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IMPROVED AND ENHANCED STAKEHOLDERS PARTICIPATION IN REINFORCEMENT OF ELECTRICITY GRID

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METHODOLOGIES FOR THE LIFE CYCLE ASSESSMENT

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Abstract

The present document describes the methodology for the assessment of the environmental impacts of a grid project by applying life cycle assessment (LCA). The proposed methodology follows the standard LCA framework: goal definition, scope definition, life cycle inventory and life cycle impact assessment. An approach using consequential LCA is proposed. The procedure for data collection and life cycle inventory is presented. Finally, two sets of indicators relevant for the assessment of a grid project are selected.

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1 ACRONYMS

AC OPF: Alternative Current Optimal Power Flow
ALCA: Attributional Life Cycle Assessment
AoP: Area of Protection
CBA: Cost Benefit Analysis
CLCA: Consequential Life Cycle Assessment
DALY: Disability-Adjusted Life Years
DC OPF: Direct Current approximation Optimal Power Flow
ED: Economic Dispatch
ENTSO-E: European Network of Transmission System Operators for Electricity
GHG: Greenhouse Gases
GWP: Global Warming Potential
GTC: Grid Transfer Capability
HVTL: High-Voltage Transmission Line
ILCD: International Reference Life Cycle Data System
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
PDF: Potentially Disappeared Fraction of species
RES: Renewable Energy Sources
TSO: Transmission System Operator
TYNDP: Ten Years Network Development Plan

2 EXECUTIVE SUMMARY

Based upon the state of the art elaborated in deliverable 4.1, the present document presents the methodology for the assessment of the environmental impacts of a grid project by applying life cycle assessment (LCA). Only the methodological aspects are covered in this deliverable; the added-value of performing an LCA on a grid project in the frame of a stakeholder engagement procedure will be discussed in deliverable D6.3. The recommendations to apply the LCA methodology to a grid project will be presented in deliverable D4.5.

Goal definition

The goal of the study is defined as evaluating the environmental impacts resulting from the decision to carry out a grid project. In this deliverable, the expression "grid project" is used to refer exclusively to a project with the following characteristics:

- Alternative current high voltage (AC 220 kV to AC 400 kV);
- Overhead line or underground cable;
- New line or upgrade of an existing line;
- With or without modifications to the equipment in the connected substations.

LCA would be performed at the need definition phase of a project and shall take into account the interaction between the assessed grid project and the rest of the power system. Its results might be communicated to stakeholders and decision makers in order to help them having a better picture of the project's costs and benefits. LCA indicators might also be included in a broader assessment methodology evaluating the costs and benefits of a grid project.

Scope definition

The scope definition is derived from the goal of the study. A functional unit must be defined to describe qualitatively and quantitatively the service provided by the to-be-analysed system. A transmission grid reinforcement project aims at enabling a power transfer between two substations. The functional unit for this study is therefore defined as follows:

> *"Provide a power transfer capacity of up to a <u>power P</u> in standard conditions, at <u>voltage V</u> and complying with the applicable regulation, between substations <u>A</u> and <u>B</u> of the transmission network, for the <u>reference year Y</u>".*

An analysis of the consequences of the decision to carry out a grid project is performed, differentiating direct effects, linked to the decision by a physical relationship or by predictable decision to be taken by the TSO, and indirect effects, linked to the decision by market mechanisms or other types of relationship. Three main direct effects were identified:

- First, a high voltage transmission line infrastructure must be built, maintained along its lifetime, dismantled when it reaches end of life and the waste generated must be treated.
- Secondly, the power transfer capacity between the two substations connected by the line will increase. This will affect the operation of the systems connected to the transmission network, through two separate chains of cause-effect relationships. First, there will be less congestion situations thanks to the grid project, which will result in fewer use of the congestion solving mechanism. Secondly, the power losses in the network will change, causing a change in power demand by the TSO.

- Finally, the grid infrastructure will be a support for various services from the TSO to telecommunication companies (e.g. renting optic fibre bandwidth).

Possible indirect effects have also been identified:

- Local impacts could lead to changes in global environmental impacts, for instance by influencing the real-estate market and associated environmental impacts.
- A grid project could affect the future development of the transmission network
- The installation of new power generation capacity could also be affected.

Based on this analysis of the consequences of a grid project, and given the goal of decision support, the consequential LCA approach is deemed to be the most appropriate approach, as it is designed to generate information on the consequences of actions (Ekvall, Weidema, 2004). However, this approach is still an active research field and lacks a proper systematisation (Zamagni et al., 2012). The proposed approach is to use consequential modelling to define the system boundaries around the consequences of the analysed decision. For solving multifunctionality of processes, the system expansion approach is adopted, by substituting the avoided process as its market mix (excluding the to-be-substituted function/route).

Some of the identified consequences will however not be modelled, due to both methodological and practical constraints. Indeed, the assessment will focus exclusively on the consequences related to the infrastructure life cycle, and its consequences on the electricity production of existing or planned power plants. The operation of the power system will be simulated both with and without the assessed grid project for a reference year, which can be chosen at the commissioning date or later in the future. The impacts due to the grid project infrastructure will be calculated for an operation of 80 years (corresponding to the lifetime of conductors and towers) and scaled to one year of operation.

Life cycle inventory

The methodology for data collection needed to assess the environmental impacts of a grid project is described. Regarding the infrastructure of a grid project, it mainly consists in describing the activities happening at the different phases of its lifecycle (purchase of components, construction, maintenance and dismantling). The electricity production of each power plant must also be calculated for each alternative. This requires first the development of scenarios to forecast the power demand and the availability of power plants for the chosen reference year. Then, a power system modelling software can be used to perform a simulation. An example of the RTE procedure for scenario development and power system simulation is presented, as it will be applied to the French Cergy-Persan case study in deliverable 6.3.

Once the relevant data has been collected, it needs to be processed to obtain an inventory of all elementary flows (natural resource consumption, pollutant emissions) which can be assigned to a grid project. Data from the ecoinvent database version 3.1 with the system model 'Allocation, default' will be used for describing the background system.

Life cycle impact assessment

Following the recommendations of the ILCD handbook (EC-JRC, 2011), a selection of the most relevant indicators for the assessment of the environmental impacts of a grid project is performed, taking into account the intended use of the results. A complete set of seventeen indicators is defined, covering all the scientifically relevant impact categories, using midpoint models, deemed to have a lower uncertainty.

However, as part of INSPIRE-Grid, LCA results of grid projects are intended to be communicated to stakeholders in order to support their decision making. As explained in the D6.1 and D6.2, the most appropriate way to present the LCA data and results to stakeholders and to analyse how LCA has provided an effective support to the decision-making process will be clarified during the first months of the implementation of LCA. This will be done in cooperation with the TSO's project manager, who will be in charge of both providing the necessary data for the elaboration of the LCA methodology (through phone calls, email exchanges and bilateral meetings) and framing interactions with stakeholders. As for the categories of stakeholders to involve, they will largely depend on the progress of the Cergy-Persan project and on the results of the LCA.

However, as the amount information to be communicated to decision-makers and stakeholders regarding a transmission grid reinforcement project is quite significant, having seventeen indicators only for LCA could overload the information and interfere with a good understanding of its global environmental impacts. A reduced indicator set, composed of six indicators, is therefore also proposed. Damages to human health (resp. ecosystems quality) from several impact categories are aggregated using endpoint models, although the corresponding LCIA models are considered still immature for recommendation by the ILCD handbook.

Table 11 – Example of reduced indicator set

Impact category	Reduced indicator set	
	Model	**Indicator**
Climate change	IPPC,2007	GWP100
Energetic resource depletion	Cumulative energy demand	MJ primary energy
Abiotic resource depletion	CML 2002 (Guinée et al., 2002)	Scarcity (Antimony equivalent)
Water resource depletion	Net water consumption	m^3 of water
Radioactive waste	Weight of radioactive waste	kg
Ozone depletion, endpoint human health	ReCiPe2008 (Struijs, van Jaarsveld, et al., 2009 ; Struijs et al., 2010)	Damage to human health (DALY)
Human toxicity, cancer effects	DALY calculation applied to CTUh of USEtox (Huijbregts et al., 2005)	
Human toxicity, non cancer effects	DALY calculation applied to of CTUh USEtox (Huijbregts et al., 2005)	
Particulate matters	Adapted DALY calculation applied to midpoint (van Zelm et al., 2008 ; Pope et al., 2002)	
Ionising radiation	(Frischknecht et al., 2000)	
Photochemical ozone formation	(van Zelm et al., 2008) as applied in ReCiPe2008	
Acidification	(Van Zelm et al., 2007) as applied in ReCiPe	Damage to ecosystems (PDF)
Euthrophication, aquatic freshwater	ReCiPe2008 (Struijs, Beusen, et al., 2009)	
Land use	ReCiPe2008	

LCA calculations will be performed using both indicators sets. Depending on the aims and requirements of a particular stakeholder information process, one of the two indicator sets can be chosen. The reduced set represents the minimal information which shall be communicated in order to provide a global picture of the environmental impacts of a grid project at a global scale. Individual indicators from the complete set can be added when communicating results to stakeholders if they are deemed relevant to a particular context.

3 INTRODUCTION

The present document will focus exclusively on the methodology to be applied for assessing the environmental impacts of a grid project. The added value of performing a life cycle assessment on a grid project and communicating its results to stakeholders as part of an effective decision-making process will be analysed in deliverable D6.3.

A review of existing life cycle assessments (LCA) evaluating the environmental impacts of the transmission network was performed in deliverable D4.1. The need definition phase was identified as being the most relevant for applying LCA as a significant share of the environmental impacts of a grid project come from its interaction with the power system. By providing additional indicators, LCA could therefore complement existing cost benefits analysis (CBA) methodologies already measuring socio-economic, technical and environmental impacts of grid projects, such as the CBA methodology from ENTSO-E (2014).

Life cycle assessment is a standardised methodology (ISO 14040 and ISO14044). The European Commission Joint Research Centre published the ILCD handbook (EC-JRC, 2010b), providing a comprehensive and detailed guidance covering all aspects of conducting an LCA. The life cycle methodology for the assessment of the environmental impacts of grid projects will follow the provisions from this guidance as strictly as possible, while also considering other practical constraints.

In the present document, the general life cycle assessment framework, presented in deliverable D4.1, is followed, starting with defining the goal of the assessment. The scope of the study will be defined, describing a grid project and the consequences of carrying it out. Two different modelling approaches will be presented and the most appropriate will be discussed. Data to be collected on the system in order to perform a life cycle inventory will then be presented. Finally, a selection of LCA indicators and associated models will be conducted.

The case study for LCA will be the Cergy-Persan project, described in deliverable D6.2. The methodology developed in this document will be applied to quantify the environmental impacts of this project.

4 GOAL DEFINITION

In the context of this study, life cycle assessment (LCA) is used for the evaluation of environmental impacts resulting from the decision to carry out a transmission grid reinforcement project. The term "transmission grid reinforcement project" covers the following modifications of the transmission network (non-exhaustive list):

- Construction of new circuits (overhead and cable), DC and AC.
- Reinforcement of overhead circuits to increase their capacity (e.g. increased distance to ground, replacement of circuits);
- Duplication of cables to increase rating;
- Replacement of network equipment or reinforcement of substations (e.g. based on short-circuit rating);
- Extension and construction of substations;
- Installation of reactive power compensation equipment (e.g. capacitor banks);
- Addition of network equipment to control the active power flow (e.g. phase shifter, series compensation devices);
- Additional transformer capacities;

The INSPIRE-Grid project aims at enhancing stakeholders' participation in the development of future grid infrastructures. The LCA methodology described thereafter is therefore focused on those transmission grid reinforcement projects, referred as "grid projects" in this deliverable, for which a stakeholder engagement process may be conducted, namely projects regarding an high voltage AC transmission line (220 kV to 400 kV, overhead line or underground cable, new line or voltage upgrade of an existing line). LCA would be used at the need definition phase of a grid project, and its results could be communicated to stakeholders of the project, to help them judge the relevance of carrying it out. The main goal of this study is therefore decision support.

The move to a more diverse power generation portfolio due to the development of renewable energy sources will entail significant change to the geographical breakdown of production facilities. The transmission network is developed to adapt to these changes. Conversely, carrying out a grid project will have a number of consequences, in particular on the operation of the power system. The consequences of the decision to carry out a grid project will be assessed by comparing the environmental impacts that would occur if the project was carried out, to the ones which would occur in a reference situation where the project would not exist. A high-voltage transmission line has a technical lifetime of several decades. The environmental impacts resulting from a grid project are therefore very dependent on the evolution of the electricity mix during its lifetime. By nature, future is impossible to know, but prospective work can be carried out to create a scenario describing a possible future. In order to have a contrasted analysis of the possible consequences of a grid project, several scenarios shall be considered. The boundaries of the system under study and the procedure to identify the consequences of this decision will be discussed in the following section.

The developed methodology is meant to be generic and applicable to any grid project with the following characteristics:

- Alternative current high voltage (AC 220 kV to AC 400 kV);
- Overhead line or underground cable;
- New line or upgrade of an existing line;
- With or without modifications to the equipment in the connected substations.

