.5 % biomass + waste. For the supply scenario 'Renewables+Imports', new trade agreements are assumed to be made to allow the imports to increase and supply the long-term marginal mix with 36.5 %. Besides for the imports, the 'renewables and imports' variant (variant E) consist of the same shares as variant C+E.

6.1.2 Discussion on inventory results

Generally, the compositions of the new consequential electricity markets are more diverse when it comes to types of supplying technologies compared to status quo. The new consequential approach results in datasets which are supplied by the same technologies as the attributional markets with a few exceptions where supplying technologies are considered outdated nor new, i.e. not yet supply the attributional market such as Geothermal power plants in Switzerland. The new shares however are different from the current consequential markets. The main reason for the difference between the new and current consequential markets is that the projections are based on country-specific conditions and constraints revolving the power sector, such as policy measures supporting or limiting certain technologies. The magnitude of the identified shortcomings found in chapter 3.4 (concerning estimation of future competitiveness of specific technology categories more or less without considering market specific conditions and calculation long-term marginal shares of the unconstrained suppliers based on current supply volumes), is clearly displayed when comparing current and new consequential mixes. The constraints that are modelled in the current consequential system model in ecoinvent are indeed discriminating against technologies that are likely to be installed in the future in the studied countries. The results are in line with the observations made by (Treyer & Bauer 2014).

Electricity from CHP plants is considered constrained in the current consequential modelling approach by the product classification 'by-product'. This modelling constraint was identified as a shortcoming (see chapter 3.4). In the suggested approach, electricity from such technologies is projected to some extent, although the largest part of the new power plants will be from combined cycle power plants. That CHP plants could be a part of the long-term marginal supply is supported by the results in (Mathiesen et al. 2009). For Switzerland for example, a small addition of CHP plants are projected until 2035, but the larger part of the additional gas power plants will be combined cycle power plants. For Russia, combined cycle power plants has been assumed for the new consequential datasets, but CHP plants could also be installed since the large heat demand could allow for electricity from CHP plants not to be constrained as by-product.

6.2 Life cycle impact assessment results

In this chapter, the life cycle impact assessment results using the methods IPCC 2007 GWP, 100a, and ReCiPe 2008 are presented. The results from using the new consequential modelling approach are analyzed and discussed with respect to the environmental impact of the current consequential supply mixes and the attributional supply mixes for the respective electricity markets.

Not all indicators are analyzed due to time constraints, but indicators that play a main role concerning the environmental impact of electricity production (see chapter 5.4.1.1 and 5.4.1.2) are presented and analyzed: climate change, particulate matter formation, and terrestrial acidification. A further justification for choosing these indicators is that they are dominated by fossil fuels, which is still the energy carriers that currently dominate the global power sector, as well as in 2035 (see Figure 3) The modelled indicator values for all impact categories and markets can be found in Appendix III.

6.2.1 Climate change

The global warming potential per kWh associated with the projected marginal mixes compared with the consequential and attributional markets can be seen in Figure 12.

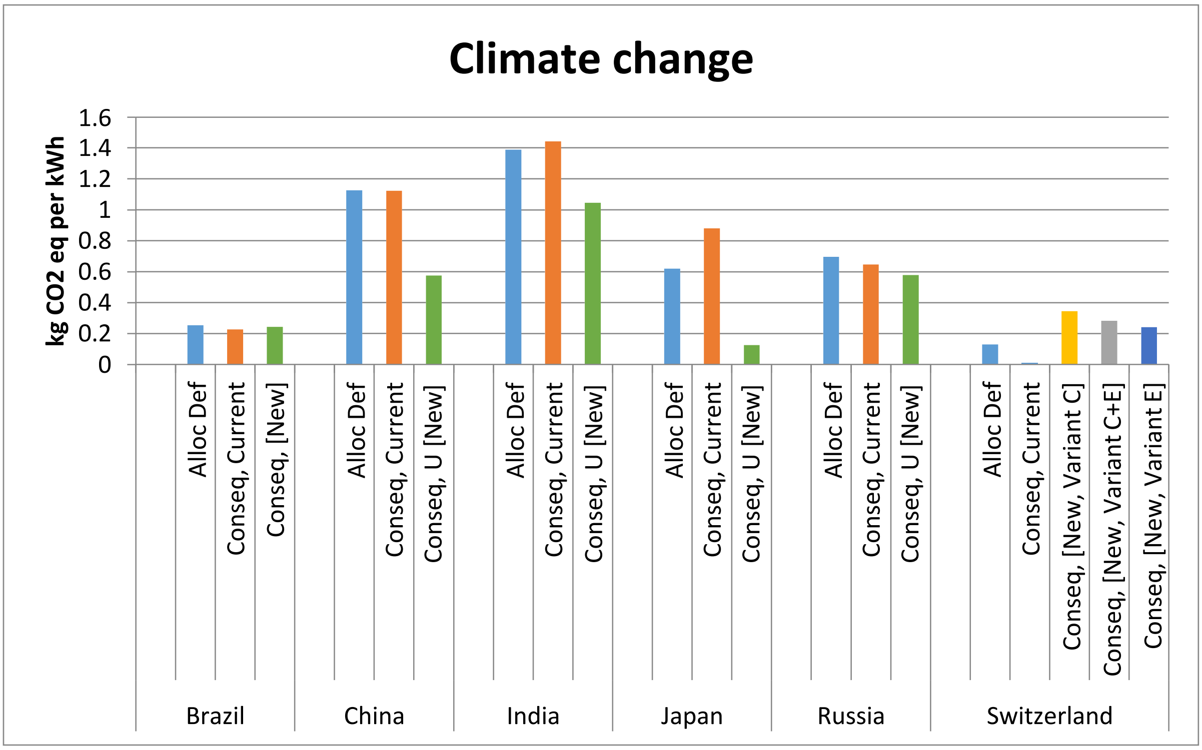


Figure 13 Climate change (kg CO2-eq/kWh) associated with attributional, current consequential and new consequential electricity markets.

6.2.1.1 Country-specific results

The global warming potential (GWP) of all ***Brazilian*** mixes is generally stable around 0.2 kg CO2-eq/kWh. Even though a large share of hydro power is replaced with fossil-fueled power plants, GWP associated with the projected market mix shows a low increase, compared with the current consequential and attributional markets. This can be explained by the decomposition of submerged organic matter caused by the utilization of hydro power and the GHG emissions associated with the natural gas CCPP generation and the small share of conventional coal PP generation (CO_2, CH_4 and N_2O). These results are confirmed in literature (Alves & Uturbey 2010).

For ***China***, the modelled deployment of supporting measures for renewable energy sources, further natural gas CHP and nuclear power installations, and the decrease of coal PP contribution from 78% to 33 % of the market (also related to CO2 taxes modelled in the NPS), can be correlated to a decrease in GWP per kWh down to nearly half compared to current consequential market (from 1.12 to 0.58 kg CO2-eq/kWh). Lower GWP per kWh could be expected for China in the long-term marginal mix than is displayed in this LCIA results: The use of current datasets for future installations, with current country-average efficiencies included does not take technology development to reduce greenhouse gas emissions into account.

For ***India***, the decrease in GWP per kWh in the new consequential mix compared to the current consequential mix (from 1.4 to 1.05 kg CO2-eq/kWh). Fossil fueled technologies will still supply the long-term marginal mix with 65 %, which can explain the still (compared to the other markets) high impact indicator value. As for China, another explanation is the use of current with current country-average efficiencies. Lower GWP per kWh could be expected for India in the long-term marginal mix.