However, when general recommendations would not be specific enough, a detailed recommendation will be made for application on the Cergy-Persan grid project to be assessed in deliverable D6.3. The methodology presents several limits which shall be stated: when applying it to a project, the results will not be transferable to another project without carrying out another study. Indeed, the studied system provides a service with an identified position in time and space: the two substations connected, the power capacity of the line, its commissioning date and its economic lifetime are specific to each project. The geographical location is very important as providing the same service between two different substations would result in different power plants being affected, and therefore in different environmental impacts. Likewise, results are only valid for the defined period of time, as the system's context evolves over time (e.g. evolution of the electricity production mix). Therefore, it will only be possible to compare technical solutions enabling the same power transfer capacity between the same substations. Moreover, the scope of this study does not include the comparison of a grid project with another grid project connecting a different couple of substation or with another technical solution which would fulfil a given demand (e.g. smart grid or energy storage).

Finally, results from studies following this methodology are not be additive. The environmental impacts of a project are evaluated against a reference situation where the project is not carried out. Therefore, if two studies are carried out using the same reference situation, adding the two results is not valid as the probable interaction between the two projects is not dealt with in any of the two studies.

5 SCOPE DEFINITION

The scope definition is derived from the goal of the study. First and foremost, the analysed decision and its main consequences are described. Then, a general modelling approach is derived from the goal and the identified consequences. Finally, detailed recommendations are made, specifying the functional unit to be defined and the boundaries of the to-be-analysed system.

5.1 Description of the systems affected by a grid project

A transmission grid reinforcement project consists in building a high-voltage transmission line (HVTL), which can either refer to an overhead line, an underground cable or a submarine cable. It is a system which function is to enable to transfer electrical power between two substations. A high voltage transmission line can be built to transmit either three-phase alternative current (AC) or direct current (DC). AC is the dominant technology, but DC is a viable solution for some specific uses, in particular to transmit large amounts of energy over long distances. Typically in Europe AC 400 kV and 220 kV HVTL are used to transport electrical energy over large distances (ENTSO-E, 2012). Thereafter, the expression "grid project" is used to refer exclusively to a project with the following characteristics:

- Alternative current high voltage (AC 220 kV to AC 400 kV);
- Overhead line or underground cable;
- New line or upgrade of an existing line;
- With or without modifications to the equipment in the connected substations.

The transmission network is a complex system formed by many components interacting with each other. This is a meshed network formed by transmission lines connecting substations. Transformers are used in substations to connect power lines using different voltages. The function of the transmission network is to connect generators and loads and to transport energy from the former to the latter. This function cannot be fulfilled by a line independently, only the interaction of all the components of the grid can result in fulfilling this global function. Moreover, the transmission network interacts with the other systems connected to it. The terminology 'power system' is commonly used to refer to the system formed by electricity generation, delivery and demand, such as illustrated in figure 1 (Machowski et al., 2008). The transmission network can be considered as one of the component of the power system, the others being the power plants producing electricity, the facilities storing it, as well as the distribution network distributing it to clients. A high-voltage transmission line is then one of the components of the transmission network. While regrouping many different systems operated by different entities, the power system forms a single large complex system where every component is required to fulfil the global function, and where the state of any of its components affect the state of all the others. In such case, a component-system relationship can be established between a grid project and the power system (EC-JRC, 2010b, p. 7.2.2). The life cycle assessment shall therefore not be limited to the grid project, but shall take into account its influence on the whole power system.

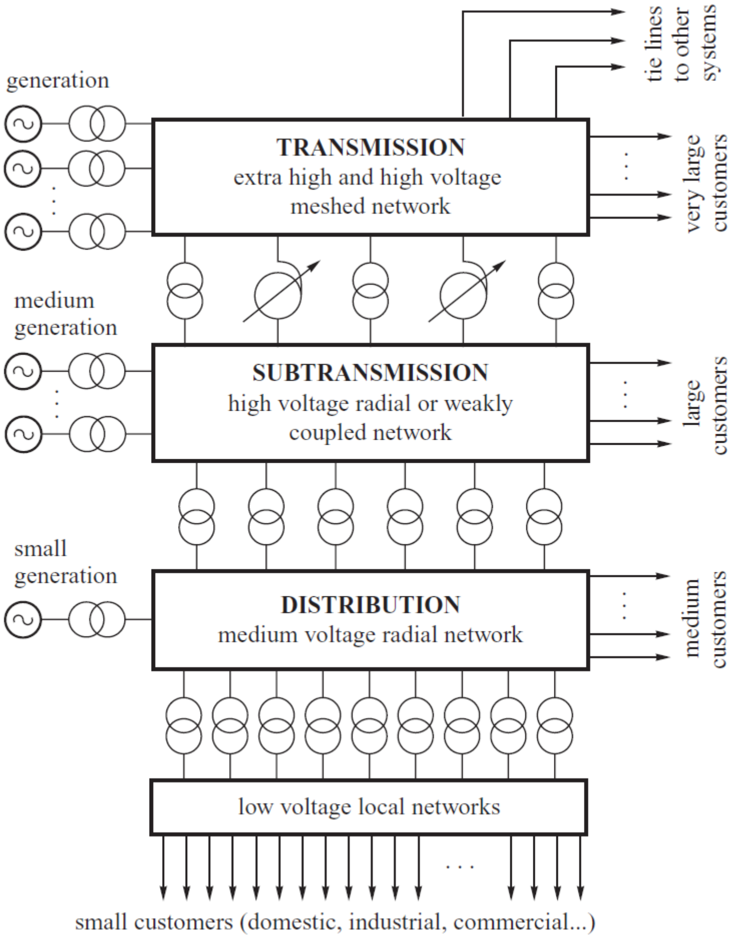

Figure 1 – Structure of an electrical power system (Machowski et al., 2008)

Hessen and Lind (2009) defined power systems as *"means to the end of supplying and distributing energy to all members of society"*. They categorise these means according to their purposes:

- Electric technology means: grid, generators, active / reactive power, control, supervision, system balancing...
- Information technology means: networks, protocols, software agents...
- Control means: measurement, actuation and decision-making equipment...
- Economical means: market, bids, money value...

According to Hessen and Lind (2009) these means interact with each other in order to achieve goals related to the three values associated to power systems: Security of Supply, Resource Efficiency and Sustainability.

Security of Supply covers both continuity of supply and quality of the electrical wave under ordinary conditions. Continuity of supply refers to the ability of the system to deliver electricity to all clients demanding it whenever they do. It can be altered by failures in generation or in delivery. While the main objective of power systems ought to be the reliable supply of electrical energy, a certain level of failure is tolerated. Common indicators used to measure continuity of supply are "outage frequency" (number of power outage per year and per delivery site) and "equivalent outage time" (energy not supplied as a result of customer power cuts and load shedding, expressed as a ratio to the total annual power supplied to customers). Quality of the electrical wave corresponds to the ability of the system to maintain everywhere in the network voltages' amplitude and frequency close to the reference values. A target level for security of supply is defined by regulation, and this target should be achieved while at the same time cost should be minimised. This relates to the value Resource Efficiency. However, cost is not the only criterion and Sustainability is at the core of some regulations concerning power systems.

The power system covers the activities of producing electricity from various fuels, transmitting it to substations with the transmission network and distributing it to final clients through distribution networks. In Europe, transmission and distribution are natural monopolies, regulated by an energy regulatory authority. The service provided by power systems can be defined by several characteristics:

- Geographical coverage: usually defined as the area of influence of the energy regulatory authority. In Europe, the interconnection between national power systems makes it possible to consider that they form a single power system.
- Clients: all the economic players in the considered geographic area: private individuals, companies, and other organisations.
- Time aspects: electricity must be supplied whenever there is demand. The power system must therefore adjust its electricity production to meet variations in demand. The service is therefore continuous.
- Quality: continuity of supply and quality of the electrical wave must be maintained. The service shall be available at any time and the electricity provided shall always have the same characteristics in terms of voltage and frequency. Maintaining the electricity quality is one of the responsibilities of the TSO, partially subject to laws and regulations. Contracts with industrial clients can also include specific terms related to electricity quality. In case of major climatic events, disrupting the operation of the transmission network, TSOs can be in part cleared from this liability.

5.2 Functional unit definition

A functional unit must be defined to describe qualitatively and quantitatively the service provided by the to-be-analysed system. The functional unit serves as a basis for the comparison of two alternatives fulfilling a similar function. The goal of this LCA is to evaluate the environmental impacts occurring as a consequence of the decision to carry out a grid project. Following the description of a grid project in the previous paragraph, it appears that it does not only consist in building a transmission line, but should be viewed as providing a service: enabling a power transfer between two substations. The functional unit should therefore refer to this service :

> *"Provide a power transfer capacity of up to a power P in standard conditions, at voltage V and complying with the applicable regulation, between substations A and B of the transmission network, for the reference year Y".*

The attributes *P*, *V*, *A*, *B* and *Y* shall be specified when applying the methodology on a case. *P* represents the power capacity of the grid project expressed in MW, *V* its voltage level expressed in kV, *A* and *B* are the name of the substations linked by the project. The *reference year Y* can be defined according to the goals of the assessment. If LCA is included in a broader assessment methodology including other technical, socio-economic and environmental indicators, the reference date for LCA shall be defined in compliance with the other indicators. In order to assess a single grid project, the reference date can be defined at the commissioning date of the grid project. For grid projects that are part of network development plans such as the TYNDP, the reference date shall be coherent with the one of the broader assessment methodology.

The assessment of the decision to implement a grid project will be done under the *ceteris paribus* assumption: apart from the analysed decision and the modelled consequences, all other things will be considered independent. In particular, except for electricity consumers taking part in load management schemes, power demand at a given point in time will be considered identical whether or not the grid project is implemented.

5.3 Main consequences of a grid project

The decision to carry out a grid project will have several types of consequences: direct and indirect. In this section, the various chains of cause-effect relationships following this decision will be identified. Direct effects refer to the expected consequences of the decision to carry out the project. The relationship linking them to the decision studied is either of physical nature or depends on predictable decisions to be taken by the TSO. Indirect effects refer to other types of effects, linked to the decision by market mechanisms or other types of relationships (behavioural, regulatory, etc.).

5.3.1 Direct effects of a grid project

- Direct effect DE1: related to building, maintaining and dismantling infrastructure

The first consequence of implementing a grid project is building, maintaining and finally dismantling an infrastructure. Transportation done as part of these activities is covered as well. The life span of a high-voltage transmission line is very long. RTE's experience shows that conductors of overhead lines need to be replaced every 80 years. Other sources mention conductors lifetime from 40 years (Frischknecht et al., 2007) to 60 years (CIGRE WG B2.15, 2004). The lifetime of lattice towers is virtually unlimited if it is well maintained, by regular painting and replacement of damaged parts. Their technical lifetime is therefore beyond 80 years. No information has been found on the lifetime of concrete towers, but it can also be assumed to be exceeding 80 years. In substations, equipment such as transformers, circuit breaker or gas insulated switchgears have a lifetime of 40 years, while the lifetime of disconnectors is around 20 years (ABB, 2011).

Various products will be purchased for the building and maintenance activities, which will also produce some waste. Making an assumption of full elasticity of supply, this additional demand for products (resp. waste treatment) will result in a corresponding increase of production by suppliers (resp. treatment activities).

Moreover, if towers or substations are built as part of the grid project, they will occupy some space which was previously available for other purposes (natural land, agricultural land, industrial land). This area beneath towers will not be available anymore for other use during the lifetime of the infrastructure, resulting in a decrease of supply for land of different types: agricultural land, urban land, etc.

Finally, the infrastructure will have a number of local impacts (c.f. section 4 of INSPIRE-Grid deliverable D4.1). These impacts are already assessed in existing assessment methodologies applied during the spatial planning phase (e.g. environmental impact assessment) and LCA is not well adapted to take them into account.

- Direct effect DE2: related to an increase in power transfer capacity

The reason for carrying out a grid project is to create an additional power transfer capability between the connected substations. This will of course affect other systems inside the power system, mainly through two chains of cause-effect relationships.

The first one follows the decrease in the number of congestion situations. The result of transactions on the wholesale electricity market defines the production of each generation unit at a given time. One day before production, the TSO is informed of the planned production of each generation unit and can check that the network is able to perform the physical delivery of this planned production. For some situations, a line's maximum power capacity can be reached, which is referred to as a congestion situation. The TSO can use the balancing mechanism to pay participating generation units and demand units to adjust their production and consumption in order to prevent these congestion situations. In the most extreme situations, for instance when a lot of wind power is available, the TSO can decide to disconnect some generation units to maintain network stability, resulting in a "spillage" of renewable energy. Solving present or foreseen chronic congestion issues is one of the main reasons for grid development today in Europe. Once a grid project has been implemented, TSO will use less often the congestion solving mechanism, which will lead to a change in production and consumption of affected power plants. Some power plants might increase their production while others will decrease it. In particular, carrying out a grid project can result in reducing the renewable energy spillage, and therefore maximising the use of RES. Some consumers might shift or reduce their demand. Determining which unit is affected and how, requires a modelling of the influence of a specific grid project on the congestion in the transmission grid.

The second cause-effect chain is related to power losses. By implementing a grid project, power flows in the network will change, which will result in a variation in power losses in the network. Depending on the specific situation, it can be an increase or a decrease in power losses. The TSO buys the amount of electricity lost in the network to producers. The amount of electricity demanded by the TSO will therefore change, as well as the electricity production by power plants as a consequence (both global amount produced by all suppliers and dispatch between suppliers). Unlike congestion solving, demanding units are not affected by this consequence and power plants which might be affected are not necessarily participating in the congestion solving mechanism.

These consequences on the power system will last for the whole lifetime of the high-voltage transmission line. While the line is operating, it will affect the production of generation units and demanding units connected to the transmission network. During this period, changes will happen in the power system, independently from the decision to carry out the project: some power plants will be decommissioned; some new power plants will be built. The decision to implement a grid project today can affect the operation of power plants which will be built in the future. Power demand will also vary in the future. The transmission network itself will be modified during the lifetime of the considered transmission line, as other grid projects will be implemented. All these "background" changes, while unrelated with the studied decision, will affect the influence of the grid project on the power system.

- <u>Direct effect DE3: related to services to telecommunication companies</u>

Finally, an HVTL includes an optic fibre cable used as part of the TSO's information system for managing the transmission grid. Usually, not all the available bandwidth is used by the TSO. Part of it can be rented to telecommunication companies. Moreover, transmission grid masts located on high spots can also be rented to telecommunication companies for their antennas, which avoid building a separate mast. Carrying out a grid project will therefore increase the supply for these services to telecommunication companies. This supply may or may not meet some demand during the lifetime of the grid infrastructure.

Figure 2 sums up the main chains of cause-effect relationships following the implementation of a grid project. These consequences have been regrouped in three categories: consequences related to the life cycle of the grid project's infrastructure; consequences related to the life cycle of other power system components; and consequences outside the power system's life cycle. All of them are related to TSO activities.

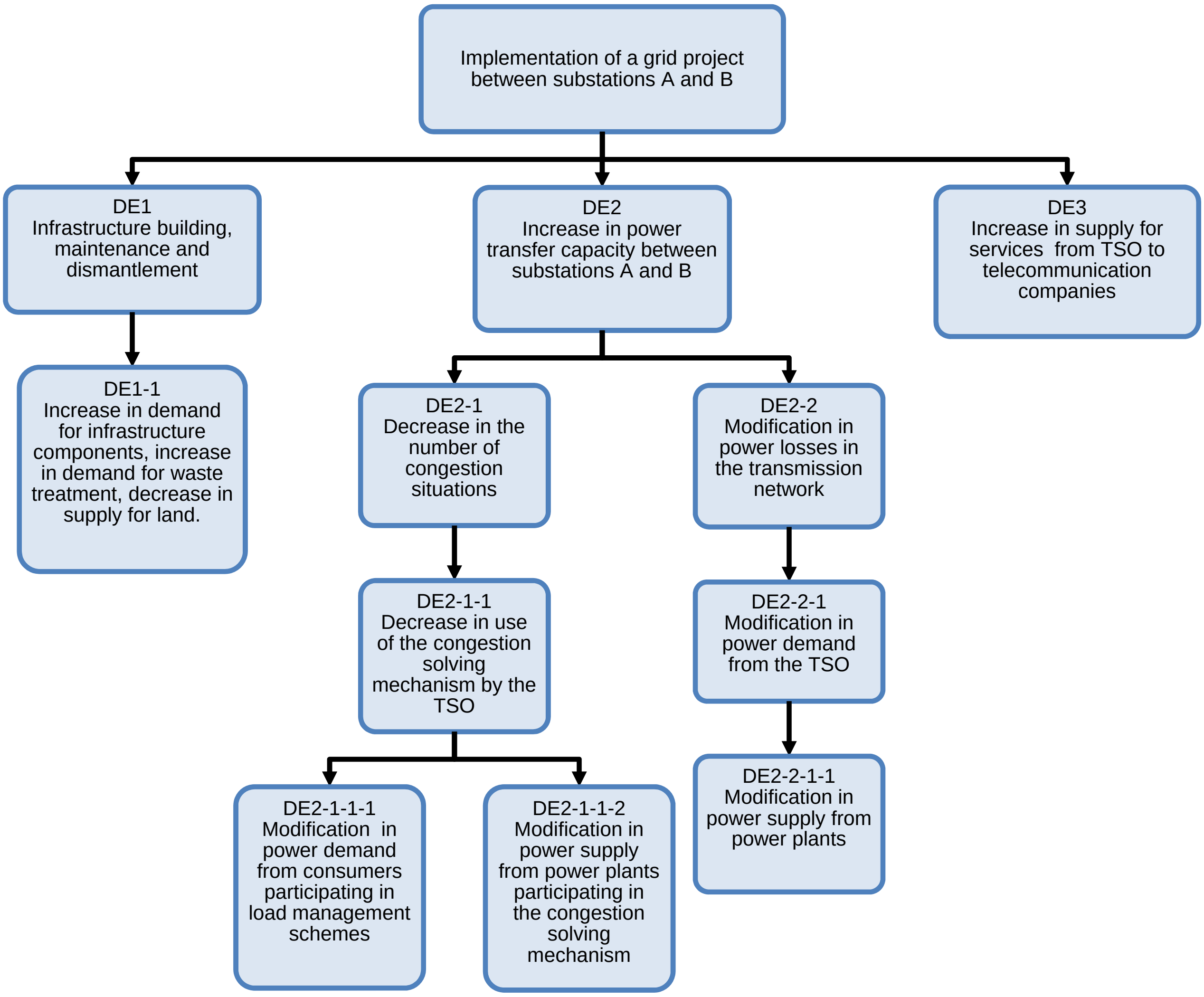

Figure 2 – Direct consequences of a grid project

5.3.2 Indirect effects of a transmission grid project

Indirect effects are more difficult to estimate. A few possible indirect effects which could lead to changes in environmental impacts at a global scale are presented hereafter. This list is not meant to be exhaustive, only the ones that could change environmental impacts on a global scale are considered. They are presented in Figure 3.

- Indirect effect DE1-IE1: related to local impacts

The high-voltage transmission line will have various local environmental impacts, in particular on landscape, which could lead to changes in global environmental impacts. In the surroundings of the transmission line, especially for overhead lines, the property value is likely to be decrease, which could result in changes in the real-estate market. These changes might themselves lead to changes in environmental impacts. For instance, some households could choose to sell their house and move because the transmission line was built, increasing the distance between their work place and living place, and thus increasing their pollutant emissions due to daily transport. However, at the need definition phase, it is very difficult to quantify the influence of the project on the real-estate market, as the exact path of the line is not yet known exactly. Local impacts are evaluated in an environmental impact assessment, carried out only at the spatial planning phase. The decision of the exact path of a transmission line takes into consideration the existing urbanisation and planned development projects such as industrial or trading areas. Moreover, compared to the other effects, especially the changes in electricity production, the global environmental consequences of the local impacts are likely to be very low.

- Indirect effect DE2-IE1: related to the development of the transmission grid

The decision to implement a grid project can affect the future development of the network itself. Indeed, grid projects are not developed independently but are part of a consistent development plan. The need for one project depends on the implementation of previous projects. For instance, two or more transmission grid projects can be competing with each other and implementing both would not be relevant. Grid projects are mainly developed to solve current or future chronic congestion situation, due to an increase of power demand or by a change in power generation (e.g. RES integration). Creating a new transmission line can solve a chronic congestion situation in the area of the line, but create new ones elsewhere in the network. Therefore, carrying out a grid project can affect the need for other grid projects elsewhere. However, the decision to carry out a project follows a complex procedure and cannot be considered in any way as a simple consequence of a previous project.

- Indirect effect DE2-IE2: related to the development of power generation

Finally, the relationship between the development of the transmission grid and changes in power generation needs to be investigated. Will a transmission grid project enable the creation of new generating units? Or is the transmission network developed as a consequence of changes in power generation? A cause-effect relationship does exist between those two phenomena but its direction needs to be clarified.

Developing interconnections between different TSOs can pool power generation capacities and therefore reduce resorting to peak load power plants by importing more electricity from another country. This could lead to lower investments in peak load power generation capacity. Moreover, when planning an investment in a power plant, the cost of connection to the transmission grid is considered, among many other criteria. If this cost is too high, it might jeopardise the power plant project. As a grid project results in an increased power transfer capacity between two substations, it might influence the development of power plants locally.

However, European regulations such as Directive 2009/28/CE on the promotion of the use of energy from renewable sources, and Directive 2010/75/UE on industrial emissions (integrated pollution prevention and control) can be viewed as the primary causes which led to technology changes in power generation. To reach the European target in terms of renewable energy sources, a shift in the generation mix is required. One of the main drivers of transmission grid development in Europe is the massive relocation of generation means induced by this shift (ENTSO-E, 2012, sec. 1.4). As an example, the recently commissioned high voltage transmission line between France and Spain, developed by RTE and REE, is presented as enabling the creation of new wind power capacity in Spain. However, Spain has set itself a target share of renewable energy sources of 20.8% in 2020, in compliance with the RES directive (Directive 2009/28/CE on the promotion of the use of energy from renewable sources). One of the reasons for the development of the grid project between France and Spain is therefore the expected increase in wind power capacity in Spain. While the project might foster this increase, it was already decided in Spain's energy policy.

As a conclusion, a grid project can influence the geographic repartition of power capacity, but it is unlikely to affect the power capacity at a macroscopic level (total power capacity in a country and capacity per type of power plant). The mix is defined in policy plans at national, regional and local level, and new transmission lines can be built if required.

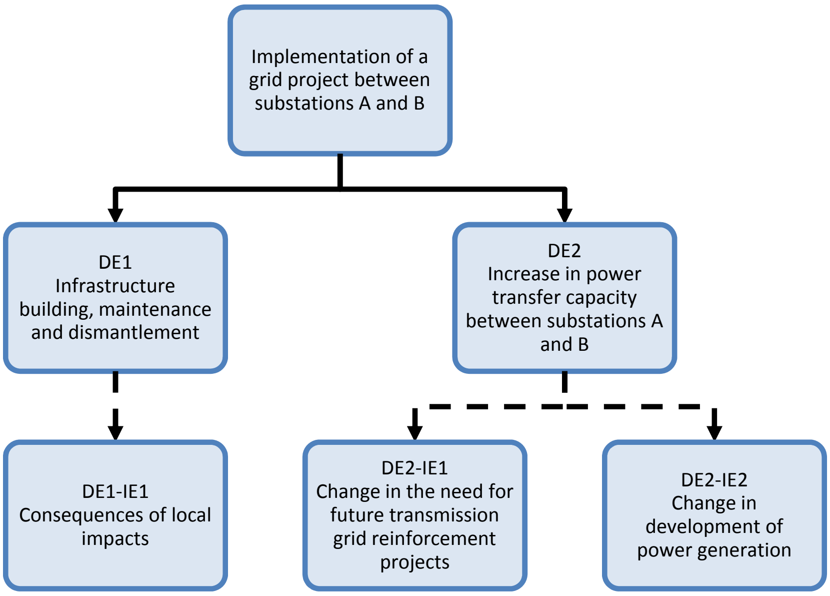

Figure 3 – Possible indirect consequences of a grid project

5.4 LCA modelling approach

Given that the assessment of the environmental impact of a grid project aims at supporting the decision to carry it out, the consequential LCA modelling approach appears to be the most appropriate one, as it is designed to generate information on the consequences of actions (Ekvall, Weidema, 2004). However, despite the aim of the ILCD handbook (EC-JRC, 2010b) to build a consensus on the criteria to choose between the available LCA modelling approaches, subsequent research work challenged their conclusions (e.g. Zamagni et al., 2012 ; Guiton, Benetto, 2013 ; Weidema, 2014). Version 3 of the ecoinvent database also includes data to be used as part of a consequential LCA (Weidema et al., 2013), which were developed following a different methodology (Weidema, 2003). Consequential LCA is still an active research topic and a proper systematisation of the approach has not yet been achieved (Zamagni et al., 2012). Based on the goal definition and on the description of a grid project and its consequences, applied consequential modelling approach is proposed. First, the most appropriate modelling approach is selected. Then, the consequences to be included in the scope of the study are discussed.

5.4.1 Justification of the modelling approach

Most of the existing recommendations for the application of consequential LCA require evaluating the magnitude of the consequences of the decision. Depending on the magnitude of the changes which happen as a consequence of the analysed decision, the methodology to apply may differ. The magnitude is considered low whenever the consequences are at the margin. It is considered high whenever the change is so important that it requires new investments in production capacity. The choice of a modelling approach therefore requires the analysis of the magnitude of the consequences previously described:

Building, maintaining and decommissioning the grid project's infrastructure results in an additional demand for products and waste treatment (consequence DE1-1 in figure 2). If the increase in demand for grid components was superior to the available market capacity, it could require the building of new production capacity to absorb it, which would imply a structural change in the market. Likewise, if a very big amount of waste was produced, the creation of new waste treatment facilities could be required. As a first evaluation, a single grid project represents only a very small fraction of all the building and construction activity every year. This change in demand can be assumed not to bring about any structural change in the concerned market: no new production plants or waste treatment facilities will be built to meet this demand. All additional demand for products and for waste treatment can be assumed to be absorbed by existing facilities. Concerning effects related to land use, it is unlikely that the decrease of supply for land will result in conversion of land of another type. For instance, it is unlikely that the transformation of agricultural land to industrial land results in a transformation of natural land to agricultural land elsewhere in the world to compensate this decrease in available agricultural land.