The build-margin for ***Japan*** according to the current consequential modelling approach is associated with larger GWP per kWh that the attributional market (0.9 comp. to 0.6 kg CO2-eq/kWh) which can be related to the contribution of 74 % coal. The efficiency of the Japanese coal-fired power plants is high (42 % in 2008) compared to the rest of the world (International Energy Agency 2008), why the absolute GWP per kWh (current consequential market) is 0.5 kg CO2-eq/kWh lower than e.g. the Indian consequential market, which is also is supplied by 75 % coal. A large decrease can be seen between current and new consequential markets: 0.8 to 0.12 kg CO2-eq/kWh. This has its explanation in the large deployment of nuclear and renewables in the NPS. However, if a policy decision is implemented to phase-out nuclear sooner than modelled in the NPS, the choice of replacing source would probably involve a technology with larger GWP per kWh associated with it, e.g. natural gas CCPP, since a build-marginal of solely renewable energy technologies in Japan 2035 can be seen as too ambitious.

The ***Russian*** new consequential market does not differ significantly compared to status quo. The deployment of natural gas in the projected marginal supply would perhaps have resulted in a lower GWP per kWh if the average efficiency of Russian natural gas power plants were not below average (International Energy Agency 2008), which is included in the current datasets. A large reduction potential in greenhouse gas emissions is eminent for new natural gas plant installations.

Switzerland has currently a low GHG per kWh in the attributional mix compared to the other markets due to large shares of nuclear and hydro power. A clear underestimation of the GWP of the current consequential mix (0.0099 kg CO2-eq/kWh) can be seen compared to the GWP of any of the new scenarios modelled. This result is expected since for the current Swiss consequential market more or less only hydro power, with some wind and PV, are considered unconstrained technologies. Depending on supply variants, the GWP per kWh is varying between 0.34 (Fossil central) and 0.24 kg CO2-eq/kWh (Renewables+imports), which is still low or equal compared to the rest of projected marginal mixes. Although, the projected marginal mixes are still associated with higher GWP per kWh than the current average mix, and looking at a longer time frame than 2035, the associated impact could be even larger if the same trends in installed sources are followed.

6.2.1.2 Discussion of the GWP results

Generally, there is a difference in GWP per kWh comparing the new consequential mixes with status quo. Brazil is the only geography where the choice of mix does not matter concerning GWP per kWh. As expected, the largest decreases in global warming contribution from the new consequential mixes compared to status quo, are for those markets that currently have a large fossil plant fleet (for the new consequential markets this mainly means coal and natural gas PP, oil PP is not part of the new consequential markets in the studied countries). The reduction is mostly related to the projected contribution of electricity from combined cycle plants, with and without CHP, (mainly natural gas and biomass fueled), and a larger contribution from different renewable sources, which are associated with less greenhouse gas emission than coal and oil fired power plants.

When taking average efficiencies for fossil fueled power plants in different countries into account, the difference in GWP between market mixes can further be explained: The efficiencies of electricity production from ***coal-fired power plants*** depend on the quality of the coal used, the technology implemented and the operating conditions of the plant. The average efficiency used in the datasets is widespread among different countries, ranging from 23.8 % in Russia to 36 % in Japan. The reason for the low average efficiency of coal-fired power plants in India (23.9%) is most likely the use of coal with high ash content in subcritical power plants along with the utilization of coal-fired plants for peak production (International Energy Agency 2008). The average efficiency of coal-fired power plants in the dataset for China is 35.7 %, and Brazil 33.2 % (Treyer & Bauer 2013). The relatively high indicator values for the Indian markets can be explained with the low efficiency value: comparing the current consequential mix for India with the Chinese attributional market, which has similar market compositions, the indicator value differs from 1.45 for India to 1.1 kg CO2-eq/kWh for China. The flue gas efficiency of coal PP has significant impact on how much CO_2 (and other related emissions) are emitted in each country. According to (Treyer & Bauer 2013), the coal PP datasets for Brazil, China and Japan include CO_2 emissions of 0.95-1.05 kg/kWh, while India and Russia has emission values around 1.45 kg/kWh, which is an increase compared to the other countries with almost 50 %. These values can explain why India has the largest GWP/kWh for all markets and add to the explanation why the new consequential market for Russia and China are associated with similar indicator values even though China has a larger share of coal PP.

Natural gas-fired power plants are generally associated with lower GWP per kWh than coal-fired PP, but have increased in market contribution in recent years and the efficiency has increased significantly in many countries. In OECD countries, the average increase in efficiency 2001-2005 was almost 8 % on average, while non-OECD showed an increase of 2 %. The deployment of high efficiency combined-cycle gas turbine plants (CCGT) in OECD countries, which can have an efficiency of up to 60 %, has been the main reason for this development. However, in Russia and India the increased average efficiency is also associated with the installation of new, high-efficient CCGT power plants (International Energy Agency 2013b). In the current datasets which were used in creating the new consequential datasets, the efficiencies are 53 % (India) and 37 % (Russia). The efficiencies for the other markets are Brazil (45 %), China (39 %) and Switzerland (53 %). Generally, countries with a high share of natural gas power plant have a higher overall efficiency of fossil-fueled electricity production. One exception is Russia, where the low gas-fired plant efficiency is low and thus an overall efficiency below the global average (International Energy Agency 2008). The low efficiency of the Russian natural gas power plants compared to the other countries, can explain the small decrease in indicator values in the new consequential mix, even with a large shift from coal to gas between the current and new consequential mixes.

As noted in previous chapter, the performance assessed in this study only takes currently installed technologies into account using datasets of technologies that already exist on the market. The plants that will be installed in the future will probably be more modern, and thus associated with higher efficiency and better environmental performance. Russia, China and India show a large potential for improving the efficiency of electricity production since China and India has a large share of coal-fueled power plant and Russia a low efficiency on natural gas plants installed (International Energy Agency 2008). The projected average efficiency of the coal power plant fleet in China and India 2035 compared to 2011 in the WEO 2013 New Policy Scenario (along with EU and USA) is shows in Figure 14.

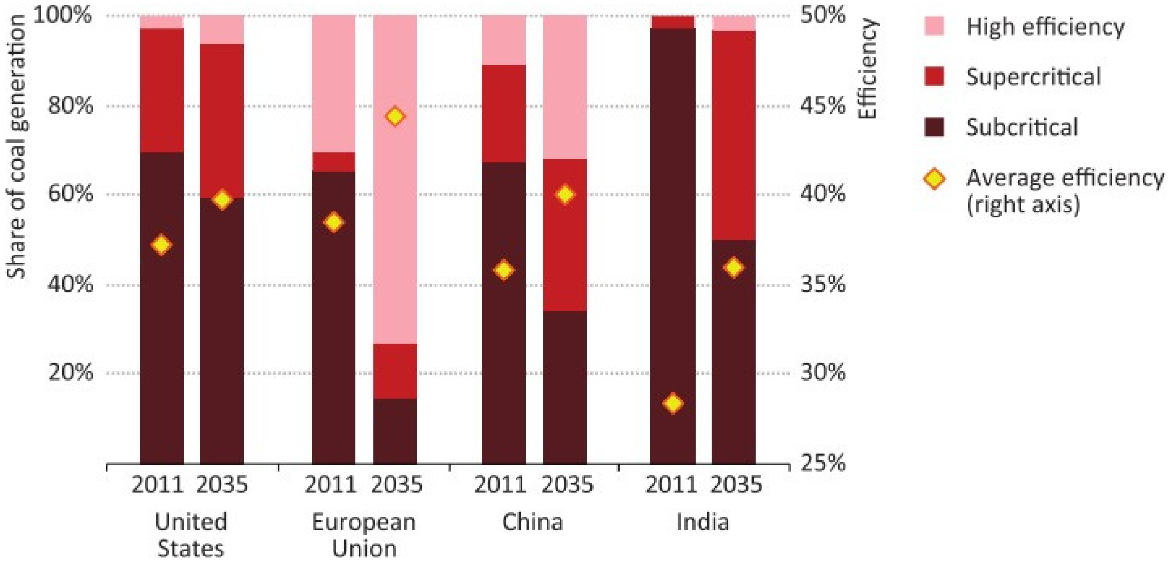


Figure 14 Share of coal-based electricity generation by technology and average efficiency for selected markets in the new policy scenario (International Energy Agency 2013b).