The change in power demand resulting from power loss variation in the network (DE2-2-1 on figure 2) can be assumed to be absorbed by existing facilities. Indeed, power losses in the transmission network represent between 2 % and 3.5 % of the generated electricity. The variation of these losses due to a single transmission grid project being implemented is fairly small (ENTSO-E, 2012, p. 68), so this change in power demand due to loss variation will not require building new power plants. For the second chain of cause-effect relationships related to congestion management, there is no change in the amount of electricity produced. Only the dispatch between various existing power plants is changed if the grid project is carried out. The decrease in use of the congestion solving mechanism (DE2-1-1 in figure 2) is therefore unlikely to result in the creation of new power plants. In an indirect way, it could however result in decommissioning of some peak load power plants, such as gas turbines, which are producing electricity only in case of high electricity demand. Their average number of operating hours per year is fairly small (around one hundred hours for a gas turbine in France), so a change of just a few hours of operation could actually represent a significant relative change and affect their profitability in a non-negligible manner. If carrying out a grid project results in a loss of profitability for an operator, he could decide to close the power plant. However, this is limited to very few grid projects and this will not fundamentally affect how electricity is produced, as the production for the decommissioned gas turbine is likely to be shifted onto another power plant of the same type.

Finally, the consequence of a grid project on the telecommunication system is also likely to be small scale. At the need definition phase for a grid project, it is impossible to know whether or not the transmission line will be used to offer services to telecommunication companies. However, some statistics about commercial activities can give an idea of the significance of the environmental impacts which could result from this consequence. In France, the turnover of the TSO's subsidiary dealing with telecommunication activities represented less than 0.2 % of the turnover of the whole group for the year 2013 (RTE, 2013). Moreover, this subsidiary is not involved in the TSO's internal process for developing a grid project[1]. If a grid project is not carried out, it seems very unlikely that a separate optic fibre connection will be built. As a result, this cause-effect chain can be neglected.

As far as indirect consequences presented in figure 3 are concerned, none of them are likely to cause large-scale changes in environmental impacts.

[1] Direct communication from RTE's technical manager for the Cergy-Persan project, 15/12/2014.

The ILCD handbook (EC-JRC, 2010b, p. 5.3) classifies the possible goals of an LCA into three so-called situations. From this classification, specific recommendations are derived to apply the LCA methodology. These three goal situations are:

- Situation A – "Micro-level decision support": decision support, typically at the level of products, with no or exclusively small-scale consequences in the background system or on other systems. I.e. the consequences of the analysed decision alone are too small to overcome thresholds and trigger structural changes of installed capacity elsewhere via market mechanism.
- Situation B – "Meso/macro-level decision support": decision support for strategies with large-scale consequences in the background system or other systems. The analysed decision alone is large enough to result via market mechanisms in structural changes of installed capacity in at least one process outside the foreground system of the analysed system.
- Situation C – "Accounting": From a decision-making point of view, a retrospective accounting / documentation of what has happened (or will happen based on extrapolating forecast), with no interest in any additional consequences that the analysed system may have in the background system or on other systems.

As presented in § 4, LCA will be used to support the decision of building a grid project, by assessing its interactions with electricity generation. Situation C can therefore be ruled out. Based on these above observations, none of the consequences of a grid project can be considered to result in structural changes in any of the affected markets. Therefore, this study fits in Situation A. The ILCD handbook (EC-JRC, 2010b, p. 6.5.4.2) states: "*the most appropriate LCI model for Situation A shall represent the supply-chain of the analysed system, applying attributional modelling. For cases of system-system relationship and multifunctionality of processes and products that cannot be solved by subdivision or virtual subdivision, the system expansion approach shall be adopted, substituting the avoided process as its market mix (excluding the to-be-substituted function/route). [...] In the case of large complexity, allocation is the next option to solve multifunctionality*."

Using a modelling depicting the supply-chain of a grid project while neglecting its influence on the power system would however conflict with the defined goal. The consequential modelling, building the boundaries of the to-be-analysed system around the consequences of the analysed decision, is therefore preferred. The recommended system expansion approach for Situation A will however be used.

5.4.2 Modelled consequences of a grid project

Some of the consequences which were described in § 5.3 can be left outside the scope of the study, as modelling them is not possible with the information available at the need definition phase of a grid project. The environmental impacts which could result from these consequences are however expected to be negligible compared to the ones which will be modelled. First, consequences unrelated to the power system will be left outside the scope. No changes in environmental impacts will be assumed to result from the increase in supply of services for telecommunication companies from the TSO (DE3 in figure 2). The consequences of local environmental impacts (DE1-IE1 in figure 3) will also be considered out of the scope of this study, as they are impossible to model at the need definition phase. The remaining consequences can be classified into two categories: consequences related to the grid infrastructure, and consequences of the increase in power transfer capacity in the network.

5.4.2.1 Consequences related to the infrastructure

For the first category, all activities related to building and maintaining the infrastructure happening during the time frame will be inventoried. The additional demand for infrastructure components (resp. waste treatment) resulting from these activities will be assumed to result only in a corresponding increase of supply from existing production facilities (resp. waste treatment facilities). In case of an upgrade of an existing line, recycling of parts of the existing infrastructure will be considered as part of the building process, and therefore will be treated as a consequence of the grid project. The expected lifetime of the grid infrastructure is 80 years, but the assessment period is likely to be shorter. To assign the environmental impacts of the grid infrastructure to the decision of carrying out the grid project, the impacts are calculated for the whole lifetime, including building, maintaining, dismantling and recycling the infrastructure, and then scaled to the assessment period. For a 15 years assessment period, every elementary flow related to the grid infrastructure would be divided by 80 and multiplied by 15.

5.4.2.2 Consequences of the increase in power transfer capacity in the network

For consequences of the increase in power transfer capacity between two substations of the transmission network, the operation of the European power system shall be simulated from the commissioning date of the grid project for the time period considered. For the direct effects, only short-term marginal consequences will be taken into account. A grid project will therefore be assumed to only affect the operation of existing facilities, without having any influence on their lifetime. Their building and future dismantling will be considered unaffected.

TSO can use power system models to simulate their actual operation and calculate an annual electricity production. In order to assess the influence of the grid project on the electricity production of power plants, the power system can be simulated using two alternatives of transmission network:

- A reference transmission network, representing the do-nothing alternative of the grid project
- The modified transmission network, as it would be if the grid project is carried out.

Depending on the required level of details, results can be differentiated by fuel type or for each generation unit individually.

A grid project can potentially affect the operation of generation units located very far away, especially when it contributes to market integration. The geographic border of the power system to consider shall be defined so that exports and imports to this isolated power system can be considered unaffected by the grid project. For instance, for projects with limited influence outside the TSO's national network, the scope can be limited to it, assuming it will not affect imports and exports from another country. For grid projects contributing to market integration, imports and exports from a national grid are affected, and therefore the geographic scope shall be extended to the whole European grid. The TSO responsible for the grid project is the one able to decide on the most appropriate geographic scope for simulating how the power system operation is affected by the line.

Scenarios must be developed for the evolution of power demand, power generation capacity, and of the transmission network itself (excluding the analysed grid project) during the time period of the assessment. This might requires the use of prospective models.

The indirect consequences of the increase in power transfer capacity (DE2-IE1 and DE2-IE2 in figure 3) should theoretically be handled through the development of specific scenarios. The power mix and the transmission network topology could be assumed to evolve differently during the assessment period if the grid project is carried out or not. Building these scenarios would rely on assumptions based on the expected evolution of the power mix and of the grid. If these consequences are to be modelled, a consistent scenario development method should be produced in order to ensure reproducibility between two projects. No detailed recommendations on this scenario development can be made.

However, considering practical limitations, the development of specific scenarios for each grid project appears to be very time consuming. This work can only be done by the TSO, who has both the required knowledge to produce forecasts of the evolution of the power system and models to simulate its operation.

Prospective work is commonly performed for grid development planning, as done in the Ten Year Network Development Plan (TYNDP) from ENTSO-E (2012). However, to be usable in practice, the prospective work and the power system modelling software must use the same spatial and time resolution. Calculating the influence of the line during a time period covering several years (e.g. 2015-2030) requires modelling not only the power mix at the end of the time period (e.g. for the year 2030), but also its evolution during this period. Power systems modelling software usually adopt an hourly time step, to reflect their actual operation dynamics. Regarding spatial resolution, while statistics about national or regional power demand and power production can be estimated from historical records and energy policy plans, increasing the spatial resolution of such forecasts requires a lot of work and depends on a lot more assumptions. However, for some grid projects, a high spatial resolution is required; otherwise results are not accurate enough. Modelling the indirect effects of the increase in power transfer capacity (DE2-IE1 and DE2-IE2 in figure 3) would require the development of separate scenarios for the future evolution of the transmission grid and of the power mix depending on whether or not the grid has been implemented. This means that the prospective work should be adapted to take into account the decision regarding each grid project assessed. The work needed for developing scenarios suited to model both direct and indirect effects of a grid project for more than a decade therefore appears to be very demanding. The use of existing scenarios from the network development plans must therefore be preferred.

Moreover, simulating the power system operation is also a very time intensive activity. In order to reduce calculation time, simplified simulation models are commonly used (see § 6.1.2.2). In these models, power losses in the transmission network are taken into account in a simplified way which does not enable to determine the influence of the grid project on power losses (DE2-2 in figure 2). For example, in the TYNDP from ENTSO-E, only a qualitative evaluation of the power losses is performed. This chain of cause-effect relationship should be part of the scope in theory, but cannot be modelled in practice at the moment.

5.4.2.3 Summary of the modelled consequences

Table 1 presents the consequences which shall be modelled, as well as their expected environmental significance.

Table 1 – Summary of modelled consequences

Consequence	Description	Potential influence on LCA results	Included in the model
DE1-1	Increase in demand for infrastructure components and waste treatment	Medium	Yes
DE1-IE1	Indirect consequences of local impacts	Low	No
DE2-1	Decrease in number of congestion situations	High	Yes
DE2-2	Modification of power losses in the transmission network	Low / Medium	No
DE2-IE1	Change in the need for future transmission grid reinforcement projects	Unknown	No
DE2-IE2	Change in the development of power generation capacity	Unknown	No
DE3	Increase in supply for services from TSO to telecommunication companies	Low	No

5.5 System boundaries

Based on the previous analysis, detailed modelling recommendations are provided hereafter. The functional unit is described. The foreground system, the context system and the background system are then defined.

5.5.1 Foreground, context and background systems

The analysed system is typically differentiated into the processes of the foreground system and of the background system. The foreground system is defined as those processes of the system that are specific to it. In the example of a study on a producer-specific product, it is composed of processes that are operated at the producer's facilities, but also of all those processes at suppliers where only one or a few operators are involved. The background system is those processes, where due to the averaging effect across suppliers, a homogenous market with average (or equivalent generic) data can be assumed to appropriately represent the respective processes. The foreground system therefore covers the activities related to the transmission line infrastructure: building, maintaining, operating and decommissioning.

As described in § 5.1, a high voltage transmission line is a component of a context system, covering all the activities of the power system: electricity production, storage, transmission and distribution. Electricity production at medium and low voltages is included as well in the context system. The activity of electricity production outside the considered power system for import to the power system is not part of the context system, as the specific providers are unknown and a market average must be used. This activity is thus part of the background system. The following diagram presents the main steps of the studied system.

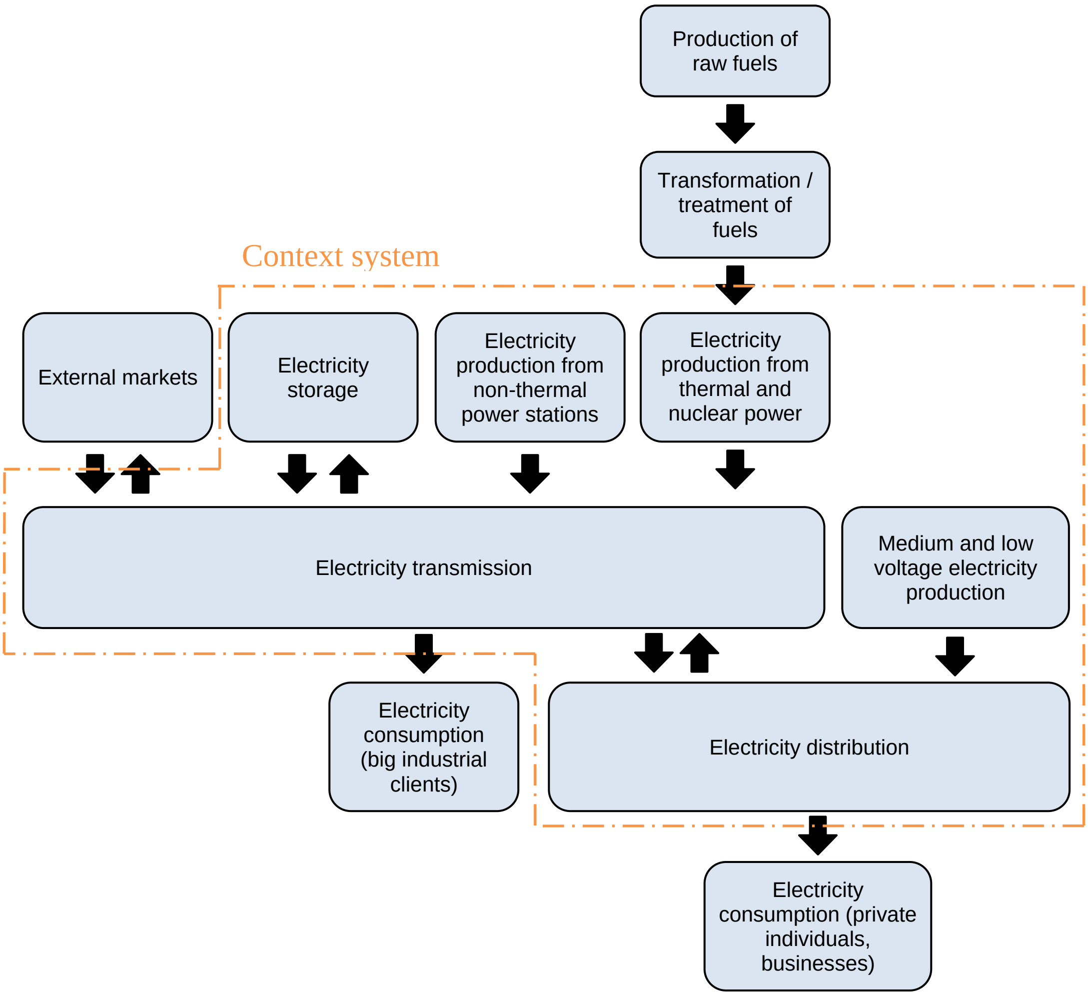

Figure 4 – Activities included in the context system

The elementary flows crossing the defined borders will be inventoried in the next step. These flows can be from the technosphere (purchase of products or services), to the technosphere (waste), from the ecosphere (natural resource consumption) or to the ecosphere (pollutant emissions). The background system is composed of all the activities inside the technosphere which are linked to the foreground system by any flow. Only flows from and to the ecosphere cross the borders of the background system.

5.5.2 Activities affected by a grid project in the context system

Figure 5 presents a simplified representation of the activities inside the foreground system. Some of the flows to and from these activities are represented, which are classified in three categories:

- Product flows between two activities inside the context system
- Product and waste flows from and to the technosphere, linking to the background system
- Elementary flows from and to the ecosphere, representing natural resource consumption and pollutant emissions.

In order to reduce complexity and ease interpretation, only part of the context system is represented. Regarding high voltage electricity production, only one example power plant, powered by hard coal, is represented. The actual context system includes the activities of electricity production at every power plant connected to the transmission system. The same simplification is applied for power plants connected to the distribution network, where only electricity production at a photovoltaic facility is represented. The electricity flow from the electricity distribution network to the transmission network was not represented in order to keep the diagram understandable. For each activity, only a set of representative flows were represented. The inventory of all the flows related to each activity of the context system will be conducted in § 6.1.

Following the analysis of the consequences of a grid project in § 5.3.1, the flows which are not affected by the grid project are represented with a dotted arrow, while the ones which can be affected are represented with a plain arrow. In compliance with the *ceteris paribus* assumption, the demand for electricity remaining the same whether the grid project is carried out or not, the electricity supplies at high, medium and low voltage are unaffected. Moreover, electricity production from generation units connected to the distribution network is not affected by a change in the transmission network. Flows related to the activities of medium and low voltage electricity production and electricity distribution are considered unaffected, these activities can therefore be excluded from the comparison.

Regarding the electricity transmission activity, electricity imports and exports to and from the power system are supposed unaffected. This is indeed the criterion for defining the geographic borders of the power system (c.f. § 5.4.2.2). Regarding the infrastructure necessary to perform the electricity transmission activity, most of it is unaffected. Indeed, only on the high voltage transmission line which will be built as part of the grid project, and the substations that it links must be considered. However, building a line can affect the pollutant emissions occurring in the transmission network during the electricity transmission activity (mainly O_3 and N_2O emission due to the corona effect).

The amount of electricity injected on the network from a given power plant can be affected, as well as electricity consumed during pumping as part of the electricity storage activity. . The lifetime of power plants infrastructure is longer than a year, so a share of the flows related to this infrastructure must be allocated to its electricity production, by dividing the flows by the infrastructure lifetime in years. As long as the lifetime of infrastructure is considered unaffected, the corresponding flows will left out of the scope of the study. The decision to decommission a power plant depends on several considerations: the age of the power plant, the number of full load production hours, its profitability, its compliance with new regulation, etc. A load factor too high or too low can reduce its lifetime. Following the analysis of the consequences of a grid project in § 5.3, the variation of load factor due to a grid project will be considered small enough not to affect the lifetime of power plants. Therefore, regarding the activity of electricity production at power plants, only flows which are proportional to the electricity production are affected. Other flows which are not affected by a change in load factor will be considered out of scope. This is especially the case of elementary flows related to land use (land occupation, land transformation), which are related to the infrastructure but independent from the load factor of the power plant.

Regarding electricity storage, it should be noted that the electricity consumed during pumping is an internal flow of the context system. Only impacts associated with flows that cross the border shall be inventoried.

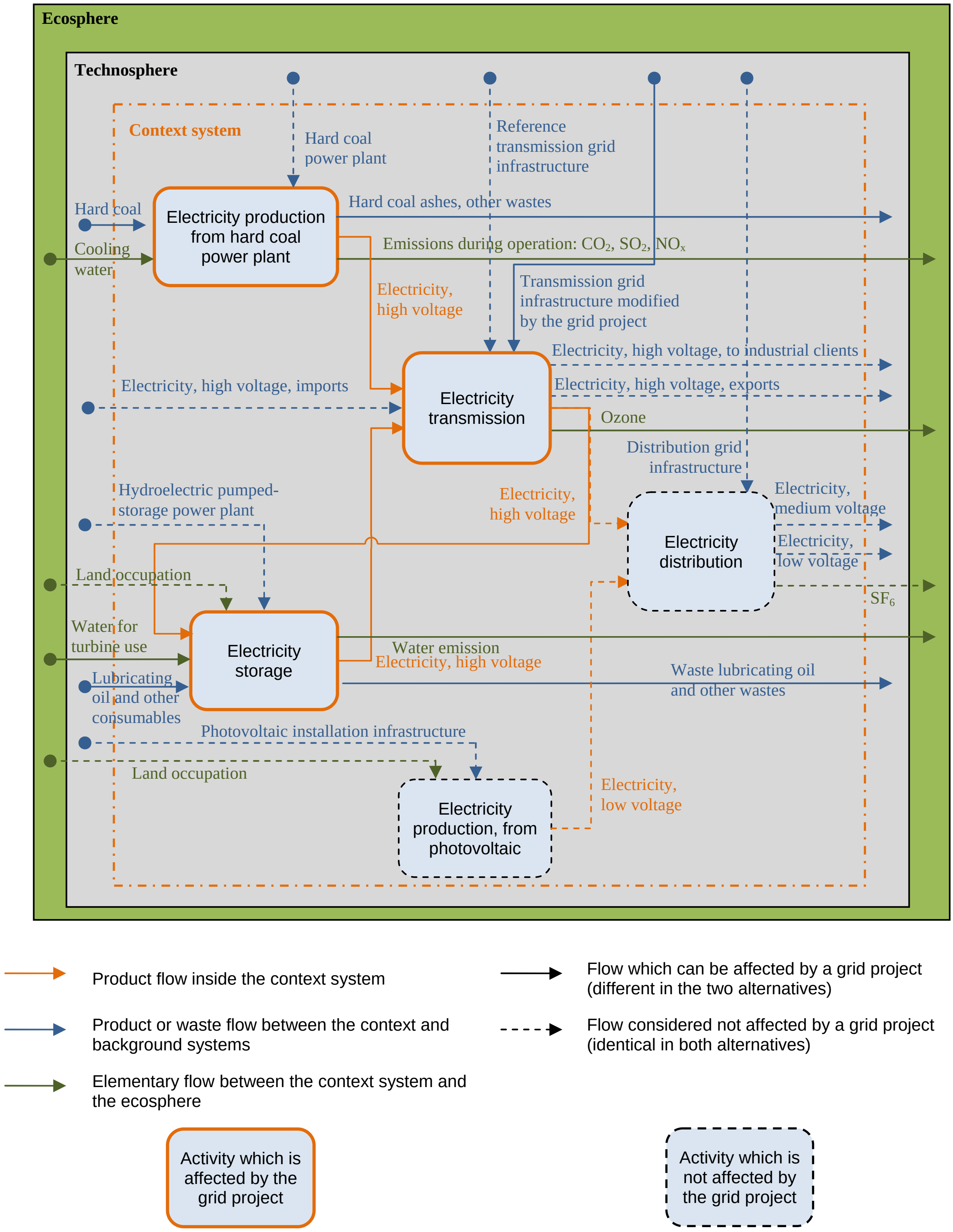

Figure 5 – Simplified representation of the activities affected by a grid project

5.5.3 Cut-off criteria

In general, all processes and flows that are affected by the studied change are to be included in the system boundaries. However, not all these processes are quantitatively relevant: for the less relevant ones, data of lower quality can be used, limiting the effort for collecting high quality data. Among these, the irrelevant ones can be entirely cut-off.

A cut-off criterion can therefore be defined. The ILCD handbook recommends setting the cut-off value depending on how much precision, accuracy and completeness is needed to show significant differences between the compared systems. This can only be done in the iteration of the LCA work after an initial LCI model has been modelled and analysed (EC-JRC, 2010b, p. 6.6.3).

6 METHODOLOGY FOR LIFE CYCLE INVENTORY

In this section, the procedure for inventorying all the environmental interactions (pollutant emission, natural resource consumption) related to the system defined previously is presented. First, specific data must be collected for each grid project. Then, this data can be processed in a common way to produce the life cycle inventory.

Two areas are to be covered: activities related to the grid project infrastructure, and power production. The annual production of all the power plants in the defined power system shall be calculated for the reference year, for both alternatives (including or not the assessed grid project).

6.1 Data collection

6.1.1 Infrastructure

Activities related to the grid project infrastructure shall be inventoried. An HVTL can either be an overhead line or an underground cable. These two technical solutions are quite different and will therefore bring about different environmental impacts. The methodology for life cycle inventory of overhead transmission lines will be presented in the following. For a grid project using an underground cable, a similar procedure can be followed, adapting to each step to the specificity of the considered technical solution. A grid project also often requires making modifications in existing substations or creating new ones. Data about these activities shall be inventoried as well.

As the LCA is performed at the need definition phase, only data from preliminary technical specification can be used, which might change as the project progresses. EDF R&D and RTE performed two life cycle assessment studies (2008, 2010) aimed at evaluating the environmental impacts of transmission lines infrastructures. The same life cycle phases as in these studies are presented thereafter.

6.1.1.1 Grid project components

The aim of data collection for grid project components is to obtain a bill of materials of each component. Components of an overhead line can be sorted into three categories: structures, foundation and grounding systems, conductors, overhead ground wires, and insulators. Table 2 presents the data to be collected for each of these categories.

Table 2 – Data to be collected for grid project components

Category	Data to collect
Structures	Type: lattice tower, concrete, other Technical designation Number Type of corrosion protection: galvanised steel, paint
Foundation	Mass of concrete per tower Mass of steel for reinforcement
Grounding systems	Material: copper, galvanised steel, other Mass
Conductors	Type: ACSR, AAAC, AAC Technical designation Section Total length to be purchased
Overhead ground wires	Type : optical, non-optical Technical designation Section Total length to be purchased
Insulators	Type: toughened glass, porcelain, composite, other. Total number of insulators
Substation equipment	Type: Technical designation: Number:

6.1.1.2 Construction

Construction activities consist mainly in clearing the right-of-way of the line, building foundations, erecting the towers and laying the conductors. Data to be collected for this life cycle phase is presented in table 3.

Table 3 – Data to be collected for grid project construction

Category	Data to collect
Clearing of the right-of-way	Operating time of machines Mass of green waste Type of waste treatment Distance to waste treatment facility
Foundation work	Volume of excavated earth Distance to landfill
Erection of towers and stringing work	Operating time of lifting equipment

6.1.1.3 Emissions during the operation of the grid project

For high voltage overhead lines, corona discharges create ozone (O_3) and dinitrogen monoxide (N_2O) form the air surrounding the conductor. This phenomenon is also the source of the crackling noise that can be heard near transmission lines. Corona discharges happen when the electric potential near a conductor is high enough. It is not correlated to the power transmitted, so building a new line, regardless of how it affects the power transmitted elsewhere in the network, will increase the energy lost by corona discharge and the emissions of O_3 and N_2O. As a first approximation, these emissions can be considered proportional to the transmission line length.

The estimation of these emissions in the ecoinvent database (Frischknecht et al., 2007) are based on an inventory of 250 tonnes of O_3 and 280 tonnes of N_2O emitted every year in the whole Swiss transmission network, representing 40,000 km of high voltage lines, which corresponds to 6.25 kg of annual ozone emissions per km and 7.0 kg of annual N_2O emissions per km. This is an average regardless of the voltage level of the line. In reality, these emissions increase when the voltage increases and depend on climate conditions.

In the absence of more accurate information about the future emissions of the grid project due to corona effect, this data of average emissions per kilometre will be used. Other types of emissions during operation of the line, such as grease leakage from conductors and paint emissions will be neglected.

6.1.1.4 Maintenance

Maintenance activities happening during the defined time frame must be inventoried. For overhead lines, a frequent maintenance work includes tree pruning and towers painting. Transport is expected to represent a non-negligible part of the impacts associated to infrastructure maintenance. Regular inspections are performed with helicopters to check the infrastructure and plan maintenance operations.

Table 4 – Data to be collected for grid project maintenance

Category	Data to collect
Inspections	Time duration between two inspections Means of inspection: helicopter, car, other. Average distance travelled per inspection
Tree pruning	Length of line to be covered Average mass of green waste produced per kilometre of line Average time required per kilometre of line Distance with green waste treatment facility
Towers painting	Time duration between two painting Volume of paint per tower

6.1.1.5 Dismantling

Dismantling activities will be considered similar to the erection of towers and stringing work performed during construction. Data to be collected concerns the fate of waste that will be generated, which is presented in table 5. As dismantling will happen in several decades, this information can only be collected by educated guess. The bill of materials from components will be used to calculate the mass balance for wastes.