This gives an idea of the difference in environmental performance of coal- and natural gas-fired power plants in the different countries and also implies that the GWP associated with electricity supply depends on technology level of the fossil power plants. For this thesis, no new datasets were made, but using the above projected efficiencies for the coal power plant fleet in India and China could give more appropriate GWP indicator results for the consequential electricity supply in these countries. This would also hold true for other impact indicators dominated by fossil fuels.

6.2.2 Particulate matter formation

As mentioned in 5.4.1.2, SO_2, NH_3 and NO_X emissions along with dust, soil, and metal particles and so on, are the main contributors to particulate matter formation (PM). The emissions can mainly be related to electricity production from oil-, coal-, natural gas- and biomass-fired power plants. Coal, oil and biomass power plants are associated with primary and secondary PM formation and natural gas power plants only with secondary PM formation (only SO_2, NH_3 and NO_X). The resulting particulate matter (PM) formation values are presented in Figure 15.

Basically, the trend of this impact indicator follows a similar trend to that of GWP since both are dominated by fossil fuels. Thus, the analysis has many similar correlations between indicator values and contributing technologies. Essentially, the markets with the largest PM formation per kWh are the market with large market shares of coal fired power plants (compare with Figure 12). A larger contribution from biomass fired power plants can also be related to elevated indicator values in the new consequential markets compared to status quo.

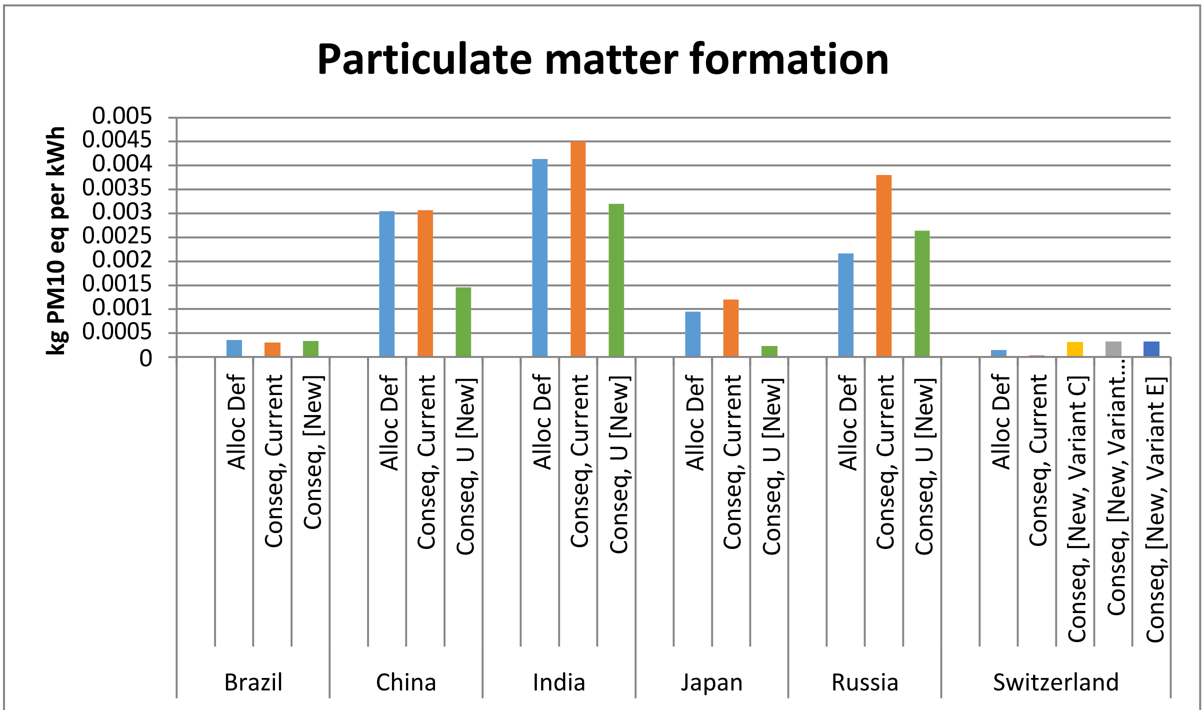


Figure 15 Particulate matter formation (kg PM10 eq/kWh) associated with the attributional markets, current consequential markets and consequential markets using suggested approach.

6.2.2.1 *Country-specific results*

The 3 markets for *Brazil* are associated with low PM formation (0.0003 kg PM10-eq/kWh). The projected decommissioning of oil power plants, and increase in natural gas can explain why the indicator is similar in the new consequential mix compared to status quo.). Using biomass co-generation from e.g. sugar cane waste also contributes to nitrogen oxide emissions that has large local impact.

The predicted reduction of contribution from coal in *China* from 78 % to 33 % per kWh and an increase of natural gas fired combined cycle plants from 2 % to 12 % per kWh in the new consequential market compared to the current consequential market can be correlated to an associated PM reduction from emissions to air with 51 % per kWh.

India and *Russia* have seemingly similar decrease in PM formation (-0.0013 and -0.0012 kg PM10-eq per kWh) when comparing new and current consequential mixes, while the change in contribution from coal-fired power plants is bigger for the Indian market than for the Russian (-25% and -11 %, respectively).

Japan shows a similar absolute decrease moving from current to new consequential dataset (-0.001 kg PM10-eq/kWh) and has a very similar current consequential mix to India and China, but no coal at all predicted in the new consequential dataset. This suggests that a reduction of coal in Japan of 74 % is associated with the same PM formation reduction as a reduction of coal of 25 % in India and 45 % in China (plus a small PM addition of 0.0002 kg PM10-eq/kWh from new supplying technologies such as Biomass or secondary PM formation originating from natural gas-fired power plants).

Switzerland shows a low, stable contribution to PM formation per kWh, independent on supply variant chosen. The results are similar to those of the Brazilian markets at 0.0003 kg PM-eq/kWh.

6.2.2.2 *Discussion of the PM formation results*

As mentioned in the discussion on GWP indicator values, the difference in PM formation (between current and new consequential markets) compared to difference in market shares of PM sources is related to the country-average energy efficiency of the coal, natural and biomass fueled power plants. Further, since direct PM emissions consist of larger particles that can be filtered away through different flue gas treatment steps, the PM filter technologies that are installed for coal PP is decisive for the country-average emissions of PM formation. The flue gas treatment technologies installed varies between countries depending on the national regulations concerning PM emission limits.

In (Treyer & Bauer 2013) Table 1, the main emission parameters for PM (<2.5 µm) in coal power plants for the electricity markets in ecoinvent are depicted. The parameters (SO_2, NO_x, particulates <2.5 µm) can be correlated to the country-specific flue gas treatment efficiencies of coal PP: Russia has the largest emissions per kWh of NO_x (5.03E-03 kg/kWh) and CO_2 (1.445 kg/kWh) of all the countries currently available in ecoinvent v.3 and the largest emissions of SO_2 (9.02E-03 kg/kWh) of the studied countries. When comparing the Russian current consequential mix with the Japanese attributional mix, which has a similar composition, the impact of the difference in current country-average efficiencies can be displayed: the PM formation in the Russian new consequential market is almost 3 times as high (0.0009 compared to 0.0028 kg PM10-eq/kWh). This can also explain the high PM values for Russia in the new consequential market, despite a small market share of coal (20 %) compared to India and China where the SO_2 and NO_x emission values are slightly lower and the new market share goes up towards 50 %. However, the emissions of particulates (<2.5 µm) in China and India is the largest for the studied countries (4.12E-03 kg/kWh) compared to the rest of the studied countries with values around 1.6-1.9E-03 kg/kWh. The low filter efficiency concerning these particulates for China and India has a strong correlation to the new consequential PM indicator values, both direct PM emissions from the stack and the formation of secondary PM formed in the atmosphere.

Due to the use of current datasets, with current country-average efficiencies, it can be assumed that the future installation of power plants will consist of modern plants with high efficiency in those countries with low efficiencies today, such as India, China and Russia. The flue gas efficiency will most likely be subject to further regulations as the PM emissions has large local health impact, especially in densely populated countries, like China and Russia.

6.2.3 Terrestrial acidification

As mentioned in chapter 5.4.1.2, terrestrial acidification is mainly caused by deposit of nitrogen and sulfur in acidifying form, like NO_X, NH_3 and SO_X. The indicator values for terrestrial acidification are dominated by the same electricity sources as global warming potential and particulate matter formation. The values can be seen in Figure 16. The trend in values is essentially the same for the different markets and approaches as for the other indicators dominated by fossil fuels. The explanation of results of the new consequential mixes compared to status quo can thus be made with a similar analysis considering market composition and country-average energy and flue gas filtering efficiency (SO_2 and NO_X removal from the combustion gases) of fossil power plants as for particulate matter formation and GWP (see chapter 6.2.1 and 6.2.2).

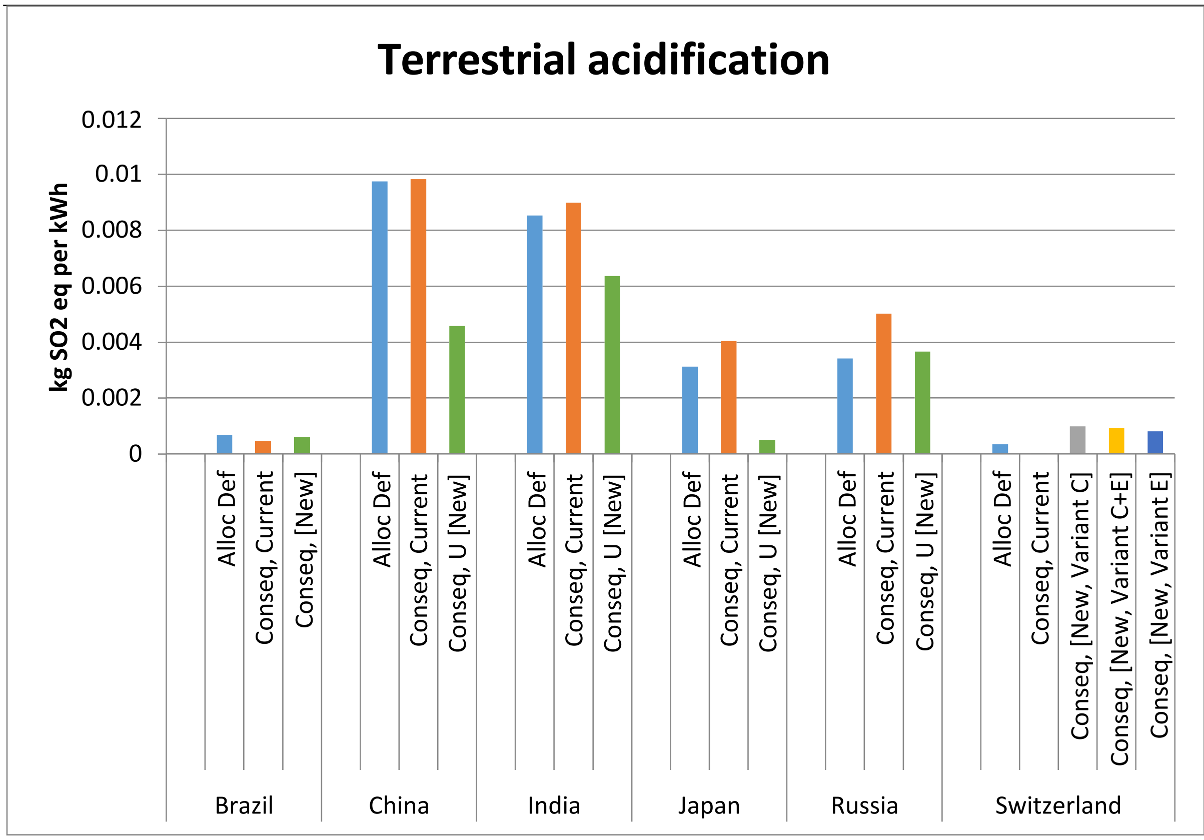


Figure 16 Terrestrial acidification (kg S02 eq/kWh) associated with the attributional markets, current consequential markets and consequential markets using suggested approach.

Since the emissions of SO2 mainly has coal and oil-fired power plants as source, the countries with large contribution of coal in the attributional and current consequential markets, show the largest decrease compared to the new consequential markets, as for PM formation and GWP. The new consequential mixes of Brazil, Japan and Switzerland are associated with low indicator values for this reason. When comparing new and current consequential mixes, China shows a change in kg SO2 eq/kWh -53%, India -29%, Japan -88%, and Russia -27%.

6.3 Discussion of LCI and LCIA results from the case study

The implications of applying the suggested approach have been discussed in detail in the sections above (see chapters 6.1.2, 6.2.1.2 and 6.2.2.2). The general implications that can be drawn from the case study and a widening of perspective are presented in this subchapter.

The new, suggested approach overcomes current shortcomings for modelling of consequential electricity supply (that has been identified in chapter 3.4): Electricity produced as by-product, like natural gas CCPP with CHP in Russia and wood chips CHP plants; The markets are more diversified and are being supplied by more fundamentally different technologies, since technologies are now included in the long-term marginal supply based on market-specific conditions and constraints (instead of a general technology classification for most markets).

New technologies that are not supplying the current consequential markets, like natural gas CCPP and geothermal, are now present in the new consequential markets. Climate and energy policies are explicitly modelled for each new consequential market and when comparing the current and new consequential mixes, it is eminent that modelling support of renewables or prolonged lifetime for nuclear power plants etc., has a large influence on the environmental impact of long-term marginal supply for China, India, Japan, Russia and Switzerland.

The results from case study gives the implication that using the attributional markets or the current consequential markets as background LCI data for cLCA studies may result in misleading decision support. For Japan, for example, the new consequential mix is associated with less GWP than the attributional while the current consequential mix is associated with larger GWP. If a decision to place a production, for which electricity is considered a hot-spot, depends on the expected long-term environmental impact of the production, using the new electricity markets would imply a considerably smaller environmental impact per kWh than today. However, using the current consequential electricity market for Japan would yield a larger environmental burden and may in worst case signalize to place production elsewhere.

It can be assumed that the studied countries, with a large projected fleet of fossil power plants and relatively low current average efficiency (energy and flue gas), will install more efficient plants it the future. This is also forecasted in the World Energy Outlook for India and China (see Figure 14). Since the current average efficiency is used in the approach, the environmental impact connected to fossil fuels will most likely be lower for the fossil dominated markets in the future than indicated in the results from the performed case study. E.g. if a country like India would instead be modelled with a dataset of a modern coal or natural gas CCPP run at optimal conditions (e.g. datasets for Germany), the impact indicators would better represent future operating conditions.

It is uncertain if and how official nation-wide forecasts would diverge compared to status quo for the rest of the 71 electricity markets in ecoinvent that were not a part of the study. How extensively the shortcomings act upon the modeling of each consequential electricity market will most probably differ from market to market, due to country-specific conditions for producing electricity in a long-term perspective (e.g. resource availability) and differing energy strategies to supply the future demand for electricity. However, a reasonable assumption is that the current shortcomings in the consequential modelling approach, resulting in exclusion of new technologies, electricity produced in CHP plants and disregard of market-specific promotion and/or limitation of specific technologies in a long-term perspective etc., will give rise to somewhat irrelevant long-term, marginal market composition for other electricity markets in ecoinvent.

7 Limitations and uncertainties in the suggested modelling approach

In this chapter, the identified limitations in the approach and the correlated uncertainties in the results are discussed. The choice of which approach to apply to ecoinvent was discussed in 4.1 and the LCI and LCIA results from using the approach for selected markets was discussed in 6.1, 6.2 and 6.3, why these topics are not included in this section.