Table 5 – Data to be collected for grid project dismantling

Category	Data to collect
Structures	Type of waste treatment
Foundation	Type of waste treatment
Grounding systems	Type of waste treatment
Conductors	Type of waste treatment
Overhead ground wires	Type of waste treatment
Insulators	Type of waste treatment

6.1.2 Electrical power production

For both alternatives, the power system operation will be simulated in order to determine the annual production of each power plant, for the reference year. First, scenarios describing the evolution of power demand and power generation from the current date to the reference date for the study must be developed. Then, power system models which can be used to simulate how the power demand is dispatched between generation units in both alternatives.

A general description of the main steps for performing these tasks is described. As an illustration, the procedure used by RTE for modelling the French power system in order to provide input for the LCA of the Cergy-Persan case study is described.

6.1.2.1 Scenarios development

Scenarios shall provide coherent visions of the evolution of the power system, including the expected evolution of power generation, power demand and future changes in the transmission network. If LCA indicators are included as part of a broader assessment methodology including other technical, socio-economic and environmental indicators, such as ENTSO-E's CBA methodology (ENTSO-E, 2013), the use of coherent scenarios among all indicators shall be preferred, when possible. RTE develops such scenarios as part of their generation adequacy report on the electricity supply-demand balance in France (RTE, 2012). The most recent version was published in 2014, but the results from the 2012 forecast will be used for the assessment of the Cergy-Persan case study in WP6, as more recent scenarios have not been adapted yet to be usable in RTE's power system modelling software. Forecasts are made for medium term (each year from the current year to five years later) and for long-term (2030), using different approaches which are presented hereafter.

- Medium term forecasts

RTE's forecasts for power demand are usually developed following two steps: forecasting the annual energy demand, for each year of the considered time period; then forecasting the power demand, for each time step within a year, using as an input the annual energy demand previously calculated.

For both steps, a retrospective analysis of the past years is performed, adjusting the model to known outputs. A forecast is then performed to build a realistic picture of possible futures, based on the context, and current and future trends. To forecast the annual energy demand, a stacking approach is adopted. Power demand is divided into economic sectors: residential, tertiary, industry, energy (including network losses), transport and agriculture. Each sector is then split into branches or usages. The energy consumption from these branches or usages is then estimated by multiplying extensive variables (produced quantities, heated areas, level of household equipment...) and intensive variables (unit consumption per product, per m^3, per household, etc.). Consumptions obtained are then aggregated for each sector. These models are fed with data available from market research institutes, public institutions, professional federations, etc. Results from statistical survey and measurements performed by RTE are then used to adjust models. The same stacking approach is used in order to forecast the power demand. For each branch or usage considered previously, a demand profile is associated with an hourly time step. Most of these profiles come from measurements in real conditions (direct measurements from the transmission network, outcomes of measurement campaign for tertiary and residential usages, etc.). Profiles for climate-sensitive usage are modelled by RTE from statistical analysis of the part of the measured French load curve sensitive to climatic variations. Combining the annual energy demand and the load profile, a forecasted load curve can be calculated for each branch or usage. Power consumptions are then aggregated to obtain a global load curve for the whole French power system. Calculated load curves for historical years are adjusted to fit measurements.

Several demand scenarios are developed to cover the uncertainty in the main parameters influencing the power system: national GDP, effectiveness of energy efficiency measures, demography and electricity prices. RTE developed four scenarios for medium-term as part of their 2012 generation adequacy report, presented in table 6.

Table 6 – Main assumptions used in medium term scenarios (RTE, 2012)

Demand scenario	"Baseline"	"High"	"Stronger Demand Side Management"	"Low"
Main assumptions	Central	Higher overall demand	More energy efficiency	Lower overall demand
GDP	Central	High	Central	Low
Energy efficiency	Central	Lesser effect	Greater effect	Central
Demographics	Central	High	Central	Low
Electricity price	Central	Favourable to the rollout of new electricity-based solutions	Central	Unfavourable to the rollout of new electricity-based solutions

Regarding power generation, the status of the current power generation capacity is analysed. Given the time needed to develop new power capacity, a medium term horizon is short enough to have a good knowledge of its future evolution, and a single scenario for power generation can be used. All projects for which construction is in progress are added to the park and probable decommissioned units are removed. A separate analysis is conducted for each type of generation: nuclear power generation, centralised thermal power generation, decentralised thermal power generation, hydroelectricity, wind power, photovoltaic, demand response.

- <u>Long term forecasts</u>

Whereas for the medium-term horizon (five years) the structure of demand and supply can be more or less estimated based on decision already taken, long term forecasts require the creation of prospective scenarios incorporating differentiated assumptions. RTE identified significant uncertainty related to the evolution of the socio-economic context (economic growth, active population, number of households), energy efficiency (development of demand-side management, switch of some usage from other energy source to electricity) and the electricity mix itself (political decision related to the development of renewable energy sources and nuclear power). As a result, the range of possibilities for both demand and supply appears very wide. The different prospective scenarios are not intended to be an exhaustive representation of all possible futures, but they do offer a range of possibilities which are sufficiently different to enable the evaluation of the consequences for the transmission network.

For long-term forecast of power demand, the division into economic sectors is applied again and assumptions are used to forecast the evolution of each sector, before aggregation. For power generation, assumptions are made about what generation investments would be made to meet the power demand, considering the assumed legislative and economic context. Table 7 presents the main assumptions used in each of the four long term scenarios of RTE's 2012 Generation Adequacy Report.

Table 7 – Main assumptions used in the long term scenarios (RTE, 2012)

Main assumptions by scenario	Median	High demand	New Mix	Low Growth
Economic growth	Moderate	High	Moderate	Low
Demographics	Moderate	High	Moderate	Low
Energy efficiency	Moderate	Low	High	Moderate
Nuclear	Moderate	High	Low	Moderate
RES	Moderate	Moderate	High	Low
Interconnections	Moderate	High	High	Moderate

6.1.2.2 Power system modelling

Once scenarios have been developed, they can be used as inputs to simulate the power system operation and determine the actual power production of each power plant in the two compared power system alternatives. This simulation can be performed using various models, all relying on the same principles:

- The assessment period is divided into individual points in time. To be representative of the actual dynamics of the power system, a time step of one hour is generally used.
- A set of nodes is defined. For each node, loads consuming electricity or generators producing electricity can be connected. Each generator is described by its power capacity and a function links its power production to its operating cost.
- Arcs are connecting these nodes with each other, enabling a power transfer from one node to another. Each arc has a maximum power transfer capacity.
- The power demand from loads at each node is defined for each time point.
- At every time point, a solver is used to calculate the production of each generator so that all demand is satisfied while the global operation cost is minimised.

Several levels of abstraction are possible, from a detailed description of the power system, representing each substation and each transmission line of the transmission network as nodes and arcs, to a simplified representation of the European power system where a node represents a whole country. Several formulations of the dispatching problem are also possible (Cain et al., 2012):

- AC Optimal Power Flow (AC OPF): each node i is described by four physical parameters: active power Pi, reactive power Qi, voltage magnitude Vi and voltage angle δi. AC OPF is a non-linear problem, representative of the actual physical phenomena happening in the transmission network but very heavy in computation.

- DC Optimal Power Flow (DC OPF): a linearised version of the AC OPF, where all voltage magnitudes Vi are assumed to be fixed and all voltage angles δi are close to zero. In particular, power losses in the transmission grid are not calculated in DC OPF. They can be included after the optimum has been reached, by distributing a share of the total amount of power generated between generators and loads.
- Economic dispatching (ED): the most simplified formulation. The least-cost generation dispatch to serve a given load is determined, simplifying or ignoring altogether any power flow constraint.

The selection of the right tool for the assessment of a grid project depends on the characteristics of the project. As an example, the process used by RTE to assess high voltage transmission grid reinforcement projects (400 kV) will be presented, based on the information which was communicated to ARMINES. This process will be used for the Cergy-Persan case study.

This assessment is based on a combination of tools with different abstraction levels. International imports and exports are first modelled using a first internal RTE tool, an economic market simulator which gives the national production planning of the interconnected European grid at each hour. This tool has no description of the grid, actually reduce to one node by country. Results from this first tool are then processed to calculate inputs for the second tool, enabling a more detailed modelling of the French and European power systems.

The first tool is a sequential Monte-Carlo simulator for which the simulation for hour h is coherent with hour h+1. For each of its variables, annual time-series are created with an hourly granularity. Usually, from 10 to 100 time-series are used for each variable, modelling the possible evolution of the variable during a year, for all countries of the system. The variables are wind power production, solar power production, hydroelectric power production, load consumption, and thermal power plants availability. Other variables are supposed to be deterministic (biomass, network transfer capacities, etc.). The tool chooses a time-series for each variable at random, building an annual scenario for demand and generation called a Monte-Carlo year. For each Monte-Carlo year, the total production cost is minimized while respecting commercial capacities between countries, as well as constraints related to time variability of the production from thermal units and hydroelectric power plants. For the assessment of transmission grid reinforcement projects, there is one node per country and 50 Monte-Carlo years are simulated. The production of each type of generation unit in each country is calculated for every hour of these 50 Monte-Carlo years. ANTARES thus models imports and exports between European countries for 438,000 situations (50 Monte-Carlo years and 8760 hours per year).

The economic market simulator modelling is too high level to enable an extensive evaluation of the consequences of a grid project including a fine description of the grid. For that purpose, a second tool is more adapted. It is a statistical analysis tool enabling the execution of a large number of simulation on different network situation. It generates a population of situations from probability density functions for random variables supposed independent. Results from the first tool are used as input after processing. Hourly points from the first tool are partitioned into coherent classes within which variability of the main variables is reduced. This partition is performed first by selection significant variables using principal components analysis and hourly points are grouped then by k-means clustering. Once classes are defined, probability densities within each class is determined and probability laws are entered in the second tool, which can then draw the independent variables (loads, plants availability, wind power production, etc.) to generate 1000 variants per class. This high number of variants should ensure the same variability as in the results from the economic simulator in each class. To improve the representativeness of these variants, retrospective filtering is performed to remove variants where results are incoherent compared to the original market model results.

After a given variant has been generated (drawing of load, fatal production from wind, solar, hydroelectric run-on-river), the simulation process is performed in two steps. A first step consists in determining the economically optimal production plan for the power system, without taking into account network constraints. This is considered to represent the production plan resulting from exchanges on the wholesale electricity market. The second tool starts the electric group from the one with the lowest operating cost until the balance between supply and demand is reached (production = consumption + power loss). In this first step, no network constraint is considered and power losses are considered are calculated a priori as a share of the consumption. The production plan obtained is called "Without Network".

In a second simulation step, a power flow enables to identify congestions on the network which would result from the economically optimal production plan (power transmitted on a line superior its power transfer capacity). A solver then performs a DC OPF to solve these constraints by modifying the power production of groups. Any power production modification (increasing or decreasing) increases the production cost. The production of fatal energy sources (wind power, solar, co-generation) can be adjusted, but with a very high price. In last resort, selective power cuts can be applied, but with an even higher price. The production plan obtained at the end of this process is called "With Network". The second tool results obtained for all variants are then aggregated into a single value for a statistical year. This process is called annualisation. By definition, each class contains 1000 variants, but a different number of the first tool hourly points. Coefficients (weights) are used to recreate a statistically representative year. These weights are calculated as the ratio between the number of the first tool hourly points in the class and the total number of points. A weighted sum of results for all variants is then performed to obtain the production plan for a statistical year.

For each group in the power system simulated, the second tool provides their annual production both "Without Network" and "With Network". For assessing the influence of a grid project, the simulation process is applied on the two alternatives of transmission network, and results can be compared. All steps up to the calculation of the production plan "Without Network" are common to both alternatives. The only difference is the redispatching happening for calculating the production plan "With Network", as there will be fewer congestion situations in the alternative including the grid project.

6.2 Processing the collected data

Processing the collected data does not rely on grid project specific data. Information must be found elsewhere in the literature. Data from existing life cycle inventory (LCI) database can be used. The ecoinvent database is the most complete LCI database currently available. It comprises LCI data covering all economic activities. Each activity dataset describes an activity at a unit process level. An algorithm is then used to link datasets with each other and produce an LCI data for a given process in the database.

Ecoinvent version 3.1 (Weidema et al., 2013) includes three different implementations of this algorithm, representing different system models: 'Allocation, ecoinvent default', 'Allocation, cut-off by classification' and 'Substitution, consequential, long-term'. These system models differ on how multi-functionality is solved (how the flows to and from a multi-output process are assigned to each of its outputs) and how markets are modelled (which flows to assign to a product when it is available from a market fed by different suppliers). The system model 'Allocation, ecoinvent default' will be used for providing background LCI data.

6.2.1 Infrastructure

Regarding infrastructure processes, the inventory will be realised for the complete technical lifetime of the grid project, assumed to last 80 years. The corresponding elementary flows will be scaled to the duration considered in the time period of the study (one year in the case of the attributional modelling approach). According to previous studies presented in deliverable 4.1 and the first application on the Cergy-Persan case study shows that the infrastructure contribution to most impact categories is quite low. "Abiotic resource depletion" and "Land use" are the main impact categories affected by the infrastructure. Therefore, the data processing can focus on describing the materials used for the infrastructure. A low level of detail about the building process and energy consumption during the component manufacturing phase is acceptable. When the methodology will be applied on the Cergy-Persan case study in deliverable 6.3, the need for a more detailed description of the grid infrastructure will be discussed.