For the identified shortcomings in this thesis, some has been addressed: shortcomings concerning inclusion of new technologies (not all), possibility of including electricity produced as by-product and modelling market shares determined by assumptions on future costs of energy carriers. There are still shortcomings that the approach did not overcome and limitations imbedded in the suggested approach itself. These are presented and discussed in the subchapters below.

7.1 Remaining current ecoinvent shortcomings

Use of datasets valid for the reference year 2008

In the suggested approach, only datasets covering existing technologies are used when implementing the forecasted electricity supply into ecoinvent. This means that only technologies that are currently supplying the attributional markets are included, and no new technologies that are expected to supply the consequential markets in the future are included. New technologies could include tidal- and wave power, stationary fuel cells, and implementation of carbon capture and storage (CCS) technologies. Concentrating solar power (CSP) is a new technology projected in the WEO 2013, but no dataset for this technology is currently available in ecoinvent v.3.01, why the supply volume was aggregated with PV. Further, the used datasets include current country-average efficiencies regarding energy and flue gas cleaning, which can be expected to change on a long-term basis as a result of implementation of modern power plants, especially fossil and biomass based power plants in rapidly growing markets with large efficiency improvement potential, such as India and Russia. Such development can have a large influence on impact indicators dominated by fossil fuels, which can be seen when comparing markets using modern plants (Japan, Switzerland) to countries with low average efficiency in their fossil power plant datasets (e.g. India).

Only one scenario and time-frame per market

Still only one scenario can be modelled for each market, even though it is recommended to use different scenarios of the energy sector when performing a cLCA to reduce the uncertainties inherently imbedded in future development. The user basically has to accept the underlying assumptions and estimations of the forecasted data. Even though the demand and supply scenario that lay as basis for the data can be considered the most accepted or probable outcome of all scenarios, it is still possible that new policy measures, external events and technology development etc. will change the power market situation in many countries and the forecasts change accordingly. The implications of using different scenarios on LCA case studies can be seen when looking at the environmental impact associated with the three different supply variants used in the Swiss forecasts.

Handling future electricity market boundaries

It is not unlikely that imports become more and more important for the rest of the markets in Europe due to the projected installation of stochastic energy sources, such as wind and solar, with increase in trade and transmission over the country borders needed to handle an increase in fluctuating supply. For markets in regions with an interconnected electricity grid and a projected overall change in the installed power plant fleet, import origin and volumes on a long-term basis need to be kept up-to-date to reflect the forecasted trade. Such arguments of course reflects the how electricity supply is defined in ecoinvent. The use of an average mix for a whole interconnected grid area could be more suitable. E.g., it could further be argued that a single market could make sense to use for Europe in the future. This feature is not available in the v.3.01 of ecoinvent, and also not provided by the suggested approach.

7.2 Additional limitations from suggested approach

Determining the future market shares within a technology category

According to the suggested approach, the included technologies within the same "technology category", i.e. utilizing the same energy carrier, are assumed to be installed with the same internal market shares as today. It could, in some cases, be expected that technologies will grow with a faster rate than the others within a category if they are considered more competitive, and vice versa. For example, it might be expected that offshore wind power plants in Brazil will grow with an increased growth rate than in the attributional market in ecoinvent, where onshore wind power plants has the largest market share. No complementary approach is suggested in this study to adjust these internal market shares. This is due to the fact that such decisions need to be supported by more detailed market information than given in the selected projections, in order to avoid further uncertainties in the results.

8 Conclusions and suggestions for future work

In this section, the conclusions from the previous sections are presented in chapter 8.1 and suggestions for the work can be continued in the future are presented in chapter 8.2.

8.1 Conclusions

Currently no single generally accepted methodology exists for modelling electricity supply in cLCA. The used approaches range from simplified approaches where a single or a few affected technologies are identified, to dynamic energy system analysis models using economic equilibrium modelling. Findings in literature recommend to use dynamic equilibrium models taking key parameters in the energy sector into account.

There are limitations in the approach to model long-term, marginal electricity markets in ecoinvent v. 3.01: only technologies currently supplying the attributional electricity markets are used for modelling future additional capacity installations, which also includes no development in energy or flue gas efficiency for future installations taken into account; electricity produced as by-product is considered fully constrained; technology level classification is made almost exclusively without taking market-specific conditions into account, such technology development, resource availability, policy measures etc; the consequential market shares are calculated based on the supply volumes for the attributional markets, along with no possibility to model consequential markets based on different future supply and demand scenarios, nor depending on time frame of the assessment.

A method using official power supply forecasts can be used to as a first step towards overcoming the current ecoinvent shortcomings by providing relevant long-term marginal data. Manual matching with existing transforming activities can be used to create new consequential datasets. The datasets could be implemented in the ecoinvent software structure as future second step towards supplying relevant LCI background data for consequential LCI studies.

For selected markets, the suggested approach yields more realistic market shares of specific technologies and significant change in impact indicator values, such as GWP, PM formation and terrestrial acidification. Using attributional or the current consequential markets in change oriented LCAs could provide misleading decision support.

There are limitations connected to the suggested method concerning only using current datasets for future technologies, only providing one demand and supply scenario per market for a specific time horizon, basing marginal market shares of technologies in a technology category on attributional market shares, and not allowing for change of suitability for geographical market delimitation for interconnected grids, e.g. a future single dataset for Europe.

There are clear benefits of using the new suggested approach for consequential electricity markets, compared to the current modelling approach. The added knowledge overweighs the uncertainties in the results. The more relevant information on consequences generated by the new approach supports more efficient decision making for LCA practitioners that use the consequential version of ecoinvent.

8.2 Future work

- Before the start of this thesis, ecoinvent already started investigating how to improve the consequential mixes is practice, meaning the existing software and framework. The scope investigated how to model relevant markets, but not ecoinvent software changes, why such implementations are left as future work for ecoinvent software administrators.

- A possibility for future work is to investigate if the suggested approach is relevant to use for other products in ecoinvent, where the modelled demand and supply scenarios are available as official projections. Markets for other energy carriers for which several suppliers interact and contribute, e.g. the oil market, for which projections are available in the World Energy Outlook 2013, could be an option for investigation.

- Another future possibility for improving the consequential modelling in ecoinvent is to provide data based on more modelled scenarios and time frame for each market. A user could use different scenarios to get a perspective on how different supply and demand scenarios for electricity could influence the result. E.g. by presenting LCA results based on a few selected fundamentally different power market scenarios, such as the three scenarios in the WEO 2013 (CPS, NPS and 450 S), the range of how the LCA results could possibly differ depending on future developments could be stressed.

- As a vision, the possibility of implementing economic equilibrium models into the ecoinvent software structure could be considered and investigated. The complexity of such a model environment makes the integration into the ecoinvent system model interface practically challenging. However, building up a new energy system model for each environmental assessment, would provide the user with the ability of matching the assumptions in the model to the purpose of the study for decisions that are large enough to affect the defining parameters of the energy system. In such a case, the database would not be limited to only providing background process data for small-scale decisions concerning change in electricity demand, but also be able to model large-scale decisions that changes the overall electricity market situation. Implementing economic equilibrium models is a vision but (Weidema et al. 2013) stated economic equilibrium modelling environment as a possible future extension of the consequential system models in ecoinvent.

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10 Appendixes

Appendix I – World Energy Outlook 2013 technology category definitions

Defintions cited from the World Energy Outlook 2013, Annex C. (International Energy Agency 2013b)
Bioenergy
Bioenergy Refers to the energy content in solid, liquid and gaseous products derived from biomass feedstock and biogas. This includes biofuels for transport and products (e.g. wood chips, pellets, black liquor) to produce electricity and heat as well as traditional biomass. Municipal solid waste and industrial waste are also included.
Coal
Coal includes both primary coal (including hard coal and brown coal) and derived fuels (including patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas-works gas, coke-oven gas, blast-furnace gas and oxygen steel furnace gas). Peat is also included.
Electricity generation
Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.
Gas
Gas includes natural gas, both associated and non-associated with petroleum deposits, but excludes natural gas liquids.
Hydropower
Hydropower refers to the energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.
Nuclear
Nuclear refers to the primary energy equivalent of the electricity produced by a nuclear plant, assuming an average conversion efficiency of 33%.
Oil
Oil includes crude oil, condensates, natural gas liquids, refinery feedstock and additives, other hydrocarbons (including emulsified oils, synthetic crude oil, mineral oils extracted from bituminous minerals such as oil shale, bituminous sand and oils from coal liquefaction) and petroleum products (refinery gas, ethane, LPG, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes and petroleum coke).
Power generation
Power generation refers to fuel use in electricity plants, heat plants and combined heat and power (CHP) plants. Both main activity producer plants and small plants that produce fuel for their own use (auto producers) are included.
Renewables
Includes bioenergy, geothermal, hydropower, solar photovoltaic (PV), concentrating solar power (CSP), wind and marine (Tide and wave) energy for electricity and heat generation.

Appendix II – Technology matching and new consequential supply volumes

Table 14 Technology matching for Brazil.

Brazil						
Transformation activities in ecoinvent, electricity, high/medium/low voltage level	Annual average production volumes (kWh)	Technologies without dataset	Technology alignment	New consequential supply volumes (TWh)		
				NPS	CPS	450 S
cane sugar production with ethanol by-product	7 234 293 333,33		Bioenergy	13,61	13,09	12,30
ethanol production from sugar cane	1 362 790 697,67		Bioenergy	2,56	2,47	2,32
treatment of coal gas, in power plant	1 645 000 000,00		Coal	困,64	2,46	- 1,36
treatment of blast furnace gas, in power plant	3 837 000 000,00		Coal	3,82	5,73	- 3,18
electricity production, nuclear, pressure water reactor *	13 131 000 000,00		Nuclear	15,00	15,00	26,00
electricity production, wind, >3MW turbine, onshore *	83 243 160,00		Wind	10,82	10,16	11,22
electricity production, wind, <1MW turbine, onshore *	91 441 350,00		Wind	11,89	11,17	12,33
electricity production, wind, 1-3MW turbine, onshore *	455 945 490,00		Wind	59,29	55,67	61,46
electricity production, lignite *	6 276 480 000,00		Coal	6,25	9,37	- 5,21
electricity production, oil *	16 857 000 000,00		Oil	- 4,00	- 4,00	- 8,00
electricity production, hydro, reservoir, tropical region *	365 855 000 000,00		Hydro	247,00	267,00	247,00
heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control	19 040 000 000,00		Bioenergy	35,82	34,45	32,38
electricity production, hard coal *	298 000 000,00		Coal	0,30	0,44	- 0,25
electricity production, natural gas, at conventional power plant	27 869 000 000,00		Gas	131,00	190,00	17,00
		Solar PV		12,00	10,00	14,00
		CSP		5,00	4,00	5,00
		Geothermal	Not installed	-	-	-
		Marine	Not installed	-	-	1,00
SUM				552,00	627,00	424,00

Table 15 Technology matching for China.

China						
Transformation activities in ecoinvent, electricity, high/medium/low voltage	Annual average production volumes (kWh)	Technologies without dataset	Technology alignment	New consequential supply volumes (TWh)		
				NPS	CPS	450 S
electricity production, nuclear, pressure water reactor*	64290000000		Nuclear	867	778	1547
treatment of blast furnace gas, in power plant	13336000000		Coal	9,71	20,22	-10,04
treatment of coal gas, in power plant	5715000000		Coal	4,16	8,66	-4,30
electricity production, wind, >3MW turbine, onshore*	3988048680		Wind	220,83	186,95	351,73
electricity production, wind, <1MW turbine, onshore*	3146415030		Wind	174,23	147,50	277,50
electricity production, wind, 1-3MW turbine, onshore*	5736057030		Wind	317,63	268,90	505,90
electricity production, oil*	20632000000		Oil	-3	-2	-3
electricity production, wind, 1-3MW turbine, offshore*	77689260		Wind	4,30	3,64	6,85
electricity production, hydro, reservoir, non-alpine region*	4,34501E+11		Hydro	537,74	486,74	569,99
electricity production, hydro, run-of-river*	1,44834E+11		Hydro	179,25	162,25	190,00
heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control	2079000000		Bioenergy	284	240	457
electricity production, hard coal*	2,3897E+12		Coal	1741,12	3624,10	-1799,65
electricity production, natural gas, at conventional power plant	27344000000		Gas	642	520	890
		Geothermal		13	6	17
Solar PV[3]	163400000			201	157	338
		CSP		56	10	190
		Marine		1	1	2
SUM				*5250*	*6619*	*3526*

[3] Aggregated supply volumes from: electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted.

Table 16 Technology matching for India

India						
Transformation activities in ecoinvent, electricity, high-voltage	Annual average production volumes (kWh)	Technologies without dataset	Technology alignment	New consequential supply volumes (TWh)		
				NPS	CPS	450 S
treatment of coal gas, in power plant	1336000000		Coal	2,95	4,16	0,11
electricity production, natural gas, combined cycle power plant*	34134065280		Gas	310	294	409
electricity production, wind, 1-3MW turbine, onshore*	5196193200		Wind	70,74	34,79	94,06
electricity production, lignite*	16933420000		Coal	37,47	52,84	1,49
electricity production, hard coal*	5,14016E+11		Coal	1137,56	1603,99	45,38
electricity production, wind, <1MW turbine, onshore*	6012349200		Wind	81,85	40,26	108,84
electricity production, natural gas, at conventional power plant	42058044720		Gas	0	0	0
electricity production, nuclear, boiling water reactor*	945000000		Nuclear	11,75	9,63	22,48
electricity production, oil	31757640000		Oil	-7	-6	-8
electricity production, hydro, pumped storage*	13918000000		Hydro	29,15	16,97	53,99
electricity production, hydro, reservoir, alpine region*	87227000000		Hydro	182,69	106,38	338,41
electricity production, hydro, run-of-river*	12007000000		Hydro	25,14	14,64	46,58
electricity production, wind, >3MW turbine, onshore*	2380455000		Wind	32,40	15,94	43,09
electricity production, nuclear, pressure water reactor*	12885000000		Nuclear	160,24	131,36	306,51
heat and power co-generation, wood chips, 6400kW thermal, with multicyclone emission control	1843000000		Bioenergy	87	50	147
		Geothermal		2	1	4
Solar PV[4]	19019000			142	59	168
		CSP		13	0	66
		Marine	Set to zero	1	0	1
SUM				2320	2429	1848

[4] Aggregated datasets from: electricity production, photovoltaic, 3kWp slanted-roof installation, ribbon-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, ribbon-Si, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, CIS, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, CdTe, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, a-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, a-Si, laminated, integrated; electricity production, photovoltaic, 3kWp facade installation, single-Si, laminated, integrated; electricity production, photovoltaic, 3kWp facade installation, multi-Si, laminated, integrated; electricity production, photovoltaic, 3kWp facade installation, single-Si, panel, mounted; electricity production, photovoltaic, 3kWp facade installation, multi-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, laminated, integrated; electricity production, photovoltaic, 3kWp flat-roof installation, multi-Si; electricity production, photovoltaic, 3kWp flat-roof installation, single-Si.

Table 17 Technology matching for Japan.