The background processes which were used to produce the purchased components of a high voltage transmission line infrastructure must be modelled. Data collected on infrastructure components can be used to estimate a bill of materials, using manufacturer catalogues and environmental product declarations. The corresponding data regarding the production of raw material can be taken from the ecoinvent database.

The most appropriate modelling technique regarding the future recycling of infrastructure components must be investigated. This will be done during the application of the methodology on the Cergy-Persan case study in deliverable D6.3 and general guidance will be provided in deliverable 4.5: Recommendations for the application of the methodologies.

6.2.2 Electrical power production

The data collected thanks to power system simulation describes the production of each electrical group connected to the transmission network for a statistical year. Each group can be associated to one type among the following list: combined-cycle gas power plant; gas combustion turbine; hard coal thermal power plant; hydroelectric, pumped storage facility; hydroelectric power plant, reservoir; hydroelectric power plant, run-of-river; lignite thermal power plant; nuclear thermal power plant; oil thermal power plant; photovoltaic power plant; wind turbine.

Other types can be found, such as heat and power co-generation, biomass or electricity from municipal waste incineration. However, these groups are considered as fatal energy sources. Therefore, their production will not be affected by the grid project, and it will be identical in both alternatives. Only groups which production is different between the two assessed alternatives should included in the boundaries of the life cycle assessment (c.f. § 5.4.2). Consequently, the modelled power plant types will be limited to the previous list.

As a first approximation, all generation units of the same type and of the same geographic area will be considered to have the same characteristics, and thus, the same LCI data will be used for them. The validity of this assumption will be discussed when applying the methodology to the case-study and a more accurate approach could be used if simulation results show that a grid project shift production between two generation units of the same type but having very different characteristics due to more modern technology level.

Table 8 presents the LCI data which are available in ecoinvent v3.1. Seven countries which are member of ENTSO-E are not covered: Cyprus (CY), Estonia (EE), Iceland (IS), Lithuania (LT), Latvia (LV), Montenegro (ME) and Macedonia (MK). For applying this methodology on a grid project affecting power plants located in these countries, discussion with the local TSO will be needed to decide which alternative data can be used.

Table 8 – Electricity production processes in ecoinvent©, by technology type and country

Country	Code	Hard coal	gas, conventional power plant	hydro, run-of-river	hydro, pumped storage	hydro, reservoir, alpine region	hydro, reservoir, non-alpine region	Lignite	Nuclear BWR	Nuclear PWR	Oil	Peat	Wind, < 1 MW turbine, onshore	Wind, 1-3 MW turbine, onshore	Wind, > 3 MW turbine, onshore	Wind, 1-3 MW turbine, offshore
Austria	AT	X	X	X	X	X					X		X	X	X	
Bosnia and Herzegovina	BA	X		X		X		X			X					
Belgium	BE	X	X	X	X					X	X		X	X	X	X
Bulgaria	BG	X	X	X				X		X	X		X	X	X	
Switzerland	CH		X	X	X	X			X	X	X		X	X		
Czech Republic	CZ	X	X	X	X		X	X		X	X		X	X	X	
Germany	DE	X	X	X	X		X	X	X	X	X		X	X	X	X
Denmark	DK	X	X	X							X		X	X	X	X
Spain	ES	X	X	X	X		X		X	X	X		X	X	x	
Finland	FI	X	X	X			X		X	X	X	X	X	X	X	X
France	FR	X	X	X	X	X				X	X		X	X	X	
United Kingdom	GB	X	X	X	X					X	X		X	X	X	X
Greece	GR		X	X	X			X			X		X	X	X	
Croatia	HR	X	X	X	X	X		X			X		X	X	X	
Hungary	HU	X	X	X				X		X	X		X	X	X	
Ireland	IE	X	X	X	X						X	X	X	X	X	X
Italy	IT	X	X	X	X	X					X		X	X	X	
Luxembourg	LU		X	X	X								X	X	X	
The Netherlands	NL	X	X	X						X	X		X	X	X	X
Norway	NO	X	X		X	X					X		X	X	X	X
Poland	PL	X	X	X	X			X			X		X	X	X	
Portugal	PT	X	X	X	X		X				X		X	X	X	
Romania	RO	X	X	X						X	X		X	X	X	
Serbia	RS		X	X	X	X					X					
Sweden	SE	X	X	X	X				X	X	X	X	X	X	X	X
Slovenia	SI	X	X	X				X		X	X					
Slovakia	SK	X	X	X	X		X	X		X	X		X	X	X	

Data available in ecoinvent will be used as the basis for LCI data used in the assessment. This data represents the current level of technology, but will be assumed to still be valid for the reference year of the assessment. However, LCI data available in ecoinvent is meant to be used for the background system. For 1 kWh of high voltage electricity, a share of the infrastructure production is allocated, by dividing by the expected total electricity production over its lifetime. While this assumption is valid for a background system process, it must be re-evaluated for a foreground system process. In the two assessed alternatives, the load factor of the same power plant is not the same. Therefore, the total electricity production will be different. As discussed in the system boundaries definition in § 5.5, only flows which are proportional to the electricity production shall be considered. In order to decide whether an input or output of the ecoinvent process shall be taken into account or not, the assumptions explained in the "comment" section of the ecoinvent product shall be used.

An example of modification is given for the type "hydroelectric power plant, reservoir" in table 9. Regardless of the electricity production, the land use from the power plant and the reservoir are the same. The infrastructure process "Hydropower plant, reservoir, alpine region" can also be removed. Finally, methane and dinitrogen monoxide emissions are presented as being proportional to the surface of the reservoir, which is identical in both alternatives.

Table 9 – Life cycle inventory data for the ecoinvent process and the corresponding adaptation made for hydroelectric power plants.

Flows included in the original ecoinvent dataset: Electricity, high voltage {FR} | electricity production, hard coal	**Location**	**Category**	**Subcategory**	**Infrastructure process**	**Included in the modified dataset**
Resources					
Occupation, water bodies, artificial	-	resource	land	-	No
Energy, potential (in hydropower reservoir), converted	-	resource	in water	-	Yes
Water, turbine use, unspecified natural origin	FR	resource	in water	-	Yes
Transformation, to industrial area	-	resource	land	-	No
Transformation, to water bodies, artificial	-	resource	land	-	No
Volume occupied, reservoir	-	resource	in water	-	No
Transformation, from unknown	-	resource	land	-	No
Materials/fuels					
Hydropower plant, reservoir, alpine region | market for	GLO	technosphere		1	No
Lubricating oil| market for	GLO	technosphere		0	Yes
Emissions to air					
Water/m3	-	air		-	Yes
Methane, biogenic	-	air	low. pop.	-	No
Dinitrogen monoxide	-	air	low. pop.	-	No
Emissions to water					
Water	FR	water		-	Yes
Waste to treatment					
Waste mineral oil | market for	GLO	waste		0	Yes

The same adaptation must be done for every type of power plant. As a general rule, infrastructure processes can always be left out of the scope, as well as inputs related to land transformation and occupation.

A particular attention should be paid to electricity storage in pumped-storage hydroelectric facilities. In ecoinvent, for each kWh produced by a pumped-storage facility, 1.43 kWh is consumed from the market for high voltage electricity (70% efficiency). As shown in § 5.5.2, this flow in an internal flow of the foreground system, and shall therefore not be inventoried. The adaptations made for the assessment of the Cergy-Persan project in the case study of deliverable 6.3 will be made explicit.

7 METHODOLOGY FOR IMPACT ASSESSMENT

In the previous section, the methodology for collecting and processing data for the LCA of a grid project was described. Using data available in ecoinvent, the product and waste flows which have been inventoried following data collection can be translated into elementary flows (pollutant emissions, natural resources consumption). From this inventory, environmental impacts can be calculated thanks to life cycle impact assessment models.

LCA can cover a large spectrum of environmental impacts, and not all of them are relevant to the assessment of grid projects. Moreover, life cycle environmental impact indicators will be some of the many indicators which are calculated to evaluate the costs and benefits of grid projects. A selection of the most relevant indicators is therefore necessary in order not to limit the amount of information to communicate to decision-makers and stakeholders.

7.1 Generalities on life cycle impact assessment

There are several methodologies for life cycle impact assessment. This is currently a very active research field and new methodologies are under development. All these methodologies share however common characteristics which will be presented below.

Three entities to be protected, called areas of protection (AoP), are commonly considered in life cycle assessment: Human health, Natural environment and Natural resources. Environmental impacts are linked to one or more AoP. To evaluate environmental impacts, environmental mechanisms, also called impact pathways, are modelled. They represent the chain of cause-effect relationships linking an environmental intervention (natural resource consumption, pollutant emission) to damage in one AoP. Figure 6 presents a simple environmental mechanism for the category Ozone depletion, affecting both Human Health and Natural Environment areas of protection.

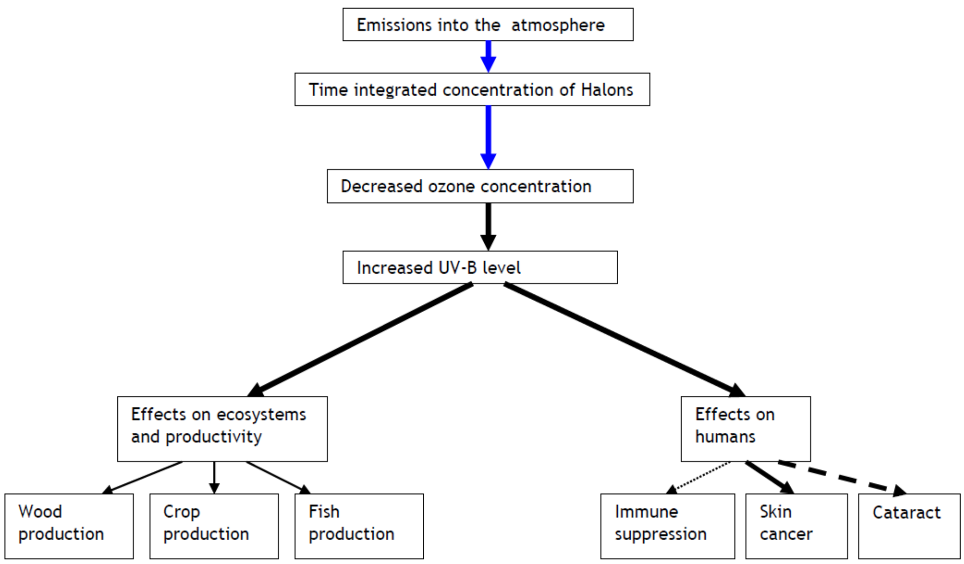

Figure 6 – Environmental mechanism for ozone depletion (EC-JRC, 2010a)

For each impact category considered in LCA, an environmental mechanism similar to the one presented in Figure 6 is identified. Environmental impact categories most commonly covered are:

- Climate change: anthropogenic emissions of greenhouse gases enhance the radiative forcing of the atmosphere (i.e. heat radiation absorption), causing the future climate to change, which will affect both human health and ecosystems.
- Stratospheric ozone depletion: the stratospheric ozone layer blocks a large part of the harmful UV radiation before it reaches the Earth's surface. Certain substances have the potential to destroy stratospheric ozone and thereby increase the amount of radiation that reaches the surface, which causes damage to human health.
- Human toxicity: the emission of certain substances can contribute to the risk of toxicological impacts and associated consequences on human health
- Ionising radiation: this category covers the impacts arising from releases of radioactive substances as well as direct exposure to radiation.
- Respiratory inorganics / Particulate matter: fine particulate matter with a diameter of less than 10 µm (PM_{10}) causes health problems as it reaches the upper part of the airways and lungs when inhaled. Secondary PM_{10} aerosols are formed in air from emissions of sulphur dioxide (SO_2), ammonia (NH_3) and nitrogen oxides (NO_x) among others.
- Acidification: atmospheric deposition of inorganic substances causes a change in acidity in the soil. For almost all plant species there is a clearly defined optimum of acidity. A serious deviation from this optimum is harmful for that specific kind of species.
- Eutrophication: Eutrophication arises from the oversupply of nutrients, which induces explosive growth of plants and algae which, when such organisms die, consume the oxygen in the body of water.
- Eco-toxicity: this impact category covers the impacts of toxic substances on aquatic and terrestrial ecosystems.
- Land use: human land use can have a range of consequences, such as land competition, loss of biodiversity or loss of life support function,
- Water resource depletion: water for food is one of the main global issues and irrigation is a limiting factor in agricultural production. Reduced water availability caused by water consumption leads to reduced availability for food production
- Abiotic resource depletion: abiotic resources are natural resources (including energy resources) such as iron ore, crude oil and wind energy, which are regarded as non-living.

Figure 7 presents the impact categories and their connection to areas of protection. The identification of an environmental mechanism is only a qualitative evaluation of an impact. To get a quantitative evaluation, defining a corresponding indicator is required. When an indicator is defined at an intermediate stage of the environmental mechanism, it is called a problem-oriented indicator, or midpoint indicator. When it is defined at the last stage of the environmental mechanism, it is called a damage-oriented indicator, or endpoint indicator. For example, the Global Warming Potential (GWP), measured in kg CO2 equivalent, is the indicator commonly used to measure an impact on Climate Change. GWP is a midpoint indicator, but climate change affects both human health and the natural environment, and endpoint indicators can also be defined.