Japan						
Transformation activities in ecoinvent, electricity, high-voltage	Annual average production volumes (kWh)	Technologies without dataset	Technology alignment	New consequential supply volumes (TWh)		
				NPS	CPS	450 S
electricity production, hydro, pumped storage*	6,99E+09		Hydro	2,12	1,27	3,81
electricity production, oil	1,24E+11		Oil	- 127,00	- 121,00	- 145,00
treatment of blast furnace gas, in power plant	2,25E+10		Coal	- 0,40	5,75	-19,91
treatment of coal gas, in power plant	7,72E+09		Coal	- 0,14	1,97	-6,83
electricity production, wind, >3MW turbine, onshore*	3,51E+08		Wind	8,36	6,34	14,97
treatment of municipal solid waste, incineration	6,87E+09		Bioenergy	10,12	8,16	11,43
electricity production, wind, <1MW turbine, onshore*	2E+08		Wind	4,77	3,62	8,54
electricity production, wind, 1-3MW turbine, onshore*	1,99E+09		Wind	47,51	36,01	85,05
electricity production, wind, 1-3MW turbine, offshore*	57128940		Wind	1,36	1,03	2,44
electricity production, nuclear, pressure water reactor	1,06E+11		Nuclear	31,40	31,40	76,76
electricity production, nuclear, boiling water reactor	1,37E+11		Nuclear	40,60	40,60	99,24
electricity production, hydro, reservoir, alpine region*	1,51E+10		Hydro	4,58	2,75	8,24
electricity production, hydro, run-of-river*	6,04E+10		Hydro	18,31	10,98	32,95
electricity production, geothermal*	2,64E+09		Geothermal	23,00	14,00	32,00
heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control	1,42E+10		Bioenergy	20,88	16,84	23,57
electricity production, hard coal*	2,48E+11		Coal	-4,46	63,28	- 219,26
electricity production, natural gas, at conventional power plant	2,66E+11		Gas	24,00	81,00	- 59,00
Solar PV[5]	2137637389			67,00	56,00	77,00
		CSP		-	-	-
		Marine		3,00	-	6,00
SUM				175,00	260,00	32,00

[5] Aggregated dataset from: electricity production, photovoltaic, 570kWp open ground installation, multi-Si; electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted.

Table 18 Technology matching for Russia.

Russia						
Transformation activities in ecoinvent, electricity, high-voltage	Annual average production volumes (kWh)	Technologies without dataset	Technology alignment	New consequential supply volumes (TWh)		
				NPS	CPS	450 S
electricity, high voltage, import from UA	3105000000		-			
electricity production, lignite*	60329860000		Coal	39,21	42,70	- 17,47
electricity production, hard coal*	95074900000		Coal	61,79	67,30	- 27,53
electricity production, peat	377000000		Coal	-	-	-
treatment of municipal solid waste, incineration	2065000000		Bioenergy	35,65	20,80	121,82
electricity production, wind, <1MW turbine, onshore*	118800		Wind	0,36	0,29	2,18
electricity production, nuclear, boiling water reactor*	69033000000		Nuclear	47,28	42,33	90,06
heat and power co-generation, natural gas, conventional power plant, 100MW electrical	4,26272E+11		Gas	-	-	-
heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	28660763250		Gas	141,00	323,00	- 253,00
electricity production, hydro, run-of-river*	1,23783E+11		Hydro	56,25	48,75	92,25
electricity production, geothermal*	446000000		Geothermal	15,00	8,00	26,00
electricity production, nuclear, pressure water reactor*	84267000000		Nuclear	57,72	51,67	109,94
heat and power co-generation, wood chips, 6667kW	20000000		Bioenergy	0,35	0,20	1,18
electricity production, oil*	14976720000		Oil	- 21,00	- 21,00	- 21,00
electricity production, hydro, reservoir, non-alpine region*	41261000000		Hydro	18,75	16,25	30,75
electricity production, wind, 1-3MW turbine, onshore*	1480050		Wind	4,49	3,59	27,21
electricity production, wind, >3MW turbine, onshore*	3351150		Wind	10,16	8,12	61,61
		Solar PV		1,00	-	3,00
		CSP		-	-	-
		Marine		-	-	-
SUM				468,00	612,00	247,00

Table 19 Technology matching for Switzerland.

Switzerland						
Transformation activities in ecoinvent, electricity, high-voltage	Annual average production volumes (kWh)	Technologies without dataset	Technology alignment	New consequential supply volumes (TWh)		
				POM Variant C+E	POM Variant E	POM Variant C
heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction	74 000 000		Fossil CHP	0,62	0,62	0,55
electricity production, natural gas, 10MW	-		-			
electricity production, hydro, pumped storage*	1 325 000 000		-			
electricity production, wind, 1-3MW turbine, onshore*	9 229 000		Wind Energy	1,44	1,44	0,61
electricity production, wind, <1MW turbine, onshore*	1 771 000		Wind Energy	0,28	0,28	0,12
electricity production, nuclear, boiling water reactor	12 339 000 000		Nuclear power	-	-	-
electricity production, nuclear, pressure water reactor	13 780 000 000		Nuclear power	-	-	-
treatment of municipal solid waste, incineration	1 966 000 000		Domestic waste incineration; Landfill gas	0,40	0,40	0,06
electricity production, hydro, run-of-river*	13 312 000 000		Hydro power	2,85	2,85	2,30
electricity production, hydro, reservoir, alpine region*	16 903 000 000		Hydro power	3,63	3,63	2,91
electricity, high voltage, hydro, run-of-river, import from France	5 144 936 944		Imports	-	1,39	-
electricity, high voltage, import from AT	934 210 649		Imports	-	0,25	-
electricity, high voltage, import from DE	8 652 334 103		Imports	-	2,34	-
electricity, high voltage, import from FR	7 972 457 050		Imports	-	2,16	-
electricity, high voltage, import from IT	4 334 346 898		Imports	-	1,17	-
electricity, high voltage, nuclear, import from France	13 042 962 488		Imports	-	3,53	-
electricity, high voltage, wind power, import from Germany	177 336 124		Imports	-	0,05	-
electricity, high voltage, hydro, reservoir, import from France	985 200 691		Imports	-	0,27	-
electricity, high voltage, natural gas, import from Germany	1 690 166 520		Imports	-	0,46	-

heat and power co-generation, biogas, gas engine	214 000 000		Biogas	1,40	1,40	0,43
heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal, with extensive emission control	1		Biomass (Wood)	0,00	0,00	0,00
heat and power co-generation, wood chips, organic Rankine cycle, 1400kW thermal	1		Biomass (Wood)	0,00	0,00	0,00
treatment of digester sludge by municipal incineration, future	-		ARA (Wastewater treatment)	0,17	0,17	0,17
ethanol production from wood	50 000		Biomass (Wood)	0,00	0,00	0,00
heat and power co-generation, natural gas, 1MW electrical, lean burn	148 640 909		Fossil CHP	1,24	1,24	1,11
heat and power co-generation, natural gas, 500kW electrical, lean burn	84 782 609		Fossil CHP	0,70	0,70	0,63
heat and power co-generation, natural gas, 200kW electrical, lean burn	84 700 000		Fossil CHP	0,70	0,70	0,63
heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control	486 000 000		Biomass (Wood)	1,01	1,01	0,48
heat and power co-generation, wood chips, 6400kW thermal, with extensive emission control, label-certified	29 000 000		Biomass (Wood)	0,06	0,06	0,03
Solar PV[6]	76923000			4,36	4,36	2,44
		Biomass (Wooden gas)		-	-	-
		Geothermal		1,43	1,43	0,39
		Fossile CCPP		11,63	-	19,05
SUM				31,92	31,92	31,91

[6] Aggregated dataset from: electricity production, photovoltaic, 3kWp facade installation, multi-Si, laminated, integrated; electricity production, photovoltaic, 3kWp facade installation, multi-Si, panel, mounted; electricity production, photovoltaic, 3kWp facade installation, single-Si, laminated, integrated; electricity production, photovoltaic, 3kWp facade installation, single-Si, panel, mounted; electricity production, photovoltaic, 3kWp flat-roof installation, multi-Si; electricity production, photovoltaic, 3kWp flat-roof installation, single-Si; electricity production, photovoltaic, 3kWp slanted-roof installation, a-Si, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, a-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, CdTe, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, CIS, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, ribbon-Si, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, ribbon-Si, panel, mounted; electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, laminated, integrated; electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted.

Appendix III - LCIA results using ReCiPe 2008 midpoint (H/A), World

Impact category		Climate change	Ozone depletion	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Terrestrial ecotoxicity
Unit		kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq
Brazil	Alloc Def	2,54E-01	6,54E-09	6,84E-04	5,08E-05	5,22E-05	4,49E-02	5,18E-04	3,54E-04	3,00E-04
	Conseq, Current	2,28E-01	6,51E-09	4,74E-04	5,11E-05	2,20E-05	3,84E-02	2,86E-04	3,06E-04	4,69E-06
	Conseq, [New]	2,43E-01	5,16E-09	6,18E-04	5,64E-05	6,21E-05	5,90E-02	5,16E-04	3,34E-04	4,29E-04
China	Alloc Def	1,13E+00	4,36E-09	9,76E-03	1,46E-04	1,70E-04	1,37E-01	4,29E-03	3,05E-03	2,17E-05
	Conseq, Current	1,12E+00	4,00E-09	9,83E-03	1,44E-04	1,71E-04	1,37E-01	4,32E-03	3,07E-03	2,14E-05
	Conseq, U [New]	5,76E-01	2,13E-08	4,58E-03	8,63E-05	8,79E-05	1,08E-01	2,09E-03	1,46E-03	2,37E-05
India	Alloc Def	1,39E+00	1,21E-08	8,53E-03	5,61E-04	2,68E-04	3,79E-01	4,34E-03	4,14E-03	2,59E-05
	Conseq, Current	1,44E+00	7,28E-09	8,98E-03	6,35E-04	2,85E-04	4,22E-01	4,51E-03	4,51E-03	1,71E-05
	Conseq, U [New]	1,05E+00	1,43E-08	6,37E-03	4,50E-04	2,05E-04	3,16E-01	3,27E-03	3,20E-03	2,20E-05
Japan	Alloc Def	6,20E-01	4,72E-08	3,13E-03	1,29E-04	8,53E-05	1,21E-01	1,64E-03	9,52E-04	3,67E-05
	Conseq, Current	8,80E-01	2,05E-09	4,04E-03	3,30E-04	1,29E-04	2,13E-01	1,80E-03	1,20E-03	7,85E-06
	Conseq, U [New]	1,25E-01	4,87E-08	5,00E-04	6,13E-05	3,49E-05	1,08E-01	4,25E-04	2,28E-04	5,32E-05
Russia	Alloc Def	6,97E-01	2,72E-08	3,42E-03	3,84E-04	1,36E-04	2,72E-01	1,72E-03	2,17E-03	2,18E-05
	Conseq, Current	6,46E-01	4,13E-08	5,03E-03	7,38E-04	2,38E-04	4,90E-01	2,38E-03	3,80E-03	1,38E-05
	Conseq, U [New]	5,79E-01	6,96E-08	3,66E-03	5,20E-04	1,75E-04	3,87E-01	1,77E-03	2,64E-03	3,93E-05
Switzerl.	Alloc Def	1,29E-01	7,12E-08	3,52E-04	8,47E-05	3,94E-05	7,84E-02	2,52E-04	1,48E-04	6,14E-05
	Conseq, Current	9,86E-03	2,80E-10	3,32E-05	2,38E-06	1,55E-06	3,61E-03	3,86E-05	3,02E-05	2,91E-07
	Conseq, [New, C]	3,97E-01	1,66E-08	1,06E-03	1,81E-04	1,31E-03	8,20E-02	8,90E-04	3,27E-04	1,85E-04
	Conseq, [New, C+E]	3,14E-01	2,51E-08	9,74E-04	1,95E-04	1,39E-03	1,01E-01	8,90E-04	3,32E-04	5,53E-04
	Conseq, [New, E]	2,42E-01	4,24E-08	8,09E-04	3,07E-04	1,41E-03	1,70E-01	8,25E-04	3,19E-04	5,48E-04

Impact category		Freshwater ecotoxicity	Marine ecotoxicity	Ionising radiation	Agricultural land occupation	Urban land occupation	Natural land transformation	Water depletion	Metal depletion	Fossil depletion
Unit		kg 1,4-DB eq	kg 1,4-DB eq	kBq U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Brazil	Alloc Def	1,39E-03	1,30E-03	3,17E-02	3,01E-02	7,49E-04	2,08E-04	6,85E+00	6,53E-03	3,71E-02
	Conseq, Current	1,30E-03	1,31E-03	3,83E-02	6,11E-03	4,42E-04	2,33E-04	7,85E+00	4,27E-03	1,97E-02
	Conseq, [New]	3,80E-03	3,32E-03	3,19E-02	4,88E-02	1,24E-03	1,49E-04	4,17E+00	1,26E-02	4,88E-02
China	Alloc Def	2,74E-03	2,75E-03	2,61E-02	1,19E-02	8,96E-03	5,97E-05	3,38E+00	6,80E-03	2,15E-01
	Conseq, Current	2,72E-03	2,76E-03	2,53E-02	3,42E-02	9,03E-03	5,69E-05	3,43E+00	8,31E-03	2,13E-01
	Conseq, U [New]	7,53E-03	6,80E-03	1,84E-01	4,57E-02	4,93E-03	4,71E-05	2,62E+00	1,80E-02	1,17E-01
India	Alloc Def	9,48E-03	9,22E-03	4,25E-02	1,37E-02	1,10E-02	8,94E-05	1,20E+00	6,96E-03	3,18E-01
	Conseq, Current	1,06E-02	1,03E-02	4,40E-02	4,18E-02	1,24E-02	6,46E-05	1,27E+00	1,20E-02	3,15E-01
	Conseq, U [New]	9,68E-03	9,19E-03	1,14E-01	4,95E-02	9,12E-03	5,90E-05	9,33E-01	1,44E-02	2,36E-01
Japan	Alloc Def	3,42E-03	2,91E-03	3,30E-01	1,27E-02	3,42E-03	2,21E-04	2,95E+00	2,03E-02	1,73E-01
	Conseq, Current	5,43E-03	5,26E-03	8,34E-03	2,49E-02	7,46E-03	3,70E-05	8,77E+00	8,20E-03	1,82E-01
	Conseq, U [New]	9,12E-03	8,40E-03	3,12E-01	4,84E-02	1,89E-03	2,68E-05	3,40E+00	3,29E-02	3,47E-02
Russia	Alloc Def	7,22E-03	6,59E-03	2,28E-01	2,38E-03	1,70E-03	1,17E-04	6,60E+00	7,61E-03	2,12E-01
	Conseq, Current	1,20E-02	1,17E-02	4,35E-01	1,93E-02	2,92E-03	3,59E-05	1,29E+01	7,36E-03	1,49E-01
	Conseq, U [New]	1,63E-02	1,49E-02	3,18E-01	2,42E-02	2,49E-03	6,66E-05	6,29E+00	3,25E-02	1,55E-01
Switzerl.	Alloc Def	2,01E-03	1,96E-03	5,62E-01	9,20E-03	6,34E-04	2,30E-05	3,39E+00	1,04E-02	3,83E-02
	Conseq, Current	4,53E-04	4,11E-04	3,70E-04	9,24E-04	1,63E-04	6,51E-06	5,06E-01	4,02E-03	1,65E-03
	Conseq, [New, C]	8,44E-03	7,23E-03	1,57E-02	1,43E-02	9,71E-04	9,36E-05	3,83E-01	1,17E-02	1,41E-01
	Conseq, [New, C+E]	1,01E-02	8,85E-03	1,83E-02	4,16E-02	1,37E-03	6,91E-05	5,35E-01	2,01E-02	1,06E-01
	Conseq, [New, E]	1,17E-02	1,06E-02	1,87E-01	4,42E-02	1,84E-03	2,73E-05	3,55E+00	2,20E-02	6,46E-02