At the midpoint level, each indicator measures an impact of a different nature, in its own unit, and therefore they cannot be directly compared to each other. This is not the case for endpoint indicators related to the same area of protection. Indeed, these indicators measure impacts having the same nature, and can be aggregated into a single value after conversion in the same unit.

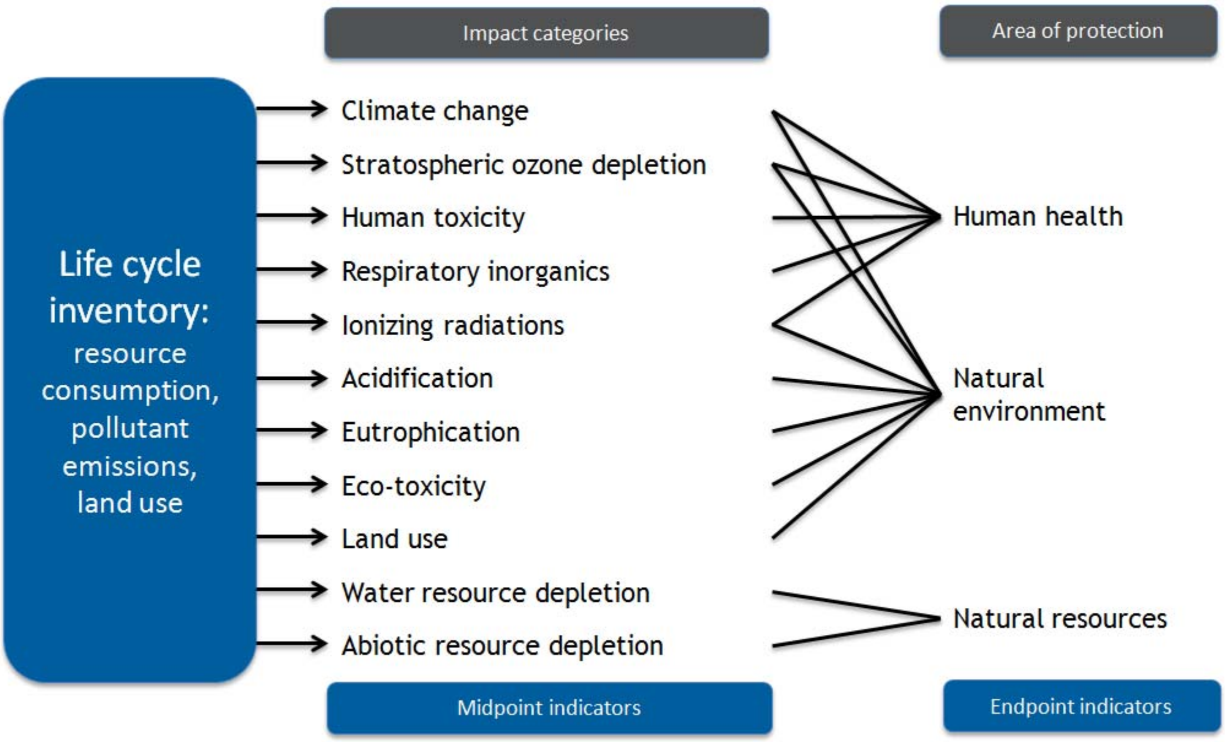

Figure 7 – Life cycle impact assessment: relationship between impact categories and areas of protection. Based on impact categories recommended by (EC-JRC, 2010a)

Midpoint and endpoint indicators have their own strengths and weaknesses. Using endpoint indicators, a unique indicator can be defined for each area of protection, facilitating results communication to an audience who is not familiar with LCA. However, this simplification implies also a bigger uncertainty, because the whole environmental mechanism has to be modelled. Midpoint indicators are generally more reliable, but their bigger number induces more difficult communication to non-specialised audience.

7.2 Selection of indicators

As part of the ILCD handbook, various life cycle impact assessment methodologies were reviewed and recommendations on the best methods for each impact categories were produced (EC-JRC, 2011). The selection of LCA indicators for INSPIRE-Grid will be based on these recommendations. ILCD handbook recommends to include by default all environmental impact categories, and to exclude only those which have been identified as not relevant. The use of midpoint indicators is preferred, as they are deemed more reliable and less uncertain.

However, some of the recommended models are not yet compatible with the ecoinvent database. The recommended model for water resource depletion for instance requires a geographically differentiated inventory of water consumptions and emissions, which is not available in ecoinvent. For water depletion, the net water consumption will be calculated, by performing an inventory of all water consumptions and all water emissions to aquatic environment.

The environmental issue related to radioactive waste is only partially covered by the impact category "Ionising radiation". Indeed, this indicator does not consider radiations during the storage of radioactive waste. The indicator from the EDIP 2003, as implemented in ecoinvent (Hischier et al., 2010), calculating the weight of radioactive waste to be stored.

Finally, as the development of the transmission grid is closely related to the European objectives in terms of energy efficiency, it would be interesting to separate energy resource depletion from mineral resource depletion. A midpoint indicator of primary energy usage expressed in MJ will be defined, using the model of Cumulative Energy Demand (Jungbluth, Frischknecht, 2010). This is the basis for the model recommended by ILCD. For mineral resources, the model "abiotic resource depletion", the model recommended by ILCD will be used, after removing all characterisation factors related to energy resources in order to avoid double counting with the Cumulative Energy Demand.

Table 10 presents the complete indicator set, composed of 17 indicators, based on the ILCD recommendations.

Table 10 – Summary of models and indicators to be used for the complete indicator set

Impact category	Complete indicator set	
	Model	**Indicator**
Climate change	IPPC,2007	Global Warming Potential 100 years (CO2 equivalent)
Ozone depletion, midpoint	WMO,1999	Ozone Depletion Potential (kg CFC-11 equivalent)
Human toxicity midpoint, cancer effects	USEtox (Rosenbaum et al., 2008)	Comparative Toxic Unit for Human Health (CTUh)
Human toxicity midpoint, non cancer effects	USEtox (Rosenbaum et al., 2008)	Comparative Toxic Unit for Human Health (CTUh)
Particulate matters	RiskPoll model (Rabl, Spadaro, 2004 ; Greco et al., 2007)	PM2.5 equivalent
Ionising radiation, human health	(Frischknecht et al., 2000)	Ionizing Radiation Potentials
Radioactive waste	Weight of radioactive waste	kg
Photochemical ozone formation	(van Zelm et al., 2008) as applied in ReCiPe2008	POCP
Acidification	(Seppälä et al., 2006 ; Posch et al., 2008)	Accumulated Exceedance (AE)
Euthrophication, terrestrial	(Seppälä et al., 2006 ; Posch et al., 2008)	Accumulated Exceedance (AE)
Euthrophication, aquatic freshwater	ReCiPe2008 ; EUTREND model (Struijs, Beusen, et al., 2009)	Phosphorus equivalent
Eutrophication, aquatic marine	ReCiPe2008 ; EUTREND model (Struijs, Beusen, et al., 2009)	Nitrogen equivalent
Ecotoxicity freshwater	USEtox (Rosenbaum et al., 2008)	Comparative Toxic Unit for ecosystems (CTUe)
Land use	(Milà i Canals et al., 2007)	SOM (kg C deficit)
Water resource depletion	Net water consumption	m^3 of water
Energetic resource depletion	Cumulative energy demand	MJ primary energy
Mineral resource depletion	CML 2002 (Guinée et al., 2002)	Scarcity (Antomony equivalent)

As part of INSPIRE-Grid, LCA results of grid projects are intended to be communicated to stakeholders in order to support their decision making. They will likely be presented with other costs and benefits of a grid project (technical, socio-economic or environmental). Having 17 indicators only for LCA could overload the information and interfere with a good understanding of its global environmental impacts. Consequently, a reduction of the number of environmental categories is necessary.

Environmental impact categories are commonly aggregated by using endpoint indicators measuring the damage to an AoP. Impacts to the same AoP due to different impact categories can be aggregated as long as they measure the same damage expressed in the same unit. This could reduce the number of indicators to only three, which would be more in line with the constraints of stakeholder communication. However, there are two issues with this approach. First, grid projects are particularly related to the European energy policy, closely connected to two environmental issues: climate change and energy resource depletion. Using only three endpoint indicators would hide the contribution of the impact categories. Secondly, although there are several LCIA methodologies with models for endpoint indicators, the review performed in the ILCD handbook concluded that there are no models which can be recommended for endpoint except for photochemical ozone formation and particulate matter. Some 'interim methods' were however identified, meaning that these methods are considered to be the most promising among the ones available for a given impact category, but still immature to be recommended. The ILCD handbook (EC-JRC, 2011) states:

"The methods and factors defined as interim are to be used only with extreme caution, and limited to in-house applications, given the considerable uncertainty, incompleteness and/or other shortcomings of the methods and factors. [...] The fact that an impact category at midpoint or endpoint has no recommended methods [...] does not mean that it is not relevant to include in a study, but merely that at the moment no existing method was found sufficiently mature for recommendation. This should not be taken as a recommendation to exclude this specific impact category, but to apply a method which has been identified by the practitioner as the current best practice for the specific application. However, in the study the uncertainty and the limitations have to be clearly stated".

Despite the lack of recommended methods for endpoint indicators, their use appears to be relevant for stakeholder communication. Indeed, using seventeen midpoint indicators would result in practice to the exclusion of some impact categories, as stakeholders would be overloaded with information and would only take into account a few of them, likely the ones they are familiar with. Given the high uncertainty of endpoint models, their use will however be limited and the reduced set of indicators will include a combination of both midpoint and endpoint indicators.

Climate change is a well-known issue, and the Global Warming Potential, expressed as a mass of CO2 equivalent, is commonly used to measure this environmental impact. Keeping this midpoint indicator seems therefore more relevant that using endpoint models, which have a higher uncertainty.

For impact categories related to the 'Natural Resource' AoP, the use of midpoint indicator shall be preferred, as endpoint models are either non-existent or have low environmental significance. The three midpoint indicators will therefore be retained.

Regarding impacts related to radioactive waste, the use of a specific indicator evaluating the weight of radioactive waste appears to be relevant. Ionising radiations from the radioactive matter can cause human health issues, but they also have to be stored for a long period of time. In the French context, where more than 75% of electricity is produced from nuclear power, including a specific indicator for this environmental issue is relevant. It is included for instance in the European standard defining the application of LCA for the building sector.

For all other impact categories, endpoint models will be used to aggregate results into two indicators evaluating the damage to human health and to ecosystems.

For impact categories related to Human Health (ozone depletion, human toxicity, particulate matter, ionizing radiations and photochemical ozone formation), the interim endpoint methods identified by ILCD will be used. Results from these methods are calculated in DALY (Disability-Adjusted Life Years), which represents a number of years of life lost, adjusted with disability. As all these endpoint indicators measure an environmental impact of the same nature (damage to human health) in the same unit (DALY), they can be added up together. The categories will therefore be aggregated in a single indicator measuring the damage to human health.

For the impact categories the categories related to Ecosystems quality (acidification, freshwater eutrophication and land use) the models from ReCiPe 2008 (Goedkoop et al., 2009), identified by the ILCD handbook as interim methods, will be used. Terrestrial and marine eutrophication, as well as freshwater ecotoxicity will not be included, as no method has been identified by the ILCD, even as "interim method".. The ReCiPe LCIA methodology, from which are taken all the other endpoint models for damage to ecosystems, also includes models for ecotoxicity (terrestrial, aquatic and marine). Nevertheless, ILCD judged that the overall concept of endpoint effects factors for ecotoxicity is hardly validated.

The choice of priorities depends on each local context and decision makers. The following set is proposed as an example. Seven indicators composing the reduced indicator set and the models used are presented in table 11.

Table 11 – Example of reduced indicator set, with associated models

Impact category	Reduced indicator set	
	Model	**Indicator**
Climate change	IPPC,2007	GWP100
Energetic resource depletion	Cumulative energy demand	MJ primary energy
Abiotic resource depletion	CML 2002 (Guinée et al., 2002)	Scarcity (Antimony equivalent)
Water resource depletion	Net water consumption	m^3 of water
Radioactive waste	Weight of radioactive waste	kg
Ozone depletion, endpoint human health	ReCiPe2008 (Struijs, van Jaarsveld, et al., 2009 ; Struijs et al., 2010)	Damage to human health (DALY)
Human toxicity, cancer effects	DALY calculation applied to CTUh of USEtox (Huijbregts et al., 2005)	
Human toxicity, non cancer effects	DALY calculation applied to of CTUh USEtox (Huijbregts et al., 2005)	
Particulate matters	Adapted DALY calculation applied to midpoint (van Zelm et al., 2008 ; Pope et al., 2002)	
Ionising radiation	(Frischknecht et al., 2000)	
Photochemical ozone formation	(van Zelm et al., 2008) as applied in ReCiPe2008	
Acidification	(Van Zelm et al., 2007) as applied in ReCiPe	Damage to ecosystems (PDF)
Euthrophication, aquatic freshwater	ReCiPe2008 (Struijs, Beusen, et al., 2009)	
Land use	ReCiPe2008	

LCA calculations will be performed using both indicators sets. Depending on the aims and requirements of a particular stakeholder information process, one of the two indicator sets can be chosen. The reduced set represents the minimal information which shall be communicated in order to provide a global picture of the environmental impacts of a grid project at a global scale. Individual indicators from the complete set can be added when communicating results to stakeholders if they are deemed relevant to a particular context. This will be discussed in deliverable 6.3 when applying the methodology on the Cergy-Persan case study.

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